

Measuring what matters in sustainable rice production

TEEBAgriFood Thailand EU-funded project

Final draft Report

2024

Prepared by Khon Kaen University



Researchers

Phumsith Mahasuweerachai

Adcharaporn Pagdee

Jakrapun Suksawat

Nidtaya Nidchaun

Nutchanat Chamchoi

Phasita Toonsiri

Piyaluk Bhuddhawongsa

Tanapipat Walalite

Voravee Saeng-awut

Warong Suksavate



Contents

Contents

Researchers	2
Introduction and background	19
1. TEEBAgriFood initiative in Thailand	19
1.1 Visible and invisible costs and benefits	20
2. Summary of TEEBAgriFood Thailand assessment on organic rice	21
3. Introducing the TEEBAgriFood Thailand assessment on sustainable rice.....	24
3.1 Global project outline.....	24
3.2 Focus in Thailand.....	24
3.3 Key partners	26
3.4 Analytical approach.....	28
Part 1: Thai policies and plans to transform agricultural sector	30
1.1 National level policies and strategic plans for transformation to sustainability.....	30
1.2 Policies and plans for sustainable rice production, healthy agricultural practices	31
Part 2: Scope of the Assessment	34
2.1 Policy questions	34
2.1.1 Pro-nature incentives for rice farmers – monetary and non-monetary	34
2.1.2 Valuing biological, and livelihoods of rice systems in the BGC economy.....	35
2.2 Scenarios of land use change.....	37
Scenario 1: Business as Usual (BAU).....	37
Scenario 2: Moderate scenario	38
Scenario 3: Enhanced Scenario	38
Scenario 4: Transformational Scenario.....	38
2.3 Definitions and parameters	40
2.3.1 Defining the geographical scope	40
2.3.2 Defining the scope of sustainable rice management practices	40
2.3.3 Defining the temporal scope	44
Part 3: Land Use Change Modelling.....	46
3.1. Method of Spatial analysis	46

3.2 Results	50
3.2.1 Geographical characteristics of the NE region, Thailand	50
3.2.2 Land use Classification of NE region	51
3.2.3 Land use change prediction in two-time period (T1 and T2)	54
3.2.4 Driving variables for land use change	56
3.2.5 Transition potential selection	58
3.2.6 Validity test of land use prediction	60
3.2.7 Land use change prediction under future scenarios	61
3.2.8 Geographical characteristics of the central region, Thailand	66
3.2.9 Land use Classification of the Central region	67
3.2.10 Land use change prediction in two-time period (T1 and T2), central region, Thailand	68
3.2.11 Driving variables for land use change in the central region*	70
3.2.12 Transition potential selection of land use in the central region, Thailand.*	73
3.2.13 Validity test of land use change prediction for the central region*	75
3.2.14 Land use change prediction under future scenarios of the central region	77
3.3 Spatial analysis integrated with data on farmer adoption of sustainable rice practices. ..	81
3.4 Summary	82
Part 4 Greenhouse Gas Emissions	84
4.1 Greenhouse gas emissions, soil carbon stock and rice grain yields	84
4.2 Material and method	85
4.2.1 Study design	85
4.2.2 DNDC model description	86
4.2.3 Validation of the model performance	87
4.2.4 Study sites	88
4.2.5 Long-term simulations of multi-site location	89
4.2.6 Rice field management practices	92
4.3 Results	101
4.3.1 Long-term GHG emission estimations under different rice field management practices	101
4.3.2 CH ₄ emissions from the rice fields	101
4.3.3 N ₂ O emissions from the rice fields	104

4.3.4 Total GHG emissions (CH ₄ and N ₂ O emissions)	107
4.4 Greenhouse gas emissions, soil carbon stock and rice grain yields from cultivation based on scenario analysis	110
4.5 Post-harvest GHG from rice residue burning	120
4.5.1 Method for calculation of emissions of GHG and PM 2.5 from rice residue burning	122
4.5.2 Results of GHG from residue burning.....	124
Summary	137
Part 5 Production Economy and Livelihood.....	140
5.1 Household economic information	140
5.2 Rice yield estimations under different field management practices and different climate scenarios	148
5.3 Factors that influence decision to adopt/ not adopt GAP or SRP rice farming	156
5.4 Consumer preference.....	159
Methodology.....	160
5.5 Summary	172
Part 6 Biodiversity: Insects and trees on farm	174
6.1 Introduction	174
6.2. Landscape Analysis for sampling schemes	176
6.3. Insects sampling	178
6.4. Quantifying biodiversity for the insects.....	179
6.5. Spatial Modeling for Biodiversity of the insects	181
6.6. Summary of Insects' diversity surveys.....	182
6.7. Observed Species Richness and diversity indices of the insects	183
6.8. Estimated pooled biodiversity; rice farming practices and geography has a different impact on biodiversity.....	186
6.9. Species Richness and diversity indices among functional groups of Insects.....	188
6.10. Relative abundance of functional groups	194
6.11. Spatial modeling and estimation of biodiversity	196
6.12. Summary for biodiversity of insects in rice cultivation landscape	214
6.13. Trees on the Farms.....	217
6.14. Farmer's climate change adaption	221
Part 7 Water use in rice cultivation: Water supply, quality, and footprint	225
Introduction	225

7.1 Methods.....	226
7.1.1 Measurement of water supply	227
7.1.2 Measurement of water quality.....	227
7.1.3 Estimation of water footprint.....	228
7.1.4 Investigation of farming practice and farmer adaptation to climate change	230
7.2 Results.....	230
7.2.1 Climatic conditions and variability in the past 25 years (1997-2021)	230
7.2.2 Hydrological ecosystem service – water supply	232
7.2.3 Water usage and farming practice in rice cultivation	235
7.3. Scenario analysis of water footprint: Green, blue, and grey	247
Part 8 Social Capital.....	253
8.1 Happiness information.....	253
8.2 Social capital.....	256
8.3 Social Network	258
8.4 Summary	262
Part 9 Health Impacts.....	264
9.1 Health-related economic costs of exposure to pesticides used in rice systems	264
9.1.1 Methodology and results	264
9.2 Health-related economic costs of exposure to PM 2.5 from rice burning.	273
Results.....	276
9.2.1 Health cost caused by PM2.5 analysis according to scenarios	278
9.3 Summary	285
Part 10 Scenario Analysis	287
Introduction	287
10.1 Financial proxies.....	288
10.2 Scenario analysis	290
Part 11 Conclusion and Policy Recommendations.....	311
Policy Discussion and Recommendations.....	314
Theory of change	317
317	
References.....	318
Appendix 1 Requirements of SRP Standard, Biodiversity, and GHG emissions	325

Appendix 2: Supplementary of biodiversity part.....	330
Appendix 3: Table 6.1. List of plant species and number of individuals recorded on the sampled rice paddies.	341
Appendix 4 <i>The greenhouse gases (GHG) emissions, soil organic carbon stocks (SOC), and rice yield from seven rice field management practices under different climate model, RCP 4.5 and 8.5, in the Northeast and Central of Thailand</i>	344
Appendix 5: Table 6.2. Amounts of water use in rice cultivation under different scenarios and cultivation practices with yearly data during 2025-2050.	401
Appendix 6: The value of GHG emission was represented by average closing spot prices of Thailand Greenhouse Gas Management Organization.....	412
Appendix 6.1 the overall benefit values of double crops option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	412
Appendix 6.2 the overall benefit values of double crops option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	413
Appendix 6.3 the overall benefit values of rice-maize option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	414
Appendix 6.4 the overall benefit values of rice-maize option in more details in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	415
Appendix 6.5 the overall benefit values of rice-sunn hemp option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	415
Appendix 6.6 the overall benefit values of rice-sunn hemp option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	416
Appendix 6.7 the net benefit values of double crops option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	417
Appendix 6.8 the net benefit values of rice-maize option comparing between the northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	417
Appendix 6.9 the net benefit values of rice-sunn hemp option comparing between northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton	418
Appendix 6.10 The shapes of trade-off chart with rice-rice option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	419

Appendix 6.11 The scenario analysis based on values with rice-rice option in more details in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	419
Appendix 6.12 The shapes of trade-off chart with rice-maize option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton.....	420
Appendix 6.13 The shapes of trade-off chart with rice-sunn hemp option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	420
Appendix 6.14 The scenario analysis based on values with rice-maize option in more details in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	421
Appendix 6.15 The scenario analysis based on values with rice-sunn hemp option in more detail in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	421
Appendix 6.16 The shapes of trade-off chart with rice-rice option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton.....	422
Appendix 6.17 The shapes of trade-off chart with rice-maize option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	422
Appendix 6.18 The shapes of trade-off chart with rice-sunn hemp option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	423
Appendix 6.19 The scenario analysis based on values with double crops option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	423
Appendix 6.20 The scenario analysis based on values with rice-maize option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	424
Appendix 6.21 The scenario analysis based on values with rice-sunn hemp option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton	424
Appendix 6.22 the overall benefit values of double crops option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton	425
Appendix 6.23 the overall benefit values of double crops option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton.....	425
Appendix 6.24 the overall benefit values of rice-maize option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton	426

Appendix 6.25 the overall benefit values of rice-maize option in more details in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton.....	427
Appendix 6.26 the overall benefit values of rice-sunn hemp option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton	427
Appendix 6.27 the overall benefit values of rice-sunn hemp option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton.....	428
Appendix 6.28 the net benefit values of double crops option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton	428
Appendix 6.29 the net benefit values of rice-maize option comparing between the northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton	429
Appendix 6.30 the net benefit values of rice-sunn hemp option comparing between northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton	430
Appendix 6.31 The shapes of trade-off chart with rice-rice option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	430
Appendix 6.32 The scenario analysis based on values with rice-rice option in more details in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	430
Appendix 6.33 The shapes of trade-off chart with rice-maize option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	431
Appendix 6.34 The shapes of trade-off chart with rice-sunn hemp option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	431
Appendix 6.35 The scenario analysis based on values with rice-maize option in more details in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	432
Appendix 6.36 The scenario analysis based on values with rice-sunn hemp option in more detail in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	432
Appendix 6.37 The shapes of trade-off chart with rice-rice option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	433

Appendix 6.38 The shapes of trade-off chart with rice-maize option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	433
Appendix 6.39 The shapes of trade-off chart with rice-sunn hemp option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	434
Appendix 6.40 The scenario analysis based on values with double crops option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	434
Appendix 6.41 The scenario analysis based on values with rice-maize option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	435
Appendix 6.42 The scenario analysis based on values with rice-sunn hemp option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton	435

Figures and Tables

Figure a: TEEBAgriFood evaluation framework applied to the rice sector	20
Figure b: SRP Standard comprises 41 requirements structured under eight themes	26
Figure 1.1 Thailand's long-term low greenhouse gas emission scenario	31
Figure 3.1 LCM method to predict land-use change	47
Figure 3.2 The maps of rice production under the GAP program for rice and the mega rice farm project (Sources: Rice department, MoAC).....	50
Figure 3.3 the study area of land use change	51
Figure 3.4 Land use classification of the study area in NE region Year 2022	53
Figure 3.5 Land use classification in NE Year 2022	53
Figure 3.6 Land use two periods of the NE region in 2016 (T1) and 2018 (T2).....	54
Figure 3.7 Change analysis of land use in NE during 2016 and 2018 using Land Change Modeler	55
Figure 3.8 LU class contribution to the net change in the SRP rice area, northeast region.....	56
Figure 3.9 Driver variables for transition potential of land-use change analysis in the NE region.	58
Figure 3.10 Maps of transition potential of SRP rice cultivation area in the northeast region, Thailand.	59
Figure 3.11Validation of the NE land use prediction based on the observed 2021 LU and simulated 2021 LU.....	60

Figure 3.12 the sustainable rice area prediction in the NE as business as usual (Scenario 1	62
Figure 3.13 The sustainable rice area prediction in the NE under Scenario 2	63
Figure 3.14 The sustainable rice area prediction in the NE under Scenario 3	64
Figure 3.15 The sustainable rice area prediction in the NE under Scenario 4	65
Figure 3.16 The geographical characteristics of the study area in the central region, DEM 30m by 30m	66
Figure 3.17 Land use classification of the study area in central region Year 2022	67
Figure 3.18 Land use classification in Central region Year 2022	68
Figure 3.19 Land use two periods of the central region in 2016 (T1) and 2018 (T2)	69
Figure 3.20 Change analysis of land use in central during 2016 and 2018 using Land Change Modeler	69
Figure 3.21 LU class contribution to the net change in the SRP rice area, northeast region	70
Figure 3.22 Driver variables for transition potential of land-use change analysis in the central region.	72
Figure 3.23 Maps of transition potential of SRP rice cultivation area in the central region, Thailand	75
Figure 3.24 Validation of the central land use prediction based on the observed 2021 LU and simulated 2021 LU	76
Figure 3.25 The sustainable rice area prediction in the central region under Scenario 1	77
Figure 3.26 The sustainable rice area prediction in the central region under Scenario 2	78
Figure 3.27 The sustainable rice area prediction in the central region under Scenario 3	79
Figure 3.28 The sustainable rice area prediction in the central region under Scenario 4	80
Figure 3.29 Conceptual framework for analysis of farmer adoption of SRP	82
Figure 4.1 Scope of the study	86
Figure 4.2 Structure of the DNDC Model (Li, 2016, as cited in Yin et al., 2020)	87
Figure 4.3 Rice varieties in different rice sub-ecosystem (DOAE, 2017; Varinruk, 2017)	88
Figure 4.4 Mean daily temperature over 2021-2050 of the studied sites	90
Figure 4.5 Total precipitation over 2021-2050 of the studied sites	90
Figure 4.6 Schematic illustrations of the crop calendar and field management practices (Cha-un <i>et al.</i> , 2021).	91
Figure 4.7 Schematic illustrations of the seven conditions	93
Figure 4.8 Annual CH ₄ emissions from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions	104
Figure 4.9 A schematic representation of C-N interactions in the terrestrial ecosystem (Guenet <i>et</i> <i>al.</i> , 2020)	105
Figure 4.10 Annual N ₂ O emissions from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions	106
Figure 4.11 Annual total GHG emissions from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions	108
Figure 4.12 SOC stocks of topsoil (0-30 cm in depth) from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions	110
Figure 4.13 Monthly total particulate matter emission from rice residue burning in 2002	121
Source: Garivait, S., Bonnet, S., & Kamnoed, O., 2008	121

Figure 4.14 GWP from burning rice residues according to each scenario (million tons of CO ₂ eq)	
northeast.....	132
Figure 4.15 GWP from burning rice residues according to each scenario (million tons of CO ₂ eq)	
central.....	133
Figure 4.16 Particulate emissions (PM _{2.5}) from burning rice residues in each Scenario (tons)	
northeast.....	133
Figure 4.17 Particulate emissions (PM _{2.5}) from burning rice residues in each Scenario (tons)	
central.....	134
Figure 4.18 Particulate emissions (PM ₁₀) from burning rice residues in each Scenario (tons)	
northeast.....	134
Figure 4.19 Particulate emissions (PM ₁₀) from burning rice residues in each Scenario (tons)	
central.....	135
Figure 4.20 Cumulative reduction of GHGs (CH ₄ and NO _x) from residue burning in terms of	
GWP emission relative to BAU scenario (MTCO ₂ eq) in the Northeast region	136
Figure 4.21 Cumulative reduction of GHGs (CH ₄ and NO _x) from residue burning in terms of	
GWP emission relative to BAU scenario (MTCO ₂ eq) in the Central region.....	136
Figure 5.1 Rice yields from seven practices over 2021-2050 in lower northeast, upper northeast,	
and central regions	152
Figure 6.1 The landscape characteristic of rice paddies in northeast Thailand was clustered into	
eight strata used as a guild line for the field surveyed. The strata were used as the ecotype to	
represent biodiversity assessment.	177
Figure 6.2 The landscape characteristic of rice paddies in central Thailand was clustered into five	
strata used as a guild line for the field surveyed. The strata were used as the ecotype to represent	
biodiversity assessment.....	178
Figure 6.3 Observed species richness and biodiversity indices consisting of Shannon and	
Simpson diversity indices from sampling sites in the northeastern region of Thailand. The	
boxplots compare each observed sample index between conventional practice and SRP.	184
Figure 6.4 Observed species richness and biodiversity indices consisting of Shannon and	
Simpson diversity indices from sampling sites in the central region of Thailand. The boxplots	
compare each observed sample index between conventional practice and SRP.	185
Figure 6.5: Rarefaction Curve comparing Species Richness, Beta-biodiversity (Bray-Curtis	
Dissimilarity Index), Shannon Diversity Index, and Simpson Diversity Index between	
Conventional Farming Practice and the SRP in the Northeastern Region of Thailand.	187
Figure 6.6: Rarefaction Curve comparing Species Richness, Beta-biodiversity (Bray-Curtis	
Dissimilarity Index), Shannon Diversity Index, and Simpson Diversity Index between	
Conventional Farming Practice and the SRP in the Central Region of Thailand.	188
Figure 6.7 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis	
dissimilarity index, Shannon diversity index, and Simpson diversity index of predator function	
groups between conventional farming practice and SRP in the northeastern region of Thailand	
.....	190
Figure 6.8 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis	
dissimilarity index, Shannon diversity index, and Simpson diversity index of pest function	
groups between conventional farming practice and SRP in the northeastern region of Thailand	
.....	191

Figure 6.9 Rarefaction curve of species richness of decomposer function groups between conventional farming practice and SRP in the northeastern region of Thailand	192
Figure 6.10 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index of predator function groups between conventional farming practice and SRP in the central region of Thailand.....	193
Figure 6.11 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index of pest function groups between conventional farming practice and SRP in the central region of Thailand.....	194
Figure 6.12 Relative abundance of pest and predator functional groups and abundance ratio between predator and pest in central and northeast region.	196
Figure 6.13 Importance index of random forest model to spatially predict Shannon diversity index of insect species. The predicted map of the Shannon diversity index in the northeastern region of Thailand.....	200
Figure 6.14 Importance index of random forest model to spatially predict Simpson diversity index of insect species. The predicted map of the Simpson diversity index in the northeastern region of Thailand.....	201
Figure 6.15 Importance index of random forest model to spatially predict Shannon diversity index of insect species. The predicted map of the Shannon diversity index in the central region of Thailand.	202
Figure 6.16 Importance index of random forest model to spatially predict Simpson diversity index of insect species. The predicted map of the Simpson diversity index in the central region of Thailand	203
Figure 6.17 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 1.....	204
Figure 6.18 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 2.....	205
Figure 6.19 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 3.....	206
Figure 6.20 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 4.....	207
Figure 6.21 Shannon diversity index of each spatial unit pixel (300 meters resolution) of predicted future scenarios of the northeastern region of Thailand	208
Figure 6.22 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 1	209
Figure 6.23 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 2.	210
Figure 6.24 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 3.	211
Figure 6.25 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 4	212
Figure 6.26 Shannon diversity index of each spatial unit pixel (300 meters resolution) of predicted future scenarios of the central region of Thailand.	213
Figure 6.27. Rice paddies and trees on farm in some of the SRP surveyed sites: a-b. Surin, c-d. Ubonratchathani, e-f. Chai Nat and g-h. Suphanburi.....	220
Figure 7.1. Methodological framework for the study on water use in rice cultivation.....	227

Figure 7.2. Correlations between forest areas (%) and some key climatic conditions i.e., amounts of rainfall (mm/year), relative humidity (%), minimum and maximum temperature (degree Celsius).	233
Figure 7.3. A step-through diagram of crop water requirement and crop water use calculation.	237
Figure 7.4. Water quality in the sampled rice paddies in the Central Plain and the Northeast ..	241
Figure 7.5. Grey water footprint with different crop seasons and planting methods.....	243
Figure 7.6 Projected areas of rice cultivation: irrigated vs. rain-fed rice in the Central Plain and the Northeast during 2025-2050	248
Figure 7.7 Projected amounts of crop water use (WU green = rainwater and WU blue = irrigated water) in rice cultivation: irrigated (Irr) vs. rain-fed (RF) rice in the Central Plain and the Northeast during 2025-2050	248
Figure 7.8. Amounts of water use (m ³ /ha): green, blue and grey water based on the projected yields of dry-season (DS) and rain-fed (RF) rice in the Central Plain and the Northeast.	250
Figure 7.9. Amounts of water use in rice cultivation based on the projected yields under different scenarios: SC1-SC4 and cultivation practices: the CON and SRP practice during 2025-2050. Note: DS = dry-season rice and RF = rain-fed rice	251
Figure 7.10. Amounts of water use based on the projected yields under different scenarios: SC1-SC4 and cultivation practices: the CON and SRP practice with yearly data during 2025-2050.	251
Figure 8.1 Characteristics and eigenvector centrality of individuals who have been chosen as role models in different social statuses.	262
Figure 9.1 Spatial distribution of provincial economic health cost in 2021 assessed by AHC method. The northeast region is on the left panel and central region is on the right panel. The yellow dots indicate paddy fields from the household survey	277
Figure 9.2-A PM2.5 concentration from residue burning in each scenarios of NE region, Thailand.	280
Figure 9.3-B PM2.5 concentration from residue burning in each scenarios of central region, Thailand	281
Figure 9.4. Comparison of Economic cost for all-cause mortality related to PM2.5 from rice burning according to the four scenarios for years from 2021 to 2050, in all provinces of NE Thailand.	282
Figure 9.5 Comparison of Economic cost for all-cause mortality related to PM2.5 from rice burning according to the four scenarios for years from 2021 to 2050, of a central region, Thailand	283
Figure 9.6. Average health costs caused by all-cause mortality from exposure to PM2.5 from rice residue burning.....	285
Figure 10.1 the overall benefit values of double crops option in each scenario from 2021 to 2050 compared to BAU	291
Figure 10.2 the overall benefit values of double crops option in more details in each scenario from 2021 to 2050 compared to BAU	291
Figure 10.3 The overall benefit values of rice-maize option in each scenario from 2021 to 2050 compared to BAU	292
Figure 10.4 the overall benefit values of rice-maize option in more details in each scenario from 2021 to 2050 compared to BAU	293
Figure 10.5 the overall benefit values of rice-sunn hemp option in each scenario from 2021 to 2050 compared to BAU	294
Figure 10.6 the overall benefit values of rice-sunn hemp option in more details in each scenario from 2021 to 2050 compared to BAU	294

Figure 10.7 the net benefit values of double crops option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU	296
Figure 10.8 the net benefit values of rice-maize option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU	297
Figure 10.9 the net benefit values of rice-sunn hemp option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU	297
Figure 10.10 The shapes of trade-off chart with rice-rice option in central region in each scenario from 2021 -2050 compared to BAU	299
Figure 10.11 The scenario analysis based on values with rice-rice option in more details in central region in each scenario from 2021 -2050 compared to BAU	299
Figure 10.12 The shapes of trade-off chart with rice-maize option in central region in each scenario from 2021 -2050 compared to BAU	300
Figure 10.13 The shapes of trade-off chart with rice-sunn hemp option in central region in each scenario from 2021 -2050 compared to BAU	301
Figure 10.14 The scenario analysis based on values with rice-maize option in more details in central region in each scenario from 2021 -2050 compared to BAU	301
Figure 10.15 The scenario analysis based on values with rice-sunn hemp option in more details in central region in each scenario from 2021 -2050 compared to BAU	302
Figure 10.16 The shapes of trade-off chart with rice-rice option in the northeast region in each scenario from 2021 -2050 compared to BAU	304
Figure 10.17 The shapes of trade-off chart with rice-maize option in northeast region in each scenario from 2021 -2050 compared to BAU	304
Figure 10.18 The shapes of trade-off chart with rice-sunn hemp option in northeast region in each scenario from 2021 -2050 compared to BAU	305
Figure 10.19 The scenario analysis based on values with double crops option in more details in northeast region in each scenario from 2021 -2050 compared to BAU	305
Figure 10.20 The scenario analysis based on values with rice-maize option in more details in northeast region in each scenario from 2021 -2050 compared to BAU	306
Figure 10.21 The scenario analysis based on values with rice-sunn hemp option in more details in northeast region in each scenario from 2021 -2050 compared to BAU	306
Figure 10.22 The distributional accumulated value in rice-rice option from the fourth scenario, 2021 to 2050	307
Figure 10.23 The distributional accumulated value in rice-maize option from the fourth scenario, 2021 to 2050	308
Figure 10.24 The distributional accumulated value in rice-sunn hemp option from the fourth scenario, 2021 to 2050	309
Figure 10.25 The fourth scenario middle term accumulated net benefit of revenue and cost of production dimension in northeast region during 2021 to 2035	310
Figure 10.26 The fourth scenario middle term accumulated net benefit of revenue and cost of production dimension in central region during 2021 to 2035	310

Table 2.1 Summary projected expansion of sustainable rice practice in alternative scenarios	39
Table 2.2 Parameters / assumptions for analysis for each scenario	43
Table 3.1 Data for the LCM analysis	48

Table 3.2 The elevation of Northeast region classification	51
Table 3.3 The classification and description of land utilization in 2022 used for this study.....	52
Table 3.4 the change analysis of NE land use in each class between 2016 and 2018	56
Table 3.5 Cremer's V association test of driving factors for the NE region	58
Table 3.6 The elevation of Central region classification	66
Table 3.7 the change analysis of land use in central region each class between 2016 and 2018 .	70
Table 3.8 Cremer's V association test of driving factors for the central region	73
Table 4.1 Thai rice field experiment and parameters for model validation	87
Table 4.2 Study sites in Central and Northeast regions, Thailand	89
Table 4.3 Soil properties in the study sites.....	91
Table 4.4 Crop calendar and field management practices for 7 cropping conditions.....	95
Table 4.5 Rice yields (kg C/ha/y) from farmer practice and recommended yield from Rice Department.....	98
Table 4.6 Averaged yields of mung bean and maize in Northeast and Central regions	98
Table 4.7 Compound fertilizer application rates from farmer practice	99
Table 4.8 Compound fertilizer application rates from RD's recommendation and secondary data	101
Table 4.9 Accumulated CH ₄ , N ₂ O, and total emissions in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050	111
Table 4.10 The annual SOC stocks in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050	115
Table 4.11 Value of emission factors.....	123
Table 4.12 Amount of rice residues generated (RRG) from conventional rice fields in the Northeast region.....	125
Table 4.13 Amount of rice residues generated (RRG) from conventional rice fields in the Central region	125
Table 4.15 Quantity of Rice residues subjected to open burning (RRB) in the Central region ...	126
Table 4.16 Mass of burned dry matter in the Northeast region.....	126
Table 4.17 Mass of burned dry matter in the Central region	127
Table 4.18 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, BAU scenario.....	127
Table 4.19 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, Scenario 2	129
Table 4.20 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, Scenario 3	129
Table 4.21 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, Scenario 4	129
Table 4.22 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, BAU scenario	130
Table 4.23 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, Scenario 2	130
Table 4.24 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, Scenario 3	131

Table 4.25 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, Scenario 4	131
Table 5.1 Household Questionnaire – Key to issues investigated	140
Table 5.2 Gender and age characteristics of conventional, GAP, and SRP rice farmers from survey	142
Table 5.3 Cost and income of wet season rice production from rice farmer household survey .	146
Table 5.4 Key statistics from household survey of conventional, GAP, and SRP rice farmers	147
Table 5.5 Conditions of rice field management practices for the simulation	148
Table 5.6 The annual rice production in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050	152
Table 5.7 Survey responses to what do farmers switch from conventional to GAP or SRP rice	157
Table 5.8 Survey responses to the main factor preventing conventional rice farmers switching to sustainable rice practices.....	157
Table 5.9 Survey responses on the key incentives to encourage conventional rice farmers switching to sustainable rice practices	158
Table 5.10. Factors disincentivized Sustainable rice farmers to continue sustainable rice practice	159
Table 5.11 Attributes and levels	161
Table 5.12 Example of choice set	163
Table 5.13 Results of the estimation of the consumers’ choice experiment.....	169
Table 5.14 Monetary value of each attribute elicited from consumer’s choice experiment.....	169
Table 6.1 Biodiversity and functional diversity sampling schemes.	179
Table 6.2 Total number of families, genera, and species of insects across sampling sites from rice paddies in each stratum and rice farming practices in the northeastern region of Thailand. NA indicates no sampling effort was made.	182
Table 6.3 Total number of families, genera, and species of insects across sampling sites from rice paddies in each stratum and rice farming practices in the central region of Thailand.....	183
Table 6.4 Land use covariates in randomForest models to predict species richness and diversity indices.	198
Table 6.5 Bioclimatic variables used in random forest models to predict species richness and diversity indices	198
Table 6.6. Number of trees and species observed on farms by rice farming practices.....	218
Table 6.7. A summary of key indicators suggests that the SRP is more environmental-friendly than the CON practice.....	218
Table 6.8. Farmer’s water management practices and.....	221
Table 6.9. Climate change adaptation practices of the interviewed farmers.	223
Table 6.10. Information on farmer’s adaptation practice	223
Table 6.11. Farmer’s needs to assist them to adapt to climate change.	224
Table 7.1. Water footprints (WF) of different cash-crop types.	226
Table 7.2. Eight water quality parameters to be measured from different rice fields.....	228
Table 7.3. Climatic conditions during 1997-2021 by provinces.....	231
Table 7.4 Amounts of rainfall and runoff water in Thailand’s main river basins during 1995-2018	234
Table 7.5. Amounts of rainfall and runoff water in Thailand’s main river basins grouped by regions.....	235

Table 7.6. Depth of rainfall (during 1997-2021), environmental flow (EF), amounts of rainwater after subtracted by EF, natural annual runoff and available water for use in the study provinces	235
Table 7.7. Crop water requirements (ETc), effective rainfall (Pe _{eff}), irrigation water requirement (IR) and crop water use (CWU) by regions, cultivation seasons and planting methods	238
Table 7.8. Average fertilizer application rates and average rice yields for the rain-fed rice and irrigated rice cultivation	239
Table 7.9 Average concentrations of water samples from sampled paddy rice fields.....	240
Table 7.10. WF _{grey} of the rain-fed rice and irrigated rice cultivation in the study provinces...	242
Table 7.11. Rice yields, crop water use and water footprints by regions	244
Table 7.12. Rice yields, crop water use and water footprints by type of planting methods	245
Table 7.13. Rice yields, crop water use and water footprints by type of cultivation practices. .	246
Table 7.14. Rice yields and amounts of water footprints by regions and cultivation practices..	246
Table 7.15. Projected yields and amounts of water use based on water footprints (2020-2050.	249
Table 7.16. Amounts of water use in rice cultivation under different scenarios and cultivation practices with summed amounts of water use in the CON and SRP practice.....	252
Table 8.1 The happiness level and factors influencing happiness of rice farmers	255
Table 8.2 the social relations among three types of rice farmers.....	257
Table 9.A Frequency of pesticide commonly used and the average expenditure on pesticide by cultivation practice.....	265
Table 9.1 Number of households that reported health effects from pesticides by cultivation practice	266
Table 9.2 Incidence of illness (percentage of households that reported health effects from pesticides) by cultivation practice.....	267
Table 9.3 The predicted cost of illness (COI) (Reported health care and opportunity costs) by cultivation practice	268
Table 9.4 Defensive expenditure by cultivation practice.....	269
Table 9.5 The estimated health cost from survey by cultivation practice.....	270
Table 9.6 The estimated health cost from survey and benefit transfer, by cultivation practice	271
Table 9.7 Estimated Health Cost based on the AHC approach 2021	277
Table 10.1 The monetary proxy per unit of factors	289

Introduction and background

1. TEEBAgriFood initiative in Thailand

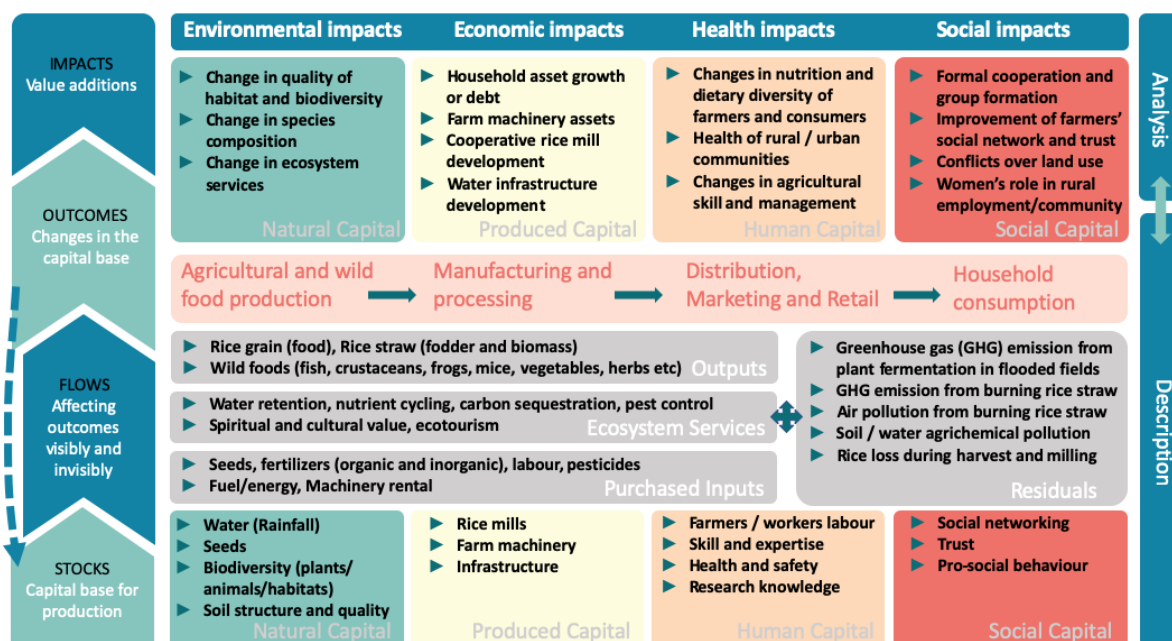
A transformative change in food systems is needed in order to meet the internationally agreed Sustainable Development Goals. The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgriFood) initiative was developed by the UN Environment Programme (UNEP) in response to this need and seeks to achieve positive human livelihood outcomes and biodiversity improvements. The overall programme goals are to measure and mainstream the values of nature in decision-making and policy, to highlight the hidden, and often invisible, contributions of nature to agricultural production, and trade-offs made in land-use decisions, to highlight links of agricultural systems with human health, culture, and other ecosystems at the landscape level, and based on this scientific research, to work with partners and key stakeholders on pathways to implementing reform of national policies and measures for meeting the Sustainable Development Goals by 2030.

The TEEBAgriFood Evaluation Framework and approach was developed through a collaboration of scientists from many different countries and disciplines. This approach is synthesized in the report “Measuring What Matters in Agriculture and Food System” (UNEP, 2018) and described in more detail in the “TEEB for Agriculture & Food Scientific and Economic Foundations” report (UNEP, 2018). The key components of the framework are illustrated below in Figure a, highlighting the dependencies of the rice system upon stocks of natural, produced, social and human capitals and the value additions and impacts that the rice production system generates.

Based on the inception workshop for the TEEBAgriFood initiative in Thailand in 2018, the rice sector was selected as the key focus for the TEEBAgriFood in Thailand. Rice production is integral to Thailand’s culture, agricultural landscapes and rural livelihoods. About 20 percent of the nation’s households, or 4.30 from 21.58 million households, are rice farmers (National Statistical Office, 2019). Significantly, the rice cultivation area extends over 50 percent of total agricultural area in Thailand, about 9.59 million hectares (Office of Agricultural Economic, 2020). The cumulative impacts of production practices at farm level are therefore significant not only at regional level but also at national and international levels. Rice production generates just under 25

percent of all raw agricultural produce in Thailand. Moreover, several agricultural industry products are developed from rice output. Rice production is not only significant for Thailand but also for global food security. Despite its relatively small area, Thailand is one of the top three rice exporters in the world (FAOSTAT, 2020).

Contributions to human well-being of rice production



Adapted from TEEBAgriFood Evaluation Framework (UNEP, 2018)

Figure a: TEEBAgriFood evaluation framework applied to the rice sector

1.1 Visible and invisible costs and benefits

As illustrated by the TEEBAgriFood evaluation framework in figure a above, rice production is dependent on the resources of natural, human, social and produced capital, as well as the flows of inputs and outputs throughout the agricultural value chain that interact with ecosystem services and residual processes. In combination, these flows create changes and impacts on natural, human, social and produced capitals, and ultimately, if the system works well, should contribute overall to human well-being.

Within this picture, purchased inputs and labor are the most visible contributions to rice production, and the economic value of the harvest is often analyzed in these terms, and influenced by local and global market demand and supply and other operational costs. However, the rice economy should not ignore all the other contributions to the production of rice, just because they exist outside the framework of the market. These “externalities” generate values that may be

equally, or in some cases such as public health and cultural heritage, that may be even more important to Thai society. If the production system, including the later stages of the supply chain from farm to fork, progressively undermine the capitals on which Thailand depends, then this system is not sustainable over the long term. Thailand relies on these capitals for its rice harvests, for other critical production systems, and for well-being of the Thai people.

The TEEBAgriFood project aims to institutionalize a process that incorporates of the main key values of rice production in decision-making. We want to understand not only what is gained in terms of revenues, and spent in terms of production costs, but also the gains and costs in natural, human and social capital. When policy makers include the full range of costs and benefits in decision making, they should be better able to manage the system toward sustainability. The goals of food security and income security, improving environmental and health impacts are important and interdependent, and reaching them is likely to require trade-offs. This assessment will shed light on how to reduce trade-offs between these different goals, and to identify synergies that allow for maximizing benefits and the better well-being of farmers, while minimizing costs to environment and society.

2. Summary of TEEBAgriFood Thailand assessment on organic rice

The TEEBAgriFood assessment in Thailand funded by International Climate Initiative (IKI” project”) was completed in June 2022. In summary, this project sought to measure and make visible diverse costs and benefits of rice production as a means to identify options for promoting long term sustainability of production and management of rice landscapes. A scenario analysis was prepared based on projected land use changes from conventional to organic rice practice.

Four scenarios were developed to understand potential future impacts of government policies, including the One Million Rai Organic Rice promotion policy, and Parliamentary targets for achieving sustainable agriculture by 2030. This analysis demonstrated the potential trade-offs generated as organic rice production practices in Thailand are extended over an increasingly large area of the North East of Thailand, over the period 2019-2035. Project outputs are available online (<https://teebweb.org/where-we-work/asia-pacific/thailand/>).

The key conclusions of the organic rice assessment were as follows:

1. To reach the aims of the Bio-, Circular, and Green Economy model in Thailand of more sustainable growth and more environmental responsibility, a transition is needed towards fully sustainable rice production and sustainable landscape management.
2. The impact of changes needs to be assessed at the landscape level, as farm-level results give an incomplete picture because they fail to capture the full range of impacts, externalities and dependencies in the system.
3. It is important to make visible the connections between nature and rice food systems by quantifying the oft invisible flow of benefits from ecosystems to food systems and human well-being. This involves identifying where, how much and to whom nature provides benefits, showing the impacts of Business As Usual, and what would be the comparative impacts under alternative agri-environmental planning policy scenarios for the future.
4. Rice yields are affected by cultivation practices, seeds, and environmental conditions. Often, when considering whether a switch to organic from conventional is viable and desirable, it is assumed that rice yield under organic production will be diminished in the short to medium term. However, the findings of this study project relatively minor losses, both in terms of volume output and dollar value, as a result of adopting the alternative scenarios relative to BAU.
5. The emission of greenhouse gases (GHG) from rice fields is generated by cultivation practices (organic fermentation), post-harvest practices (stubble burning), and mitigated by soil carbon sequestration. The expansion of organic rice area as projected in the alternative scenarios 2, 3 and 4 would reduce overall GHG emissions, due to the stubble burning prohibition and high soil carbon accumulation in organic rice fields. Overall, organic rice practice generates lower overall GHG emissions per hectare than conventional rice practice.
6. Biodiversity is affected by cultivation practices. With expansion of organic rice, agrobiodiversity increases, especially insect varieties, at landscape level, which promotes natural pest control.
7. The impacts of conventional rice production have negative externalities on human health. The analysis found that policy pathways for organic rice expansion improve human health, through reduced exposure to pesticides and air pollution.

8. Organic rice production generates other benefits to human wellbeing for society, food, and culture.
9. Farmers' decision to adopt and/or continue to grow rice organically depends on policy support, particularly during the transitional period, and price incentives.

The key policy recommendations developed from the assessment were as follows:

- The main subsidy policies in agriculture have been focused on reducing farmers' financial hardship, but this does not encourage farmers to adopt more sustainable practices. To induce farmers to adopt organic practice, subsidies need to be reoriented, conditional on adopting sustainable agricultural practice, such as organic rice practice.
- On average, organic rice yields are lower than conventional rice yields, but not significantly so. The loss of income from the marginally lower yield for organic farmers would be directly offset as long as farmers can sell their organic rice at a price that is least 3.5 percent higher than that of conventional price.
- Organic rice practice generates positive externalities through health and environmental improvements. However, when these positive externalities cannot be completely included or realized by market system, government should step in to minimize market distortion to ensure the public still benefits from positive externalities generated by organic rice farmers activities. In addition, organic rice farmers receive not only positive returns from cultivation cost reduction and health improvement but also generate positive return to their local community and wider society.
- Exporting organic rice to international market requires different certifications depending on countries. To share cost of getting certification to ensure profitability for farmers, policies aimed to enhance more organic rice production should focus on promoting the grouping of farmers into discreet areas that can be certified as organic instead of at individual level.

3. Introducing the TEEBAgriFood Thailand assessment on sustainable rice

3.1 Global project outline

The scope of the global project financed by the European Union Partnership Instrument (EUPI) is to protect biodiversity and contribute to a more sustainable agriculture and food sector in seven countries (Brazil, China, India, Indonesia, Malaysia, Mexico and Thailand). The Economics of Ecosystems and Biodiversity (TEEB) Evaluation Framework will be used to test interventions that have already been applied or are proposed to stimulate positive livelihood and biodiversity benefits, and assess whether and to what extent they produce hidden or unaccounted for outcomes on natural, human, social and manmade capitals. Importantly, the focus of the project is on biodiversity and ecosystems, which underpin the delivery of the Sustainable Development Goals. The project will bring together governments, business and other key actors from civil society to implement activities with a view to influencing decisions and behaviors.

3.2 Focus in Thailand

The research scope will be a TEEBAgriFood assessment of commercial rice sector who are receptive to looking at dependencies and impacts on biodiversity and ecosystem services. This work would focus on sustainable production practices as advocated under the Sustainable Rice Platform (SRP)¹ Standard for Sustainable Rice Cultivation (SRP Standard). The study will focus on clarifying the effects of specific cultivation practices relevant to the SRP Standard on natural capital, human capital, social capital, and produced capital following TEEBAgriFood Evaluation Framework. Appendix 1 presents the details of what measures we cover in this study.

3.2.1 Sustainable Rice Platform (SRP), SRP Standard, and GAP++

The Sustainable Rice Platform (SRP), established in 2011 by internationally organizations such the International Rice Research Institute (IRRI), the United Nations Environment Programme (UNEP) and Deutsche Gesellschaft für International Zusammenarbeit GmbH (GIZ), aims to transform the global rice sector through voluntary market transformation towards sustainable production practices. It focuses on improving smallholder livelihoods, reducing the social and

¹ For more information of the Sustainable Rice Platform (SRP), <https://www.sustainablerice.org/>

environmental footprint of rice production, promoting resource efficiency, reduced carbon emissions and resilience to climate change.

The SRP Standard is an internationally accepted sustainability standard for rice, which comprises 41 requirements structured under eight themes (see figure b). The Standard presents a framework to support claims to sustainability.

In Thailand, the Rice Department of the Ministry of Agriculture and Cooperatives have drafted a new GAP Standard for Rice that is consistent with the SRP Standard and adapted to the Thai context. This is colloquially referred to as the “GAP++” Standard for rice. Specifications are available online in Thai from the Bureau of Agricultural Commodities and Food Standards ACFS (www.acfs.go.th/files/files/commodity-standard/20220602160717_661890.pdf). The GAP++ Standard is currently being introduced to farmers through the Thai Rice NAMA project in Ayutthaya, Ang Thong, Chainat, Sing Buri, Suphanburi, Pathum Thani, and Ubon Ratchathani (https://www.thai-german-cooperation.info/en_US/mainstreaming-sustainable-rice-through-the-sustainable-rice-platform-project/). The TEEBAgriFood analysis will focus on five key management practices that promote sustainability which relate directly to the SRP themes of “biodiversity” and “greenhouse gas emissions.”

Figure b: SRP Standard comprises 41 requirements structured under eight themes



3.3 Key partners

Steering Committee

TEEBAgriFood Thailand is an initiative under the political lead of the Office of Natural Resources and Environmental Policy and Planning, ONEP, in the Ministry of Natural Resources and Environment.

The Steering Committee engages agencies within the Ministry of Natural Resources and Environment including two offices within ONEP, the Climate Change Management and Biodiversity Management Offices, the Department of Pollution Control, and the Department of Environmental Quality Promotion. Agencies engaged within the Ministry of Agriculture and Cooperatives include the Department of Agriculture, Department of Agriculture Extension, Department of Fisheries, Department of Livestock Development, National Bureau of Agricultural Commodity and Food Standards, and the Rice Department.

Three additional agencies have been added to the Steering Committee: The Fiscal Policy Office, within the Ministry of Finance, the Department of Disease Control, within Ministry of Public Health, and Department of Internal Trade, within the Ministry of Commerce. In addition, the Committee includes a representative from the Office of the National Economic and Social Development Council.

Research team

The Economics Faculty of Khon Kaen University is the host research institution of the TEEBAgriFood Thailand Initiative, leading a team of researchers from local universities and government agencies to carry out a multidisciplinary analysis of rice agroecosystems.

Donor and project support

The TEEBAgriFood project is managed by UNEP with the funding and project support from the European Union through the European Partnership Instrument, with the support of the EU Delegation in Bangkok.

Private sector engagement

The TEEBAgriFood initiative engages private sector groups in transformation of the agrifood sector through a parallel set of activities under the TEEBAgrifood for business project. This seeks to support private sector actors to understand the complex ways in which they depend and impact on the health of ecosystems for their success, and provide a clear business case for investing in environmental protection and restoration. The project will identify areas where nature-based solutions can be implemented to deliver benefits for business, nature and communities and develop collaborative partnerships at regional and national levels between key players in the agri-food value chain.

The Capitals Coalition, in collaboration with UNEP and the partners of the TEEBAgriFood initiative, have developed a series of activities with national business network partners, including the Global Compact Network of Thailand and the Scholars of Sustenance.

In addition to these activities, the public sector component of the project which is described in this report, is seeking to engage private sector agencies within the membership of the Sustainable Rice Platform, who are operating in the commercial rice sector in Thailand to seek their

perspectives on the adoption of project results to make the business case for investing and incentivizing sustainable rice practices.

International partners

The TEEBAgriFood initiative is being developed by UNEP in Brazil, China, India, Indonesia, Mexico, Malaysia and Thailand in collaboration with local partners, with the support of the European Union Partnership Instrument. Opportunities for South-South exchange and learning are organized throughout the project to include government partners, research partners and private sector representatives engaged in each country.

3.4 Analytical approach

The research goes beyond comparing different rice production practices or systems, to include an analysis of the comparative impact of concrete policy instruments, frameworks and pathways at the national and subnational level. These different policy intervention scenarios will be analyzed in terms of changes in stocks and flows of produced, natural, social and human capital. Policy recommendations will put forward initiatives to achieve greater gains for sustainability of rice systems using the following approach:

- The analysis is forward-looking, applying predictive modeling; scenarios allow the presentation of information on the comparative change in four capitals under the application of different policy initiatives, instruments or programmes. This would allow decision-makers (regulators, agri-businesses and farmers) to see the trade-offs that arise through application of different policy measures, as compared with Business-As-Usual (BAU).
- The analysis is carried out at the landscape level. Spatial models generate results at a local/regional scale (e.g., watershed level) and present them on a map; Analysis at this landscape level (beyond farm-level or narrow crop focus) takes into account landscape configuration (for example habitat fragmentation) and context (for example proximity to landscape features such as watercourses), as these are key factors in determining impacts on many ecosystem services and biodiversity.
- The analysis seeks to link science and policy processes at an early stage. TEEB Country Studies are social processes - co-creation process by policymakers, the

scientific community and other stakeholders forms an important part of the achievement. It will be important not only to engage the Office of Natural Resources and Environmental Policy and Planning (ONEP), and the Ministry of Environment and Natural Resources, which Chairs the Project Steering Committee, but also to reach out to key stakeholders from other relevant Ministries, including the Ministry of Agriculture and Cooperatives, Ministry of Finance, and the Ministry of Public Health, private sector and civil society groups.

The project also develops work to mainstream the findings of both the initial and follow up TEEBAgriFood studies on rice in Thailand into the training activities and materials used by the government's agricultural extension services.

Part 1: Thai policies and plans to transform agricultural sector

1.1 National level policies and strategic plans for transformation to sustainability

Thailand's 20-Year National Strategy (2018-2037)² emphasizes sustainable development and inclusive growth. The sub strategy in the topic of agriculture and sustainable development highlighted promoting safe, biological and smart agriculture, green economy, ecosystem services and environmental quality. Sustainable agricultural products and improving the air quality index have been targeted in the strategic plans.

The Ministry of Agriculture and Cooperatives (MOAC) has enacted the 20-year Agricultural and Cooperatives Strategy (2017-2036)³, which focuses on promoting farmer institutions, increasing farming efficiency, escalating the adoption of product standards, boosting agricultural competitive advantages through the use of technologies, and balancing agricultural resource use with sustainability. One of the targets is to increase the area of sustainable agriculture from 0.81 million rai (0.13 million ha) in 2017 to 10 million rai (1.6 million ha) in 2036.

The shorter-term 13th National Development plan (2023-2027)⁴ also contains the target of sustainable agriculture, which is more challenging as it sets a target to increase the area under sustainable agriculture to 10 million rai (1.6 million ha) by the end of 2027.

Climate change is one of the main risk factors affecting the agricultural sector. The MOAC developed the Agriculture Climate Change Strategy (2017-2021)⁵, which focuses on reducing GHG emissions by using environmentally friendly technologies in agricultural production such as reducing post-harvesting burning, soil management to improve soil carbon stocks, and promoting low carbon agricultural standards.

The National Master Plan on Climate Change (2015-2050)⁶ has been introduced by Office of Natural Resources and Environmental Policy and Planning (ONEP). In the topic of agricultural sector, this plan promotes water management for flooding and drought, crop-zoning strategy, biodiversity and biological technologies, as well as maintaining ecosystem richness. Besides

² <http://nscr.nesdc.go.th/ns/>

³ www.oae.go.th/assets/portals/1/files/bapp/strategic2560-2579.pdf

⁴ www.nesdc.go.th/main.php?filename=plan13

⁵ https://old.alro.go.th/research_plan/ewt_dl_link.php?nid=1888&filename=index

⁶ https://climate.onep.go.th/wp-content/uploads/2019/07/CCMP_58-93_TH.pdf

focusing on GHG emissions reductions from the industry and transportation sectors, this plan also targets to reduce GHGs emission from agricultural sector, which includes reductions of post-harvest stubble burning, rice cultivation, and promoting low carbon agricultural standards.

At the World Leaders Summit of the Conference of the Parties in 2021 (COP26), Thailand proposed to reach carbon neutrality by 2050, and net zero GHG emissions by or before 2065. The main roadmap to reduce CO₂ for carbon neutrality in 2030 was mainly focused on the energy, transportation, waste management, and industry sectors. The agricultural sector is not yet highlighted in the road map for reaching net zero GHG emissions by 2065. However, the issue of agricultural sector in waste management, sustainable agriculture, and low carbon cultivation were mentioned.

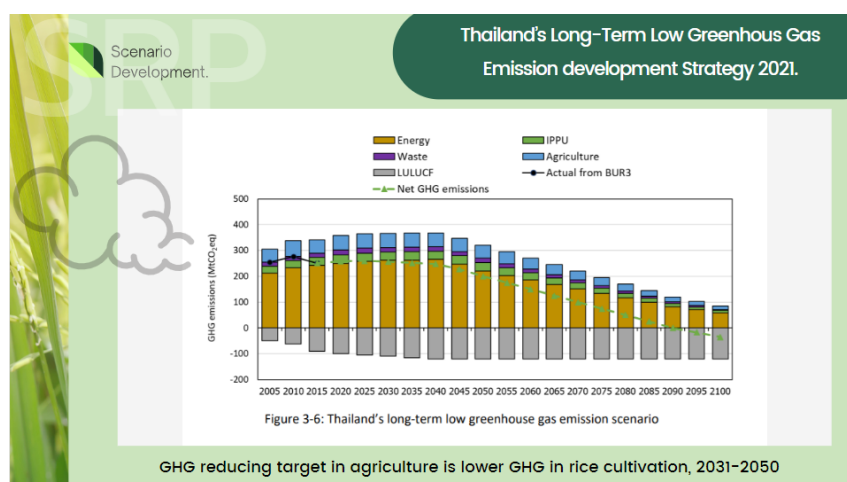


Figure 1.1 Thailand's long-term low greenhouse gas emission scenario

Moreover, the Bio-Circular-Green (BCG) Economy model has been endorsed as the national strategy for Thailand to escape from the middle-income status trap in 2021-2027⁷ which supports sustainable development goals. One of main strategies is to promote sustainable agriculture.

1.2 Policies and plans for sustainable rice production, healthy agricultural practices

To promote sustainable rice production, environmentally-friendly rice cultivation standards have been progressively adopted in Thailand. The Thai Good Agricultural Practices

⁷ https://climate.onep.go.th/wp-content/uploads/2019/07/CCMP_58-93_TH.pdf

(GAP) Standard introduced under the Agricultural Standards Act (2008) ⁸ aims to encourage farmers to produce agricultural products that are safe for consumers. The GAP+ program and GAP++ program was later introduced to extend the related Standard including verification of product quality, ensure farmers safety, and certification of GHG emissions reductions. The Standard referred to as “GAP++ for Rice” was developed on the basis of Standard of the Sustainable Rice Platform (SRP) and is currently supported under the progress of the Thai Rice NAMA project⁹.

The government’s Thai rice Nationally Appropriate Mitigation Action (Rice NAMA) project in collaboration with GIZ (2018-2023) aims to help farmers in the central part of the country to start applying low greenhouse gas emission methods, as a step towards the development of “low-carbon” rice products.

In addition, the Thai Organic Agriculture Standard was promoted under the National Organic Agriculture Development Strategy (2017-2021, BE. 2560-2564). The Organic Rice Standard developed by the Rice Department has been generated to support organic rice production that qualifies for the Organic Thailand certificate. More information about this Standard can be found in the full findings report of the TEEBAGriFood (IKI-funded) project on the expansion of organic rice.

The government also promotes the public awareness of safe food and certified agricultural products that directly link to consumer health in order to promote a change in public attitudes and consumer behavior. Thailand’s public health policy relating to the safety of agricultural food is also aligned with the agricultural pesticide regulations. The National Hazardous Substances Committee decided in 2019 to ban the herbicide paraquat and insecticide chlorpyrifos with effect from June 2020. The use of the herbicide Glyphosate was restricted by this Committee at the same time, and can be used only in certain agricultural activities, including conventional rice cultivation, as long as this is approved and supervised by local authorities. The Ministry of Public Health has supported to ban these three pesticides by educating farmers and tracking pesticide contamination in farmers’ blood for awareness raising.

⁸ https://www.acfs.go.th/standard/download/eng/GAP_Food_Crop.pdf

⁹ <https://www.nama-facility.org/news/nama-facility-funding-approved-to-support-the-implementation-of-the-thai-rice-nama/>

To increase farming efficiency, the Rice Mega Farm scheme was introduced since 2017 to encourage sharing economy in rice farms, to improve economies of scale including in farm planning, product marketing and distribution, and to support farmer institution and technology adaptation such modern equipment. The economic crop zoning from MOAC has been introduced to define suitable areas for cultivating cash crops according to soil attributes and crop requirement criteria.

In the financial sector, Green Credit provided by the Bank for Agriculture and Agricultural Cooperatives (BAAC) offers loans to support farmers who adopt organic and sustainable agricultural practices. In addition, financial subsidy schemes for rice farmers are still implemented by the Ministry of Agriculture and Cooperatives on an annual basis. These schemes include the farmers' income guarantee scheme and rice price guarantee scheme. These schemes mainly focus on reducing farmers' financial hardship by guarantee farmers' income and stabilizing rice price for farmers without imposing any conditions to adopt new technologies and practices that would be able to improve productivity and provide better environment quality. Even though, these schemes would help solving farmers financial hardship especially in the short-run, they also have the effect of disincentivizing farmers to adopt new technology and practices that could increase productivity and improve environmental quality, which would improve and stabilize not only farmers' livelihoods but also generate benefits to public.

The information of policies and plans described above is applied to develop research questions in this study. In addition, they also provide information for scenarios development that focus on the different proportion of conventional and sustainable rice practices areas in this study. The current rice areas of GAP and megafarm project are set as the initial areas for SRP rice. After that the rate of expansion will be defined by three mains strategic targets based on the 20-year Agricultural and Cooperatives Strategy (2017-2036)¹⁰, the 13th National Development Plan (2023-2027)¹¹, and the Thai Parliamentary targets relate to pesticide use regulation¹². The details of scenario set up based on these policies and plans are explained in Part 2 below.

¹⁰ www.oae.go.th/assets/portals/1/files/bapp/strategic2560-2579.pdf

¹¹ www.nesdc.go.th/main.php?filename=plan13

¹² <https://bit.ly/2QOj46D>

Part 2: Scope of the Assessment

2.1 Policy questions

Given the review of policies and plans regarding to improve agricultural sector toward sustainability described in Part 1 above, the research team has engaged the stakeholders in the process of consultation for determining the policy questions, which would be of relevance to the interests of stakeholders. The stakeholders include steering committee members, rice exporters, rice mills, rice farmers with sustainable practices (i.e. organic farmers and GAP farmers), and conventional rice farmers, as well as key resource persons, including SRP Secretariat, and GIZ etc (summary notes of stakeholders meetings are included in the Appendices).

On the basis of consultations with different stakeholders, including the Office for Natural Resources and Environmental Policy and Planning (ONEP), Steering Committee members and participants at a national workshop in Bangkok held in May 2022, farmers, millers and local officials in the Northeast of Thailand, as well as an analysis of existing policy gaps, the following focus topics and policy questions are agreed as the focus of the EU-PI-funded TEEB AgriFood assessment.

2.1.1 Pro-nature incentives for rice farmers – monetary and non-monetary

The well-being of farmers and sustainable livelihoods is a central consideration for Thai policy. The majority of rice farmers in Thailand is smallholders. They often manage plots of less than 2 hectares, and have high ongoing debt, and receive marginal cash incomes from rice farming. Many farmers have limited access to impartial technical advice, limited bargaining power with buyers, limited access to quality farm inputs, machinery and services, and are subject to price variability in unstable markets (millers do not always pay the guaranteed prices). Altogether, rice farmers have little material incentive, or effective means, to transition toward sustainable production practices in consideration of the public good and to reduce impacts upstream and downstream.

Commercial premiums for adoption of sustainable practices are not systematically available for rice farmers. Certification of compliance with internationally recognized standards, such as the SRP Standard, can nevertheless benefit farmers by opening up international market

access and linkages with private sector buyers. Certification is in some cases linked to agricultural stimulus instruments such as the new BAAC green loans scheme¹³, and programme support from the One Million Rai organic rice promotion program¹⁴ subsidizing transition costs and promoting market links.

New incentives for encouraging good practices and discouraging detrimental practices need to be devised to reduce the ecological footprint of agriculture and food systems. The majority of financial support instruments distributed to Thai farmers currently are in the form of unconditional grants and assistance particularly to relieve financial hardship. The analysis will assess reorienting existing instruments, such as subsidy with crop productivity improvement to achieve not only furthering economic development, but also increasing the efficiency of production, boosting resilience to natural disasters, as well as achieving national environmental targets, to develop multiple benefits through a systems approach.

Policy questions to be explored:

- How do small-scale farmers benefit from visible and invisible values due to adopting sustainable agricultural practice such as SRP standard? How do other stakeholders benefit from this adoption? Where could incentives be most equitably directed to encourage good practices?
- What would be the additional value and overall impact of adopting the Sustainable Rice Platform (SRP) Standard for Sustainable Rice Cultivation in Thailand in terms of impact on natural, human, social and produced capitals?
- What is the public sector return on investment (ROI) in promoting pro-nature production?
- What would be the socioeconomic dynamics/ systematic impacts of a change or reorientation of agricultural subsidies towards direct support of nature-positive production methods throughout the rice sector?

2.1.2 Valuing biological, and livelihoods of rice systems in the BGC economy

¹³ For more information of green credit, please visit https://www.baac.or.th/th/content-product.php?content_id=14262.

¹⁴ For details of One Million Rai program, see <http://www.nan.doe.go.th/scanbook%202560/v1870.1.pdf>.

As Thailand aims to achieve a bio- circular and green economy (BCG economy), awareness remains limited of the existing and significant contribution of the country's biodiversity resources to Thailand's agricultural and wider economy and well-being. Thailand is a major exporter of diverse agricultural products. The wealth of Thailand's food culture and knowledge on traditional medicines are based on and only possible due to Thailand's significant plant biodiversity. Already built into Thailand's bio- circular and green economy, there is a large amount of existing knowledge and expertise. Rice farmers in Thailand as elsewhere in the region have developed skills in breeding a high diversity of rice genetic resources. Much of this heritage has been set aside in the past decades as farmers have responded to market signals and government promotion of high yielding and standardised rice varieties. However, seed selection and rice variety breeding skills are still maintained amongst sustainable farmers networks and are supporting the development of niche rice markets.

Thailand's rice production landscapes have different characteristics in different regions. In many areas, rice fields form part of a patchwork of farms and forest areas in a heterogeneous landscape. Even in the more intensive lowland rice production areas served with irrigation, the rice landscape is often interspersed with trees and other border plants, which provide habitats for insect diversity, which links to farmland fertility, and to the rural economy. Rice plot bunds (raised soil walls to keep flood waters in place), and field borders more broadly, are very important spaces for wildlife that interact to enhance the rice ecosystem fertility and for other food plants encouraged by farmers. Maintaining agrobiodiversity in rice fields enhances rates of decomposition of organic material which is important for plant nutrition, as well as resilience to disease and climate change and mitigation.

Diverse rice landscapes, and rice farming communities therefore provide a solid foundation to develop a bio- circular green economy in the rice growing regions of the country. It also links into the increasing scientific interest globally in the multiple systemic linkages between soil health, plant health, animal health, human health, and planetary health.

Policy questions to be explored:

- What is the long-term value of promoting biodiversity in rice landscapes and health impact for farmer and public?

2.2 Scenarios of land use change

To respond to the policy questions, alternative future scenarios are modelled. The scenarios focus on the different proportions of rice area under conventional practice and sustainable rice practice. The plans and policies taken into account in the development of the scenarios for assessment include the current GAP project, GAP++ project, Megafarm project, and Thailand's long term 20-year Strategic Plan (2017-2036), and the related Master Plan for Agriculture that promotes the expansion of Thailand's sustainable products for both domestic and international markets. In addition to the policies and projects focused on agricultural goals, the scenario set up is also based on the National Master Plan on Climate Change (2015-2050) purposed by ONEP, the 13th National Development Plan (2023-2027), and Thai rice Nationally Appropriate Mitigation Action (Rice NAMA) that focus on reducing carbon emissions from agricultural activities. The timeframe for scenario analysis is 28 years, starting in 2022 and ending in 2050.

Four scenarios are presented below which differ in the proportion of conventional rice area and sustainable rice area. It is assumed that there will be no expansion or contraction of the rice growing area in the future to 2050. The projected conversion of land to sustainable rice practices are modelled exclusively in areas which are currently growing rice using conventional methods. The “sustainable rice” areas in the scenarios below are areas which will have been verified to have adopted all five management practices presented in the next section. Note that areas which adopt the more stringent requirements of organic rice farming such as Organic Thailand and IFOAM etc also qualify to be listed as “sustainable rice” areas below.

Scenario 1: Business as Usual (BAU)

The BAU assumes the steady continuation of the current rate of expansion of the GAP and GAP++ program. Since 2014, there has been an average increase of area adopting GAP and GAP++ practices of about 100,000 rai per year (16,000 ha). As of 2022, the area of adoption of “sustainable rice” practices is about 1.2 million rai (192,000 ha). It is assumed that this rate of expansion is continued so that an additional area of 500,000 rai will adopt sustainable rice practices in the Central and Northeastern regions every five years until 2050. The Business as Usual scenario projects that the “sustainable rice” area will reach a total of 4million rai (640,000 ha) by 2050, accounting for 7.58 percent of the country's total rice production area.

Scenario 2: Moderate scenario

Conversion from conventional to sustainable rice practice improves but remains at a low rate.

This scenario assumes that the sustainable rice practice area grows steadily at a moderate rate of adoption following the **target set by the 20-year Agricultural and Cooperatives Strategy purposed by MOAC**, which requires an increase in sustainable agricultural area by about 650,000 rai per year. We assume that about 54 percent of this expansion occurs in rice farming resulting in an approximate increase of sustainable rice area by about 350,000 rai (56,000 ha) per year.

From the baseline of 1.2 million rai (192,000 ha) in 2022, the second scenario projects that the total area of sustainable rice will reach 9,600,000 rai (1,536,000 ha) by 2050, accounting for 18.19 percent of the country's total rice production area.

Scenario 3: Enhanced Scenario

Conversion from conventional to sustainable rice practice occurs at a medium rate.

This scenario envisions a significantly enhanced ambition to promote sustainable agriculture in Thailand based on the **target of 13th National Development Plan** starting in 2023, which targets increasing the total sustainable agricultural area to 4.5 million rai (720,000 ha) by 2027. We assume that about half of this expansion occurs in rice farming. From the baseline of 1.2 million rai (192,000 ha) in 2022, the additional area of sustainable rice practice in this scenario is assumed to rise on average by 1,000,000 rai (160,000 ha) per year. Under this scenario, by 2050, the total sustainable rice practice area would reach 29,200,000 rai (4,672,000 ha), accounting for 55.33 percent of the country's total rice production area.

Scenario 4: Transformational Scenario

Conversion from conventional to sustainable rice practice occurs at a high rate.

This scenario represents the level of sustainable rice practice adoption that is **consistent with the decision of the Thai parliament in 2018, which takes account the 2030 Sustainable Development Goals**, and set a target of 149 million rai or 100% of Thai agricultural land to be cultivated using sustainable agriculture practices by 2030.

Approximately half of Thailand is dedicated to rice, so this target would require that approximately 68,000,000 rai of land adopt sustainable rice practices by 2030.

However, it is recognized by many stakeholders that this goal is very ambitious and may be difficult to achieve, especially in the short run. There is a large gap between current levels of adoption and proposed targets in 8 years' time. There are also many structural barriers to change, including high levels of farmer indebtedness, income poverty, and risk aversion, incomplete market development or sustainable agricultural products both nationally and internationally, limited rural infrastructure for water management, and for the processing of sustainable agricultural products, unequal access to information and resources. These barriers serve to obscure the long-term impacts of unsustainable practices etc. that fall directly on farmers, the public and on the continuance of agriculture production over time

For this scenario, we assume the government undertake extensive efforts to promote sustainable rice practice resulting in an increase of sustainable rice area in Central and Northeast region on average by 2,000,000 rai (320,000 ha) per year until 2045.

Under this scenario, the total sustainable rice practice area would reach 43,730,000 rai (6,997,178 ha), accounting for 82.86 percent of the country's total rice production area by 2045 and remain constant to 2050.

Table 2.1 Summary projected expansion of sustainable rice practice in alternative scenarios

Year	BAU		S2		S3		S4	
	Million Rai	Sustainable / Total rice area (%)	Million Rai	Sustainable / Total rice area (%)	Million Rai	Sustainable / Total rice area (%)	Million Rai	Sustainable / Total rice area (%)
2022	1.20	2.27	1.20	2.27	1.20	2.27	1.20	2.27
2030	1.50	2.84	2.10	3.98	4.20	7.96	7.20	13.64
2035	2.00	3.79	3.60	6.82	9.20	17.43	17.20	32.59
2040	2.50	4.74	5.10	9.66	14.20	26.91	27.20	51.54
2045	3.00	5.68	6.60	12.51	19.20	36.38	37.20	70.48
2050	3.50	6.63	8.10	15.35	24.20	45.85	43.73	82.86

2.3 Definitions and parameters

To inform the policy questions presented above, the research team presents an analysis of the scenarios above within the following scope for research and biophysical modelling:

2.3.1 Defining the geographical scope

The scope of this assessment includes rice cultivation area in Central and Northeast regions of Thailand. Together, the rice cultivation area of these two regions covers more than 80 percent of rice cultivation area in Thailand.

In the Central region, the project focuses on the Central plains area, in the following 5 provinces Suphanburi, Phra Nakornsri Ayuthaya, Chainat, Ang Thong, and Pathum Thani, where the GAP++ Standard is being introduced. In the Northeastern region, the project focuses on 7 of the 10 provinces with the largest rice production areas: Khon Kaen, Sakon Nakorn, Udon Thani, Ubon Ratchathani, Roi-et, Nakorn Ratchasima, and Surin. In the Northeast, the GAP++ Standard is being introduced in Ubon Ratchatani.

2.3.2 Defining the scope of sustainable rice management practices

The sustainable rice cultivation activities promoted by the SRP Standard, which are identified as having an impact on “biodiversity” and “greenhouse gas emissions” are the focus of this analysis. These comprise the following requirements (for further details, see Appendix 1):

SRP Standard Requirements

- 6 (ensuring no land conversion and enhancing site-specific biodiversity),
- 7 (ensuring no invasive species are introduced),
- 8 (recommending land leveling),
- 10 (recommending water management in rainfed and irrigated systems),
- 14 (ensuring delay of drainage to avoid agrichemical contamination),
- 15 (recommending efficient and site-specific use of organic and inorganic fertilisers),
- 16 (encouraging organic fertilizer),
- 17 (ensuring no counterfeit inorganic fertilizers are used),
- 18 (encouraging integrated pest management)
- 24 and 25 (ensuring there is no burning of residues (rice straw and rice stubble))

The management practices promoted by the SRP have many details and the scoring system allows for contingent adoption of certain practices. The following approach has been taken by the research team for the purposes of this assessment to simplify the scope of management practices to be included in the definition of sustainable rice production. Five specific practices have been selected to represent the essential compliance requirements from the above list. Each of these practices are described below.

1. Water Management

Sustainable rice farmers are assumed to time the establishment of their rice crop according to the local climate, and to maintain strong bunds to allow for effective water management.

In the irrigated areas, areas defined as “sustainable rice areas” are assumed to be managed with the Alternate Wetting and Drying (AWD) technique. AWD is a water management practice where irrigation is applied at intermittent intervals resulting in alternating wet and dry soil conditions. This technique is promoted as a means to reduce both water consumption and GHG emissions from rice cultivation, without yield penalty. In this study, farmers practicing AWD are assumed to have one “dry-down event” that is, a mid-season drainage of the rice field that lasts for 7 days.

In the rainfed areas, farmers have limited control over flooding conditions, making it difficult to comply with any pre-defined AWD regime. Therefore, in the rainfed areas, “sustainable rice” areas are assumed to be continuously flooded for 100 percent of the period of cultivation before harvest. In these areas, it is assumed that farmers adopt direct broadcast seeding (*na waan*) rather than transplanting seedlings from a nursery (*na dam*).

Water management would have a differential impact on GHG emissions in the areas studied. It would also have a differential impact on the amount of water available for other uses in the irrigated areas compared to conventional rice farming.

2. Nutrient management

Sustainable rice farmers are assumed to use fertilizer in a sustainable, efficient and site-specific way. All sustainable rice farmers are assumed to apply fertilizer according to plant needs, locally adapted recommendations, and label instructions, both in terms of timing and quantity.

Organic fertilizers are applied where locally available, and are assumed to be left to decompose before the fields are flooded. Inorganic fertilizers are used to supplement organic fertilizers, and are assumed to be from a registered source.

The efficiency of fertilizer is expected to have an impact on rice yield, cost of production, water quality and GHG emissions.

3. Natural systems of soil fertility enhancement

Rice farmers who apply sustainable rice practice in Central and Northeast regions are also assumed to apply natural systems of soil fertility enhancement. For the purposes of this assessment, the practice which is assumed to be adopted by sustainable rice farmers in the areas studied, is cover cropping.

Rice farmers in the rainfed areas in both regions who apply sustainable rice practices are assumed to plant sunn hemp (*Por Tueng*) in the fields after the rice harvest. This crop is not grown for market, but to enhance ecosystem services. Sunn hemp is a nitrogen fixing plant that is not especially prone to pest attack, and is effective at blocking out weeds. It can be harvested for use as cattle feed. Growing sunn hemp after rice is recommended to improve soil properties, reduce soil erosion, conserve soil water, and recycle plant nutrients back into the soil. All of these would impact rice yields, costs of rice production, GHG emissions, and soil carbon sequestration.

4. Integrated Pest Management

Sustainable rice farmers are assumed to use preventative pest control methods before considering the use of chemical pesticides. It is assumed that pesticides are used only if other methods are not effective on their own and they are carefully targeted to limit the area of exposure. Pesticide is assumed to be government approved, applied according to product label, follows specified preharvest interval, and does not exceed the dosage for worker and food safety. Broad spectrum insecticides are not used at all within the first 40 days after the rice crop is planted.

Appropriately and carefully applying chemical pesticides will have an impact on rice yields, rice production costs, and on aquatic, aerial and terrestrial biodiversity, as well as farmers' health.¹⁵

5. Rice straw and stubble management

Sustainable rice practice requires that there is no burning of either rice straw or any rice stubble left in the field. For the purposes of this study, it is also assumed that rice residues left in the field are allowed to decompose for at least 2 weeks before the field is tilled or flooded.

This practice would have an impact on the reduction of GHG emissions, soil carbon sequestration, and rice yield when compared to conventional rice practice.

Table 2.2 presents a summary of the different management practices to be assessed in the conventional rice area and sustainable rice area as defined above.

Table 2.2 Parameters / assumptions for analysis for each scenario

	Central region (irrigated systems)			NE region (rainfed systems)		
SRP requirement	Conventional rice production	Sustainable rice production	Post-rice crop	Conventional rice production	Sustainable rice production	Post-rice crop
No of crops per year	2	2		1	1	1
Water Management	Continuous flooding	AWD is practiced		Continuous flooding	Continuous flooding	
Nutrient management	Inorganic fertilizer is applied at current rates	Mix of fertilizers are used appropriately		Inorganic fertilizer is applied at current rates	Mix of fertilizers are used appropriately	

¹⁵ For minimum compliance requirements see SRP Standard Version 2.1 January 2020 at sustainable-rice.org

Integrated Pest Management	Average pesticide uses at current rates of application	No insecticide for first 40 days. Reduced herbicide use	No pesticides	Average pesticide uses at current rates of application	No insecticide for first 40 days. Reduced herbicide use	No pesticides
Rice straw and stubble management	36 % of rice residue is burned	No straw or stubble is burned		21% of rice residue is burned	No straw or stubble is burned	

2.3.3 Defining the temporal scope

The timeline of projection on impacts on natural capital, human capital, and social capital according to expansion of sustainable rice practice is proposed from 2022-2050.

Parts 3 – 10 present the details of methodology applied for measurements and their results. Starting from part 3, the details of spatial modeling to project the land-use change from 2022-2050 under each scenario are highlighted. The results of land-use change under each scenario with maps are also revealed in this section. Part 4 includes the details of GHG emission modeling to measure the difference of GHG emissions from sustainable rice practice and conventional rice practice. In addition, this section also contains the methodology and results of prediction for rice yield. The next section, part 5, highlights the methodology and results of variation of biodiversity caused by sustainable rice and conventional rice practices. Methodology and results of water footprint, water quality, and tree on rice fields measured from these two rice practices are presented in part 6 following by the methodology and results of health impacts caused by air pollution due to rice straw burning and pesticide poisoning generated from conventional and sustainable rice practices in part 7. The socio-economic information and social capital are explained and presented with the results of various socio-economic including cost of rice production and social capital measures in part 8. Part 9 presents the analysis of consumer preference on the effects of conventional rice practice and sustainable rice practice on various factors. All measure is then simultaneously analyzed based on four scenarios to identify possible tradeoff and synergy of different level of

expansion of sustainable rice practice compared to conventional rice practice in part 10. The conclusions, discussions, and policy recommendations are presented in part 11.

.

Part 3: Land Use Change Modelling

3.1. Method of Spatial analysis

To determine the area change from conventional rice area to sustainable rice area within 2022-2050 timeframe of each scenario, the conversion between the two practices will present the amount of change in area (i.e., hectare) and the spatial distribution. The sustainable rice area is where the rice fields apply the sustainable management practices defined in this study, while the conventional rice area has none of the management practices above. It is possible that some areas of sustainable rice do not apply all management practices regarding our SRP practices, but at least one should be registered in the Mega Rice Farm for rice cultivation.

There are two parts to the spatial analysis is conducted in this study.

1. Land use change analysis aims to investigate the changes of land use, in particular the area of the sustainable rice cultivation conversion.
2. The integrated spatial analysis and farmers' adoption of SRP cultivation.

PART 1) Land use Change Prediction

The changes in land-use has long been recognized as a major driver of environmental change. The promising precise method for understanding past land use, types of changes to be estimated, and the forces and developments driving the changes is land-use change assessment. The study aims to examine the temporal and spatial LU dynamics of the past and predict the future using Land Change Modeler (LCM). This study applies the LCM for rice production to determine the land conversion of rice production in the future. The study will generate the results presenting at the landscape level, considering the main key factors to configure the impacts on ecosystem services and biodiversity. The conceptual framework of LCM to assess the change of land-use is present in figure 3.1 Land cover is mapped at two-time steps (T1 and T2) in LCM, and the patterns and processes of change are estimated and used for model parameterization/calibration. The approach used in LCM is to analyze changes in land use between two previous time steps (T1 and T2) and create transition potential maps using Multi-layer Perceptron (MLP) with explanatory spatial variables. Markov Chain Analysis assigns the probability of change determined by projecting the historical change into the future, along with transition potential maps, presenting a

land-use scenario for most current period (T3). The T1 and T2 of land use, in particular the agricultural land, including the sustainable rice cultivation area, will be validated before being used in prediction for the future periods (T4).

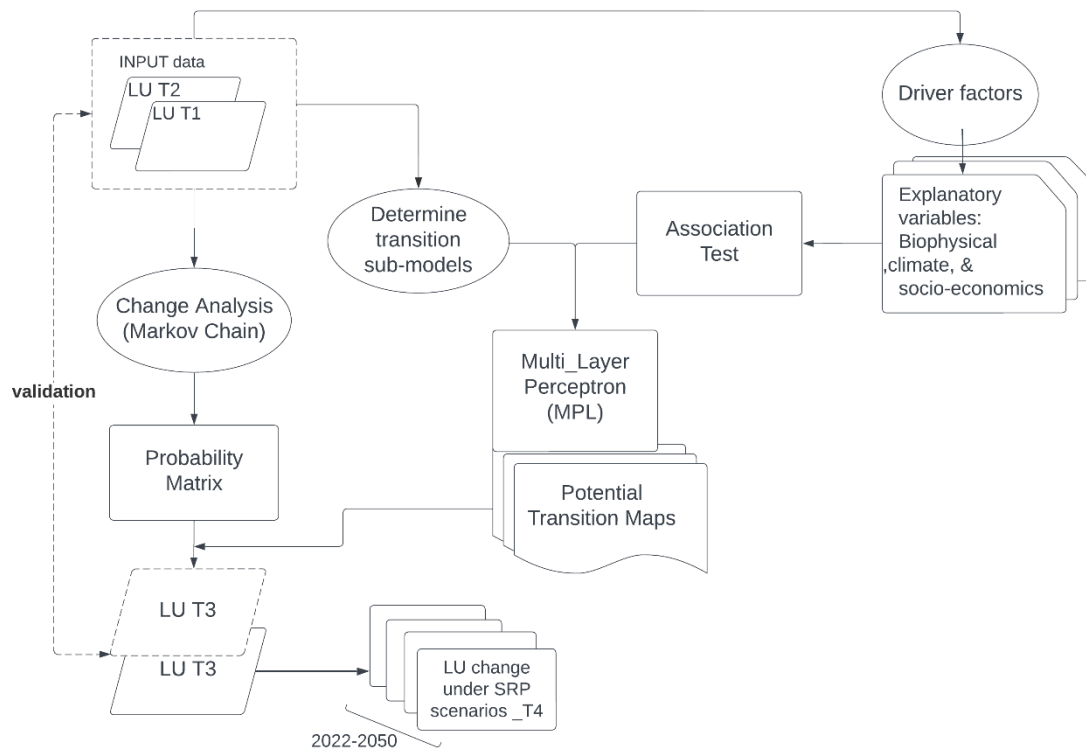


Figure 3.1 LCM method to predict land-use change

The LCM will be processed using IDRISI-Terrset¹⁶. This software provides tools for the assessment and projection of land-use change. Several factors contributed to the conversion of agricultural land and its surroundings, including population growth, urbanization, regional development. Previous studies have shown that land-use is changing, mainly from agricultural to built-up land (Ambarwulan & Munibah, 2013). The changes of agricultural land use reflect socio-economic driving forces such as land-use policy (Mottet et al., 2006). The presence of rice fields is intrinsically linked to population growth. The pressure of providing space for a region's population will increase as the region's population grows (Dwinanto & Sudadi, 2016). Table 3.1 presents a set of driver variables of primary change in the LCM.

¹⁶ v.18.31 Clark Labs, Clark University, Worcester, MA, USA.

Eastman, J.R. IDRISI Terrset Manual; Clark Labs-Clark University: Worcester, MA, USA, 2016.

Table 3.1 Data for the LCM analysis

Variables	Description	Sources
Administrative boundary	A vector of administrative limits of provinces and municipalities	Department of Public Works and Town & Country Planning, Ministry of Interior
Land-use	Land use maps (2013 and 2021)	Land Development Department, MoAC
Land suitability	Land suitability for rice agriculture	Land Development Department, MoAC
Organic rice paddy	Land use for organic rice cultivation (available years)	Rice Department, MoAC
Mega rice farm paddy	Rice paddy fields area under the Mega rice farm project	DOAE, MoAC
Rice paddy fields	Rice cultivation area suffered from drought (under the rice department observation project in 2021)	Rice Department, MoAC
GAP Rice paddy	The Good Agricultural Practice for rice (GAP) certified paddy fields in 2013-2017.	Rice Department, MoAC
Slope	A slope in degree calculated from Digital Elevation Model (DEM)	Author calculation
Elevation	Digital Elevation Model > Shuttle Radar Topography Mission (SRTM) 30m. Elevation, aspect	Digital Chart of the World
Road	Thailand road network, including all types	GISTDA Thailand
Distance to urban area	Euclidean distance from LU type U1, U2, and U3 defined by LDD	GISTDA Thailand
Irrigation zone	Irrigation types and boundary	Royal irrigation department, MoAC
Climate data	Maximum, minimum, average temperature, and average daily precipitation sum using RCP4.5 emission scenarios.	Center of Regional Climate Change and Renewable Energy, Ramkhamhaeng University Thailand ¹⁷

This component of the study aims to investigate the variation of land-use under different future scenarios of rice production. The land-use change predictive scenarios are shaped by the

¹⁷ <http://www.rucore.ru.ac.th/>

potential changes of rice production area from conventional rice to sustainable rice production from 2022 to 2050. We simulate the land-use change to reflect all four scenarios.

The spatial variation of land-use presented in scenarios reflects the government targets and relevant policies. The expansion of rice area for potential future changes under scenarios is considered to address the associated uncertainties of different sectors in the study. We assume that the variation of government promotion associated with rice production has the potential to reflect the change in rice area. This means that the government-promoted projects are used to represent the sustainable rice area in this study. It is worth noting that the changes at the landscape scale also can link the uncertainties of biodiversity and ecosystem services so that the comparative impacts can be visible to suggest different stakeholders through the land change modeling. The projection of land-use change is based on Thailand's agricultural policies under the Twenty-Year National Strategy and other policies as discussed in the Research Scope above. According to our assumptions, the LU of rice area is controlled where rice is suitable to cultivate as defined by LDD.

The available spatial data is collected and used to visualize the current situation of the sustainable rice cultivation in Thailand. For instance, maps of rice production under the Good Agricultural Practice (GAP) for rice production are employed. The geographic data of GAP rice production (see red dots in Figure 3.2 below) is used to present one location under the sustainable rice practice in this study. The top left panel in Figure 3.2 shows the Thailand suitability for rice production classified into suitability levels, ranging from high to unsuitable for growing rice (marked from high-low as S1-S3 and N on the map). The right and bottom panels show that GAP rice production areas in 2016–2017 are clustered in the central and northeastern regions, the study area for this assessment (blue polygons). Similarly, the mega rice farms (purple dots) are concentrated in the same areas.

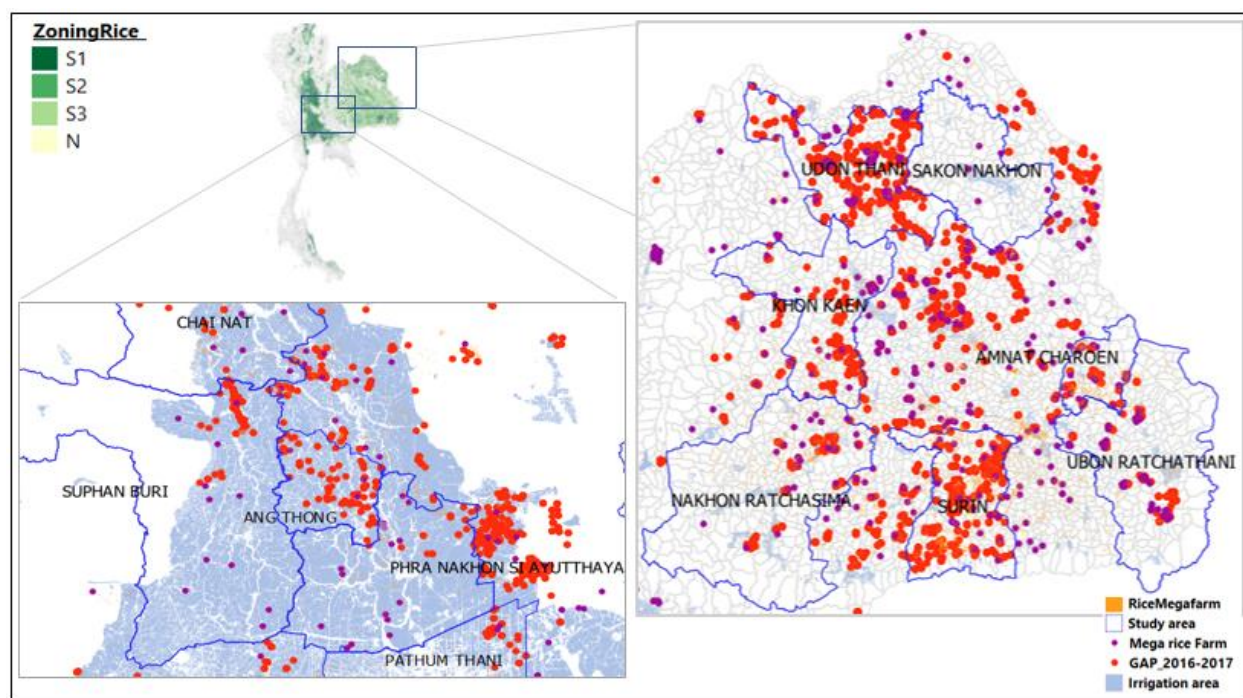


Figure 3.2 The maps of rice production under the GAP program for rice and the mega rice farm project (Sources: Rice department, MoAC).

3.2 Results

1.1 This section describes the land use change prediction for the sustainable rice cultivation. The presentation of findings starts with a geographical description, then continues on to a change analysis, a transition potential test, and lastly, validation and prediction outcomes. The land use study is divided into two sections: the northeast region (shown first) and the center region.

3.2.1 Geographical characteristics of the NE region, Thailand

The northeastern region of Thailand covers 16,699,700 ha. and consisting of 20 provinces. The topography of the study area has a boundary on the west side that declines to the south, which is a mountain range ridge. Digital Elevation Model (DEM) data with a resolution of 30 meters by 30 meters was used to calculate the elevation (Figure3.3). The elevation determined from DEM data is roughly 150–250 meters above mean sea level (MASL), with a lower slope in the eastern portion of the basin, which contains the confluence of the Mun river and Mekong rivers. According to Table 3.2, approximately 33.8 percent of the area in the NE region falls within an elevation range of 165–213 meters.

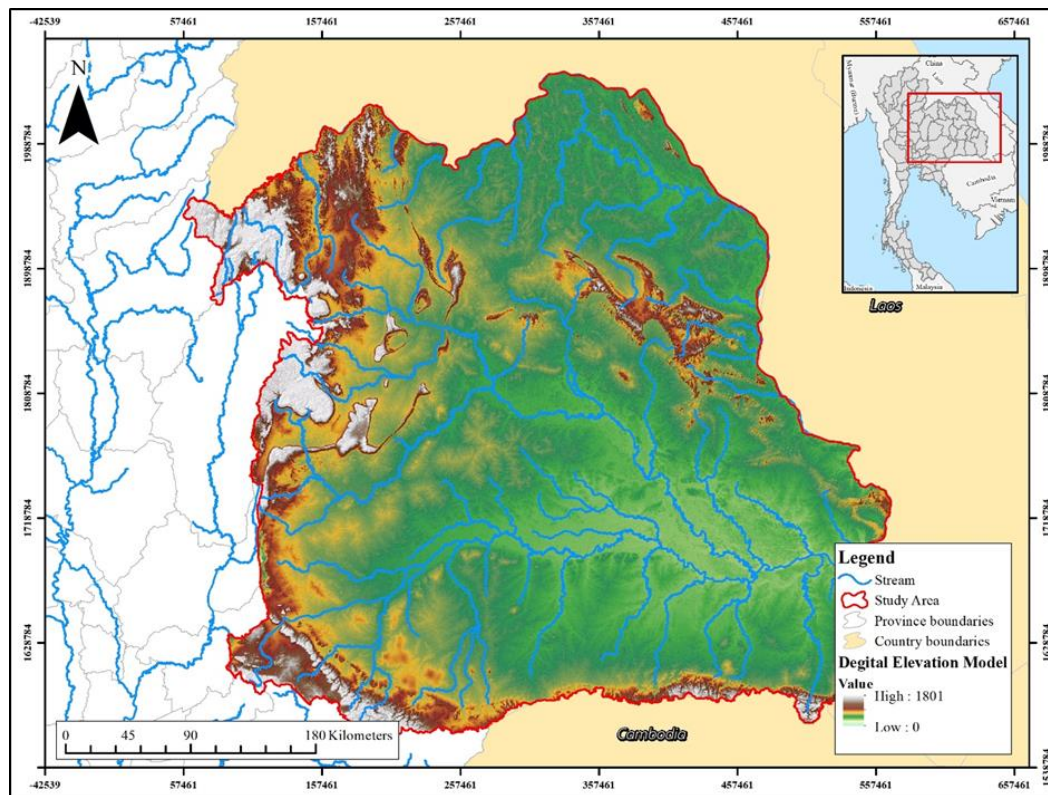


Figure 3.3the study area of land use change

Table 3.2 The elevation of Northeast region classification

Order	Elevation range (meter)	Area (square meter)	Area Percent
1	0 - 165	58,206.15	34.85
2	165 - 213	56,568.08	33.87
3	213 - 284	24,775.07	14.84
4	284 - 383	11,711.84	7.01
5	383 - 507	6,551.49	3.92
6	507 - 656	4,073.35	2.44
7	656 - 833	2,737.59	1.64
8	838 - 1,094	1,870.36	1.12
9	1,094 - 1,801	502.87	0.30
Total		166,996.81	100.00

3.2.2 Land use Classification of NE region

According to the Department of Land Development (2022), the land use in the NE is mainly categorized into four classes, including

- 1) Agricultural land accounts for 11,566,507 ha (69.23%) of the total area of the Northeast, which is mainly rice paddy fields, field crops, and orchards.
- 2) Build-up land accounts for 1,019,329 ha (6.10%) of the total area of NE land. It includes mainly urban land, buildings, roads, and highways.

- 3) Water accounts for 641,673 ha (3.84%) of the total area of NE land where the natural water resources are included.
- 4) Miscellaneous land includes grass land, forest land, and wetland, which account for 3,472,172 ha (20.79%) of the total NE area.

Land use is classified into ten classes in this study in order to forecast land use change. The proportions in each land use class are shown in the table and figures. Approximately 40 percent of NE land is used for rice cultivation, which is 38.9 percent of the land used for conventional rice cultivation, while less than 1 percent of land is used for sustainable rice practice. Due to the lack of geographic data on rice conducted in sustainable practice, this study assumes that the way rice is grown under the GAP program is a good example of how to grow rice in a sustainable way.

Table 3.3 The classification and description of land utilization in 2022 used for this study

	Class	Description	Area (Sq. km.)	Percent (%)
1.	Conventional rice	Rice paddy field area	64,955.76	38.90
2	Sustainable rice	Rice paddy fields area includes the rice paddy in the good agricultural practice program and sustainable rice practice defined by the rice department and the OAE.	140.11	0.08
3	Field crop	Field crops consist of sugar cane, cassava, and valuable crops.	32,142.06	19.25
4	Tree plantation/Orchard	Timber or tree farm and fruit gardens	18,427.13	11.03
5	Rangeland/grassland	Grass, shrub and lotuses used as pastures for the livestock.	4,627.97	2.77
6	Forest	Disturbed forest and dense forest	26,958.69	16.14
7	Urban	Building, village settlement, highway, road	10,193.29	6.10
8	Wetland	Mangroves forest and nonforested land	2,251.34	1.35
9	Water	Water body resources, canal, river, irrigation	6,416.73	3.84
10	etc.	Other land and unclassified land	883.73	0.53
		Total	166,996.81	100

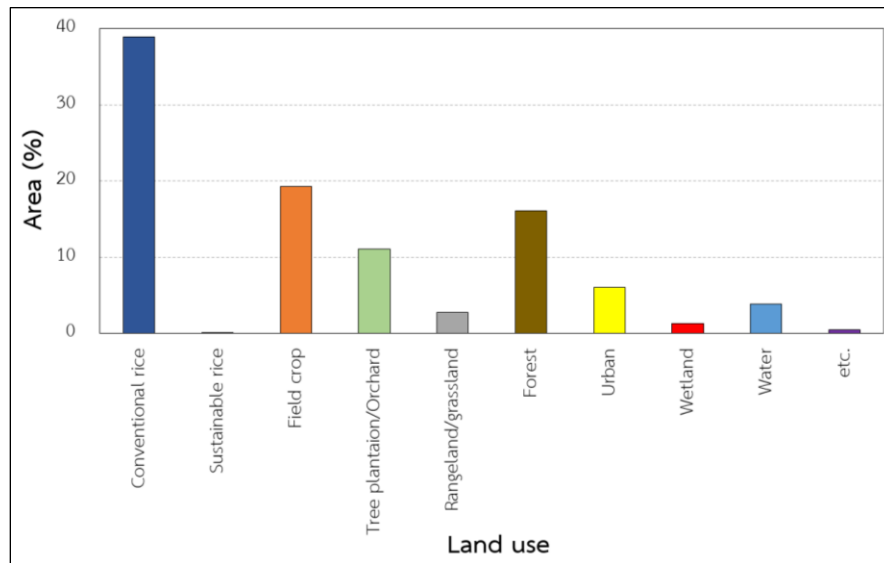


Figure 3.4 Land use classification of the study area in NE region Year 2022

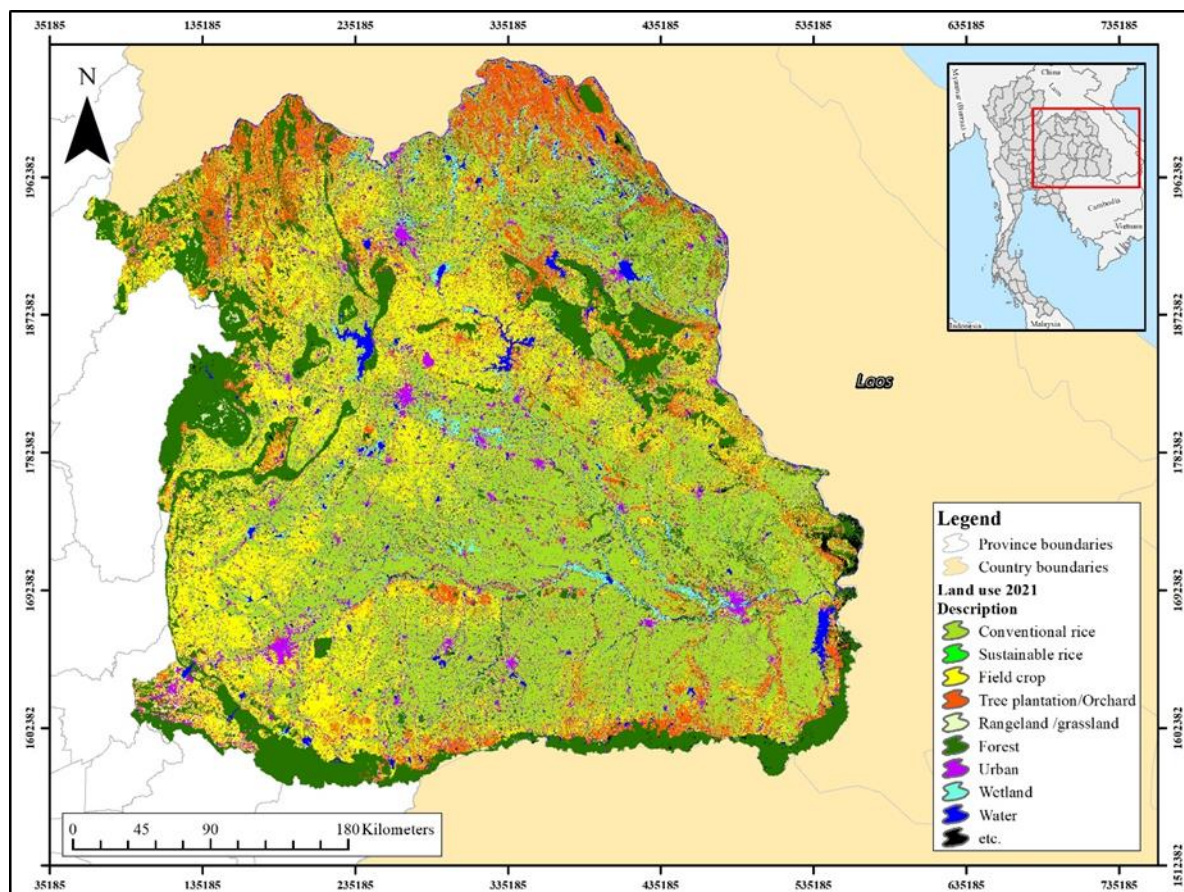


Figure 3.5 Land use classification in NE Year 2022

3.2.3 Land use change prediction in two-time period (T1 and T2)

The change analysis is conducted using TerrSet program which capable of performing the transition potential and predicting the changes of land use in the future (Eastman, 2020). First, this study investigates the change of land use based on the two historical land use years in 2016 (T1) and 2018 (T2) (Figure 3.6 and 3.7 respectively).

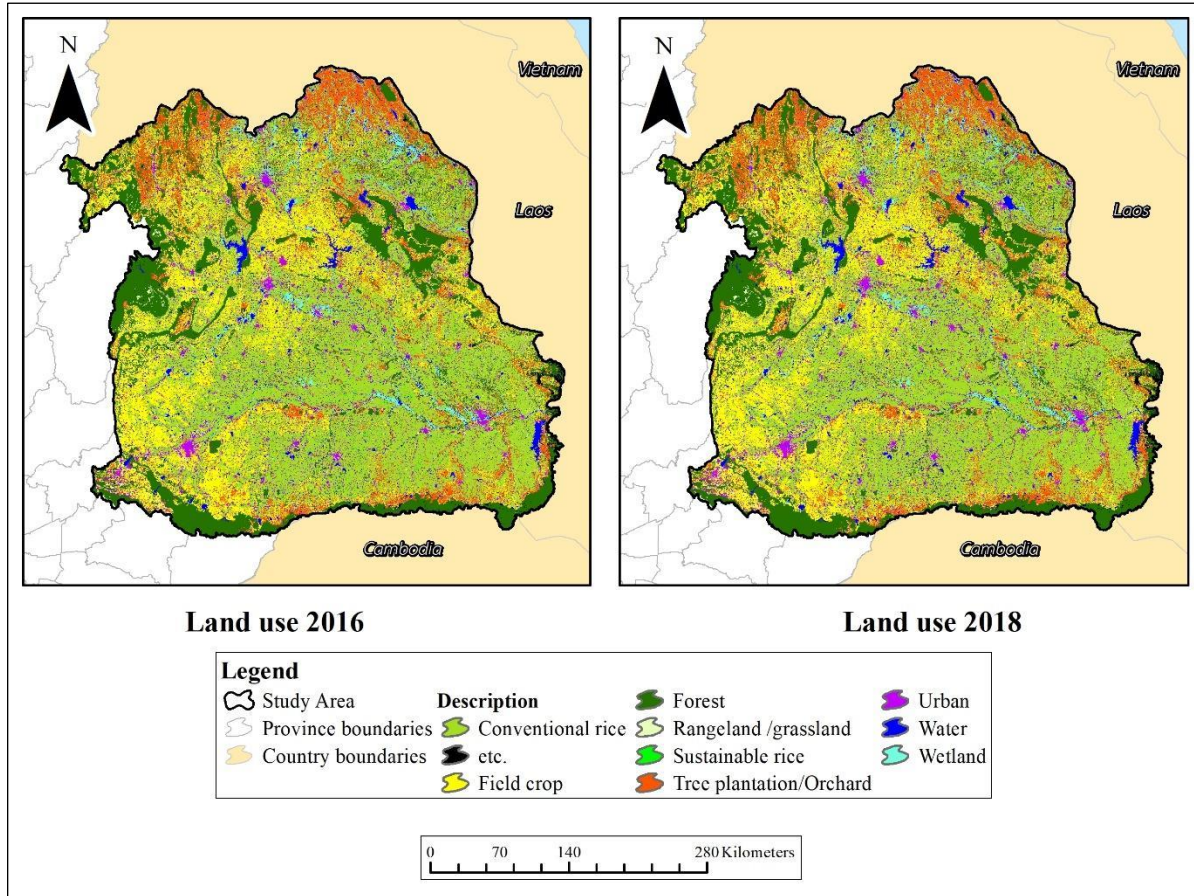


Figure 3.6 Land use two periods of the NE region in 2016 (T1) and 2018 (T2)

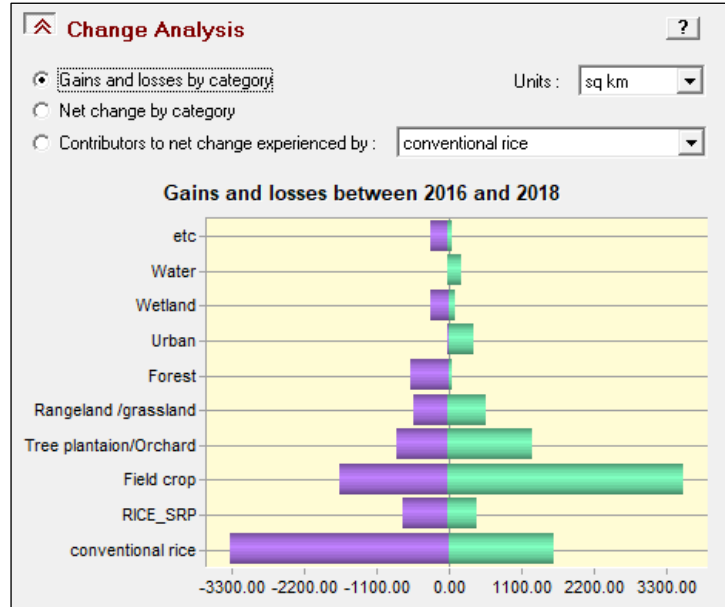
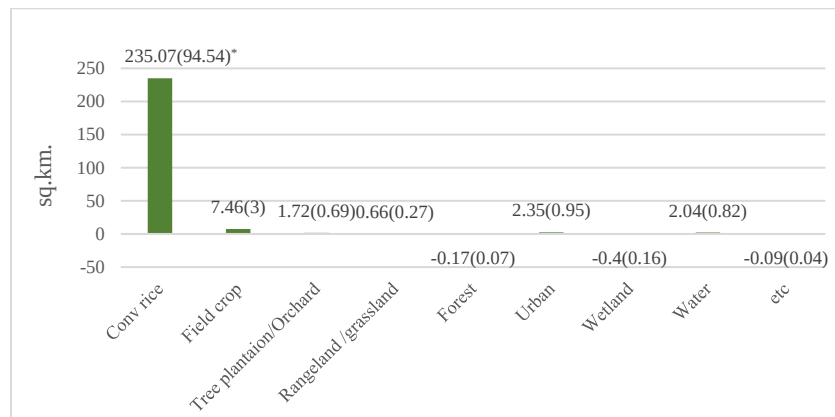


Figure 3.7 Change analysis of land use in NE during 2016 and 2018 using Land Change Modeler

Table 3.4 displays the changes in the NE region land use area for ten different categories. Considering within the same class, the field agriculture, tree plantation or orchard, and urban area all underwent changes, with the most significant net increases of 1,910.20 square kilometers (6.32%), 478.39 square kilometers (2.67%), and 324.66 square kilometers (3.29%), respectively. Furthermore, the land use for conventional rice paddy fields, forest, and sustainable rice paddy fields has the lowest net decrease of 1,747.91 square kilometers (2.63%), 530.23 square kilometers (1.93%), and 248.64 square kilometers (35.67%), respectively. Note that the negative sign of the changes in the last column shows that the relative lower land area in 2018 is less than was in 2016 on its own. In particular, a decline in the sustainable rice land of 248 sq. km. contributes the most 235 sq. km. (94.54%), to conventional rice paddy, followed by field crop, urban land, water area, tree planation, and rangeland, respectively (Figure 3.8). In contrast, around 0.66 sq.km. (0.27%) of forest, wetland, and other type of land are converted into SRP rice paddy fields.

Table 3.4 the change analysis of NE land use in each class between 2016 and 2018

Order	Land use category	Area (Sq. meter)		Change	
		2016	2018	Sq. meter	Percent
1	Conventional rice	66,434.41	64,686.50	-1,747.91	-2.63
2	Sustainable rice	697.16	448.52	-248.64	-35.67
3	Field crop	30,213.63	32,123.82	1,910.20	6.32
4	Tree plantation/Orchard	17,942.83	18,421.23	478.39	2.67
5	Rangeland /grassland	4,597.96	4,625.68	27.72	0.60
6	Forest	27,490.91	26,960.68	-530.23	-1.93
7	Urban	9,866.05	10,190.72	324.66	3.29
8	Wetland	2,433.54	2,248.19	-185.36	-7.62
9	Water	6,238.55	6,421.11	182.56	2.93
10	etc.	1,091.62	883.87	-207.74	-19.03



Note *a percentage is displayed in parenthesis; a positive sign denotes that SRP converted into other LU class, while a negative sign shows that a particular class converted to SRP.

Figure 3.8 LU class contribution to the net change in the SRP rice area, northeast region

3.2.4 Driving variables for land use change

After the land use change analysis between two time periods was established, the LCM then conducted a transition potential analysis to determine which driving factors may be significant in future land use change using the multi-layer perceptron method (MLP). The driving factors in this study are slope, average precipitation, maximum temperature, mean temperature, minimum temperature, and distance from an urban area. Figure 3.9 depicts the spatial distribution of all driving factors. Cramer's V statistic was used to determine the significant driving forces to be included in the modeling in order to quantify the relationship between each type of land use and the driving factors. Using Cramer's V, the most offerings that are compatible in two LU maps are identified. If Cramer's V values of 0.15 or higher have a moderately substantial influence on land

use change; if the coefficient values more than 0.4 have a very significant influence on land use change (Eastman, 2012).

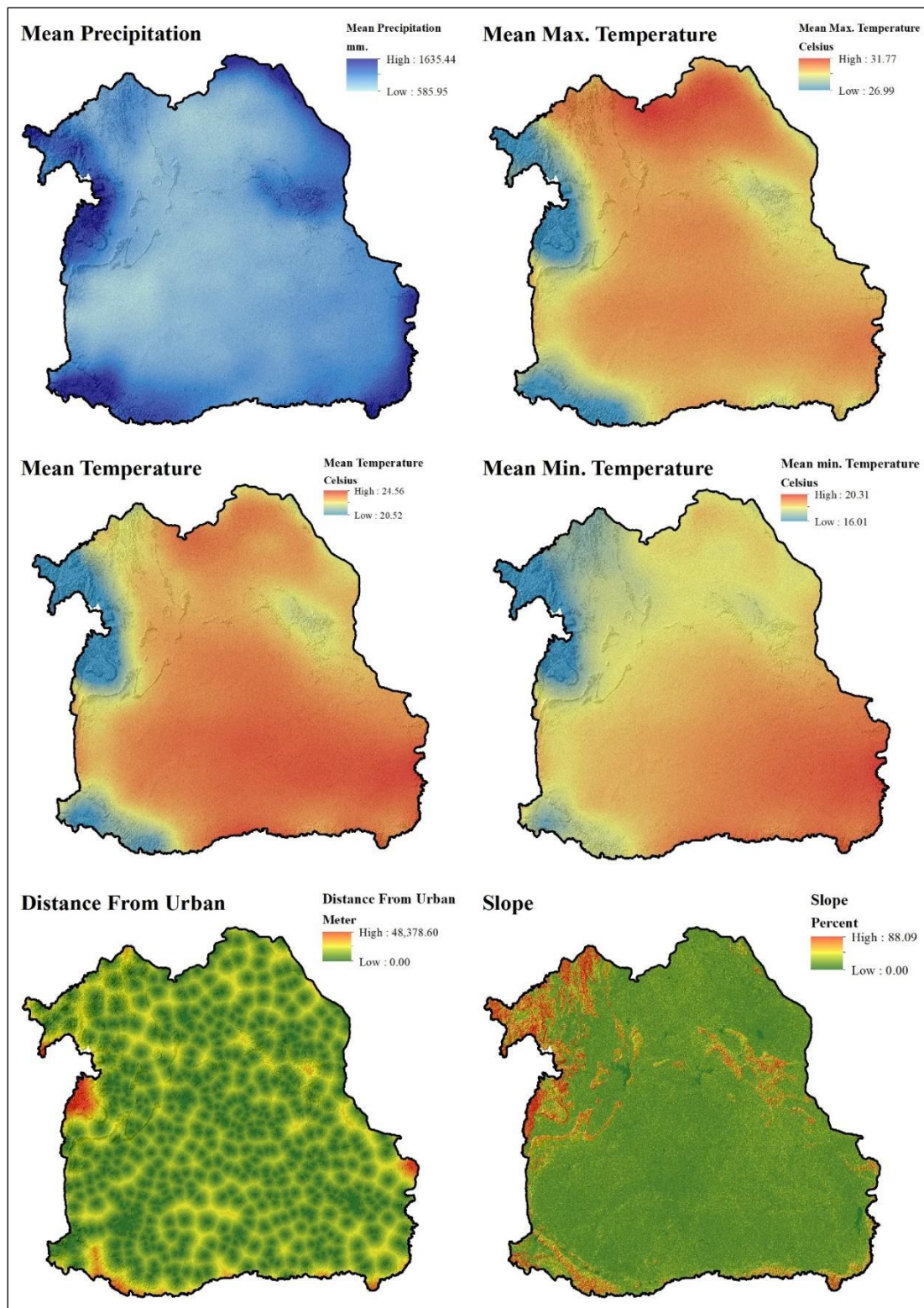


Figure 3.9 Driver variables for transition potential of land-use change analysis in the NE region.

Table 3.5 Cremer's V association test of driving factors for the NE region

Order	Land use\Variables	Cramer's V					
		Mean precipitation	Mean max. temperature	Mean temperature	Mean min. temperature	Slope	Distance from urban
1	Overall	0.1485	0.1667	0.1799	0.1715	0.1901	0.1424
2	Conventional rice	0.2410	0.3034	0.3783	0.3587	0.2755	0.1914
3	Sustainable rice	0.0208	0.0240	0.0314	0.0301	0.0190	0.0167
4	Field crop	0.1273	0.1660	0.2268	0.2154	0.0872	0.0710
5	Tree plantation/Orchard	0.1120	0.1232	0.1217	0.1524	0.0617	0.0675
6	Rangeland/grassland	0.0337	0.0410	0.0295	0.0337	0.0311	0.0378
7	Forest	0.3763	0.4125	0.3978	0.3464	0.5521	0.3500
8	Urban	0.0476	0.0444	0.0510	0.0570	0.0722	0.1958
9	Wetland	0.0714	0.1022	0.0649	0.0560	0.0456	0.0403
10	Water	0.0381	0.0558	0.0663	0.0813	0.0636	0.0400
11	etc.	0.0988	0.0320	0.0592	0.1131	0.0397	0.0915

3.2.5 Transition potential selection

The LCM generates a series of potential change maps based on the two time periods of land use to study prospective changes in land use. In each area, the transition of potential change indicates a propensity for land use conversion. A high value in a transition potential map indicates a higher potential shift in red. Figure 3.10 depicts the possibility for each land use category to shift to SRP. It is obvious that conventional rice cultivation has the highest transition potential to SRP. The majority of the transition is more likely to take place in the central region toward the southern northeast.

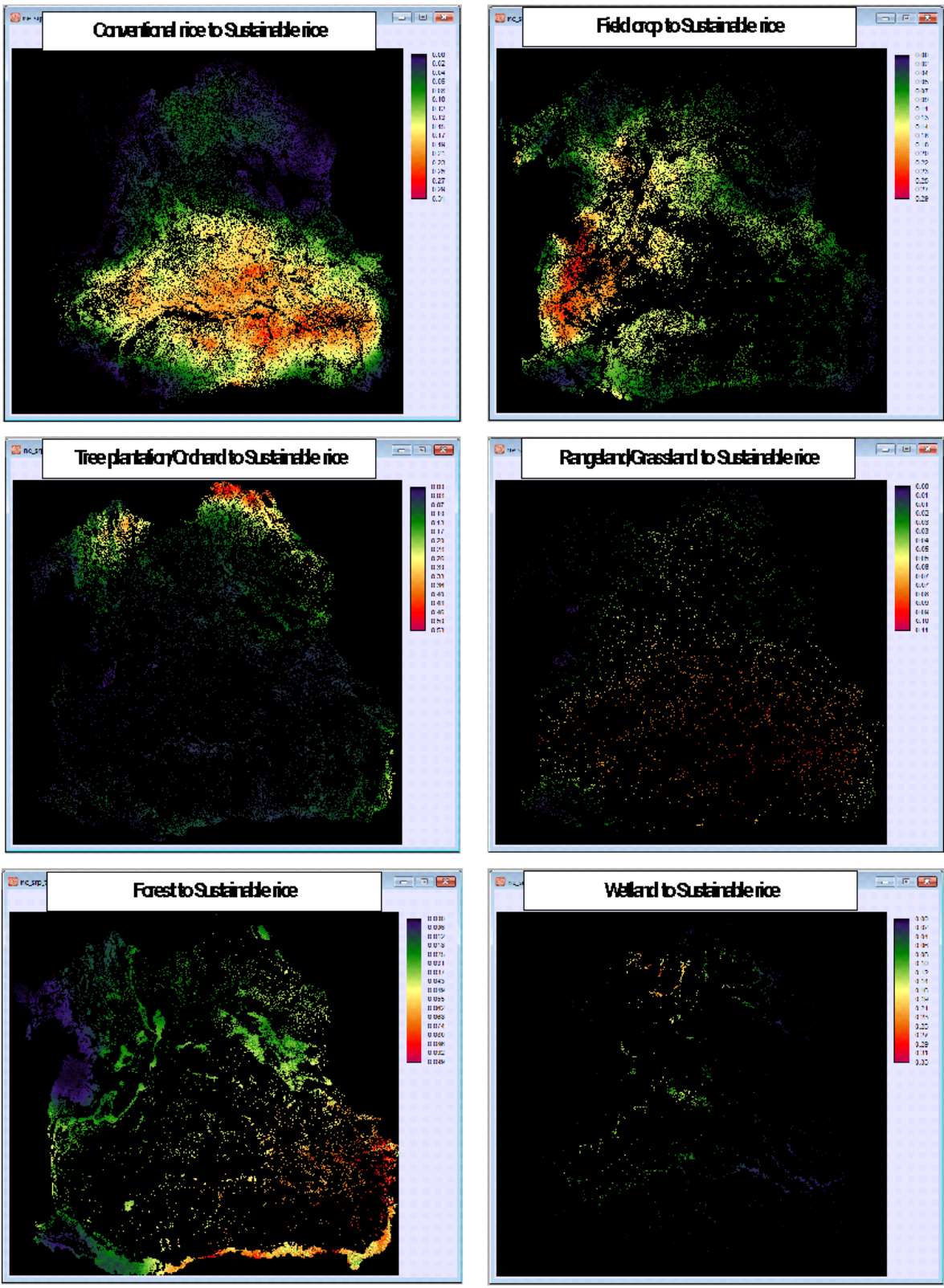


Figure 3.10 Maps of transition potential of SRP rice cultivation area in the northeast region, Thailand.

3.2.6 Validity test of land use prediction

To guarantee a precise forecast result based on the earlier rounds of analysis, the land use prediction needs to undergo a validation test. The most recent land use, the historical land use map, is used to achieve this. We used modified LDD 2021 land use data. The following equation can be used to determine the Kappa coefficient, which measures overall accuracy. The validation maps and results are displayed in Figure 3.11 and Table 3.5, respectively.

$$\text{Kappa} = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r x_{i+} \cdot x_{+i}}{N^2 - \sum_{i=1}^r x_{i+} \cdot x_{+i}}$$

$$\text{Overall Accuracy} = \frac{\text{No. of correct plots (Value)}}{\text{Total number of plots (Value)}} \times 100$$

where, X_{ii} denotes the observation pixels in row i and column i , and X_{+i} , X_{i+} denotes marginal total of row i and marginal total of column i , r denotes the number of rows in an error matrix, and N denotes a total number of observation pixels. The application of the Kappa coefficient (K) to measure agreement quantitatively was done with the assumption that a Kappa equal to 1 indicates perfect agreement, while as a value close to zero indicates that the agreement equal is no better than would be expected by chance.

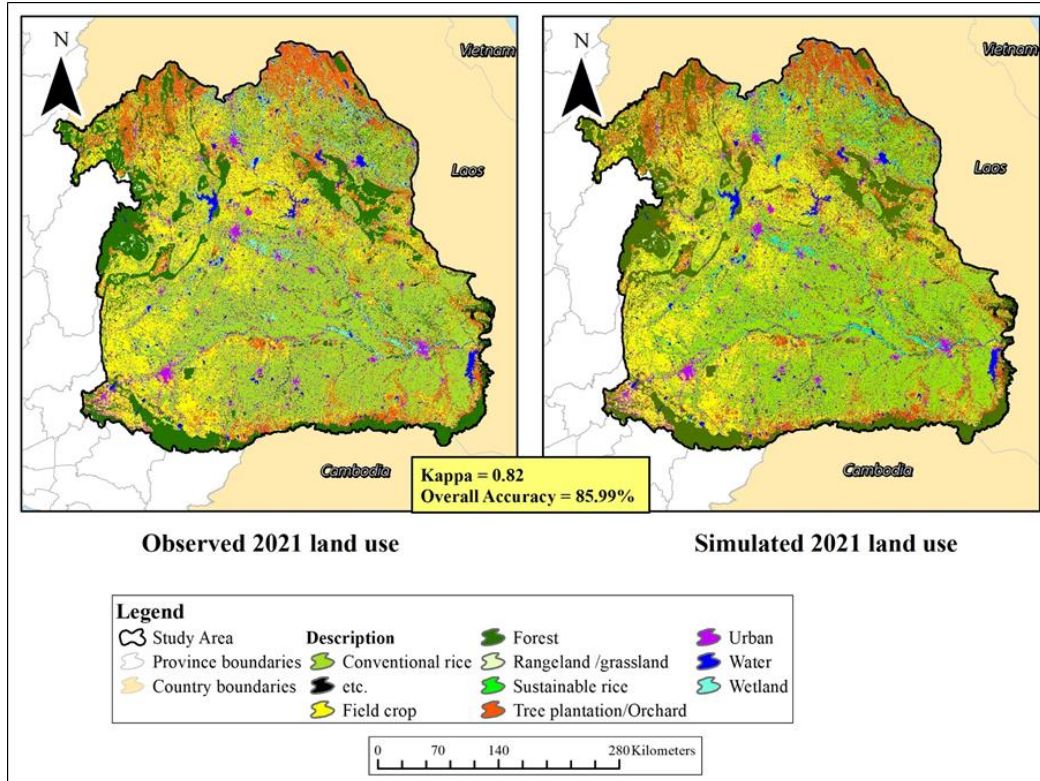


Figure 3.11 Validation of the NE land use prediction based on the observed 2021 LU and simulated 2021 LU.

As a result, the overall accuracy assessment of land use prediction for the NE region shows that the observed land use and simulated one has an overall accuracy of 85.99% and the kappa coefficient value was 0.82. According to Congalton (1991)¹⁸, an overall accuracy value greater than 70% is considered as acceptable and with a kappa statistic of 0.4-0.85 is considered as the reliable agreement. Thus, the outcomes of both regions are appropriate for use in the further stage of land use prediction.

3.2.7 Land use change prediction under future scenarios

The prediction of land use change in this study is based on four scenarios due to the conversion from conventional rice to sustainable rice cultivation. The proportion of conventional rice area and sustainable rice area forecast every five years: 2025, 2030, 2035, 2040, 2045, and 2050. Business as usual (Scenario 1), moderate change (Scenario 2), enhanced change (Scenario 3), and transformational change (Scenario 4) are the four scenarios of the sustainable rice area conversion. In scenario 5, the transformational change of sustainable rice expansion ends in 2045 and remains constant since sustainable rice production accounts for 75% of the national total rice production. Beyond 2050, it is anticipated that there won't be any more expansion of sustainable rice. We also assume that the GAP program and the GAP++ program are both part of the sustainable rice industry that the Thai government is promoting and are considered sustainable rice in this analysis.

For the northeast region, as rice is mostly grown by rain in the northeast, sustainable rice farming seems to predominate in areas near Mun river basin (purple). The consistent support of sustainable rice expansion in BAU demonstrates that sustainable rice has a little edge in the southern part of the area, close to the provinces of Surin and Ubon Ratchathani. As in scenarios 3 and 4, the conversion rate increases after 2045, and sustainable rice is more prevalent in the central and southern parts of the Northeast, around Maha Sarakham and Buri Ram province.

¹⁸ Congalton, R.G. A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data. Remote Sens. Environ. 1991, 37, 35–46.

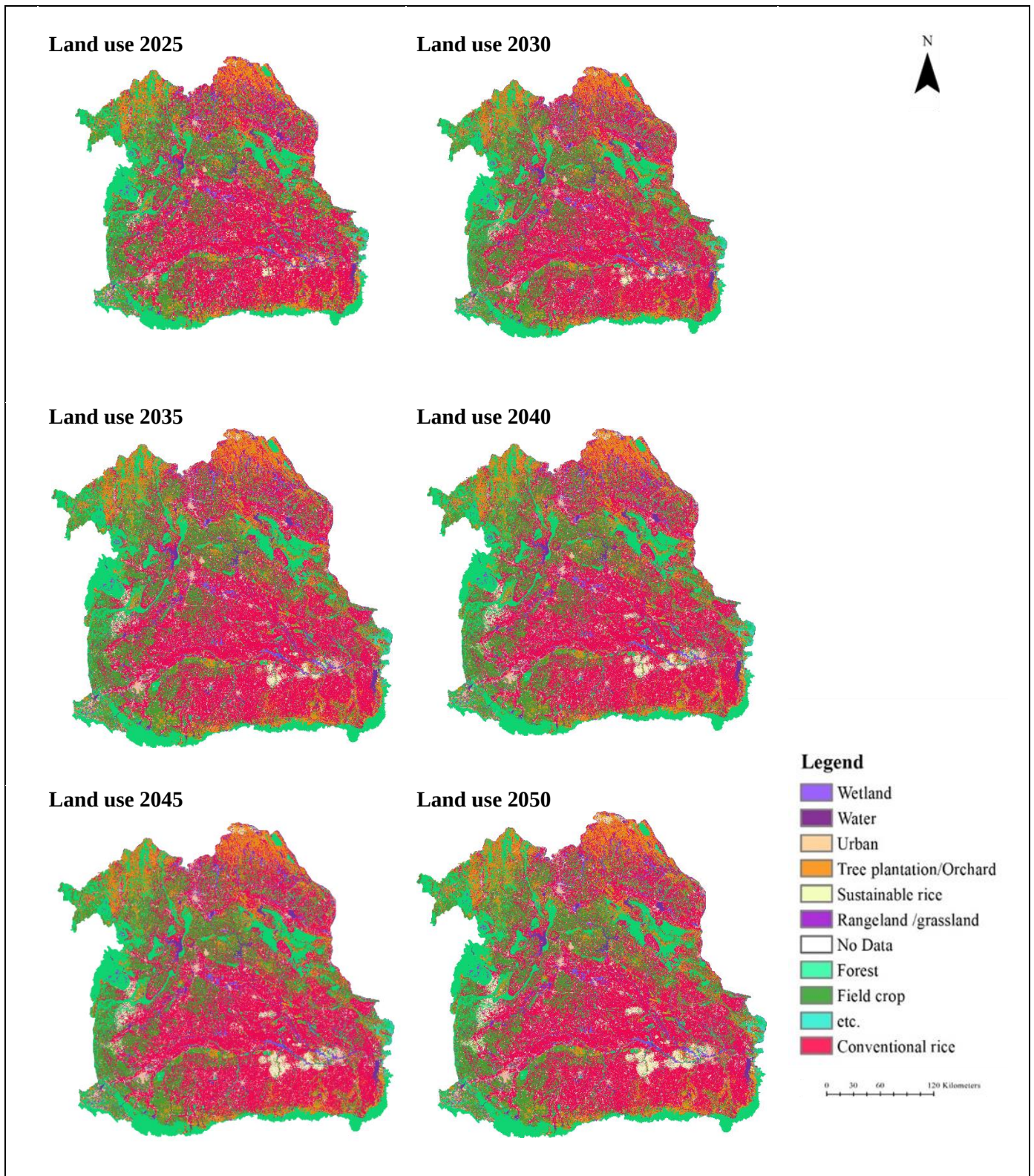


Figure 3.12 the sustainable rice area prediction in the NE as business as usual (Scenario 1).

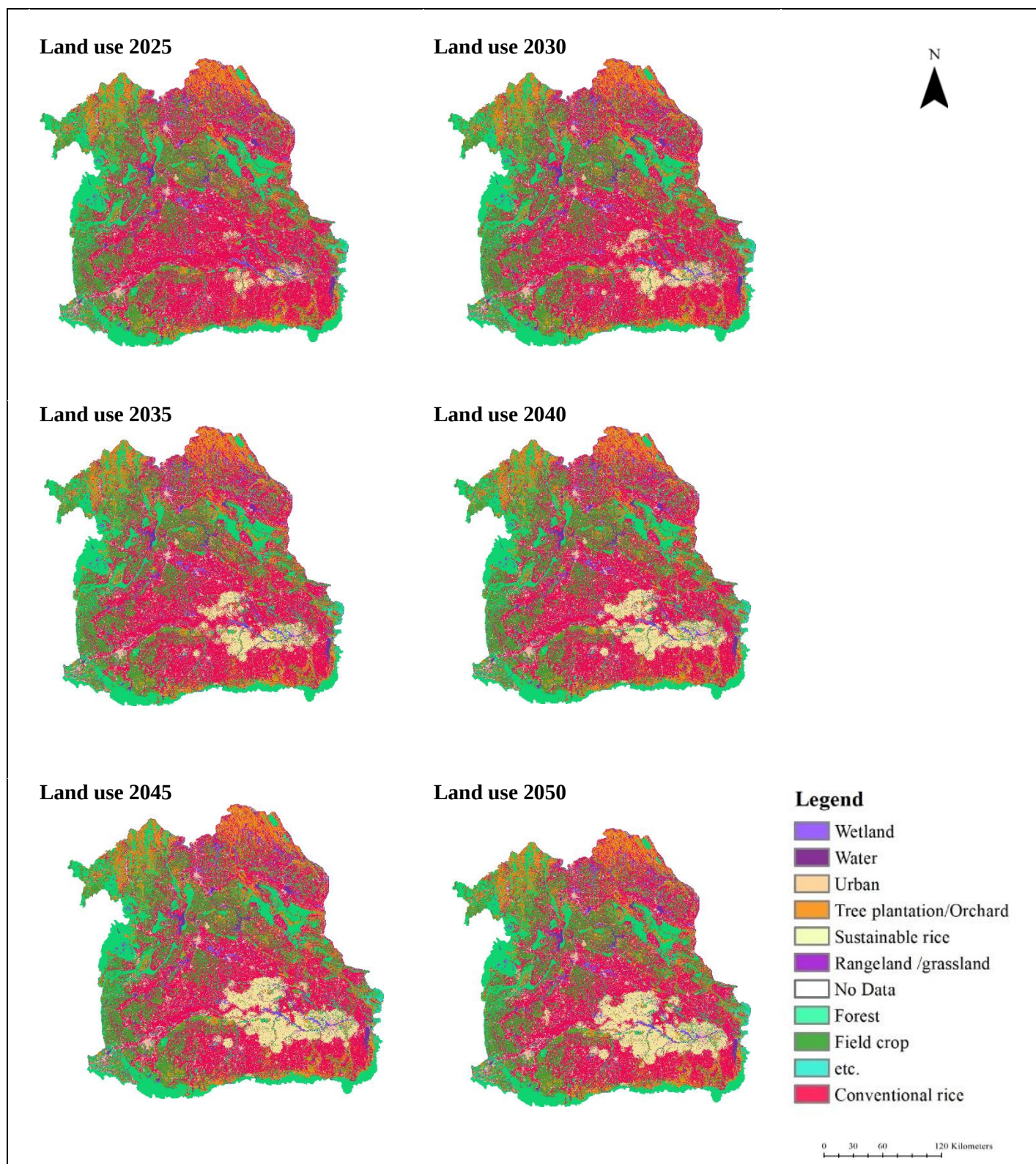


Figure 3.13 The sustainable rice area prediction in the NE under Scenario 2

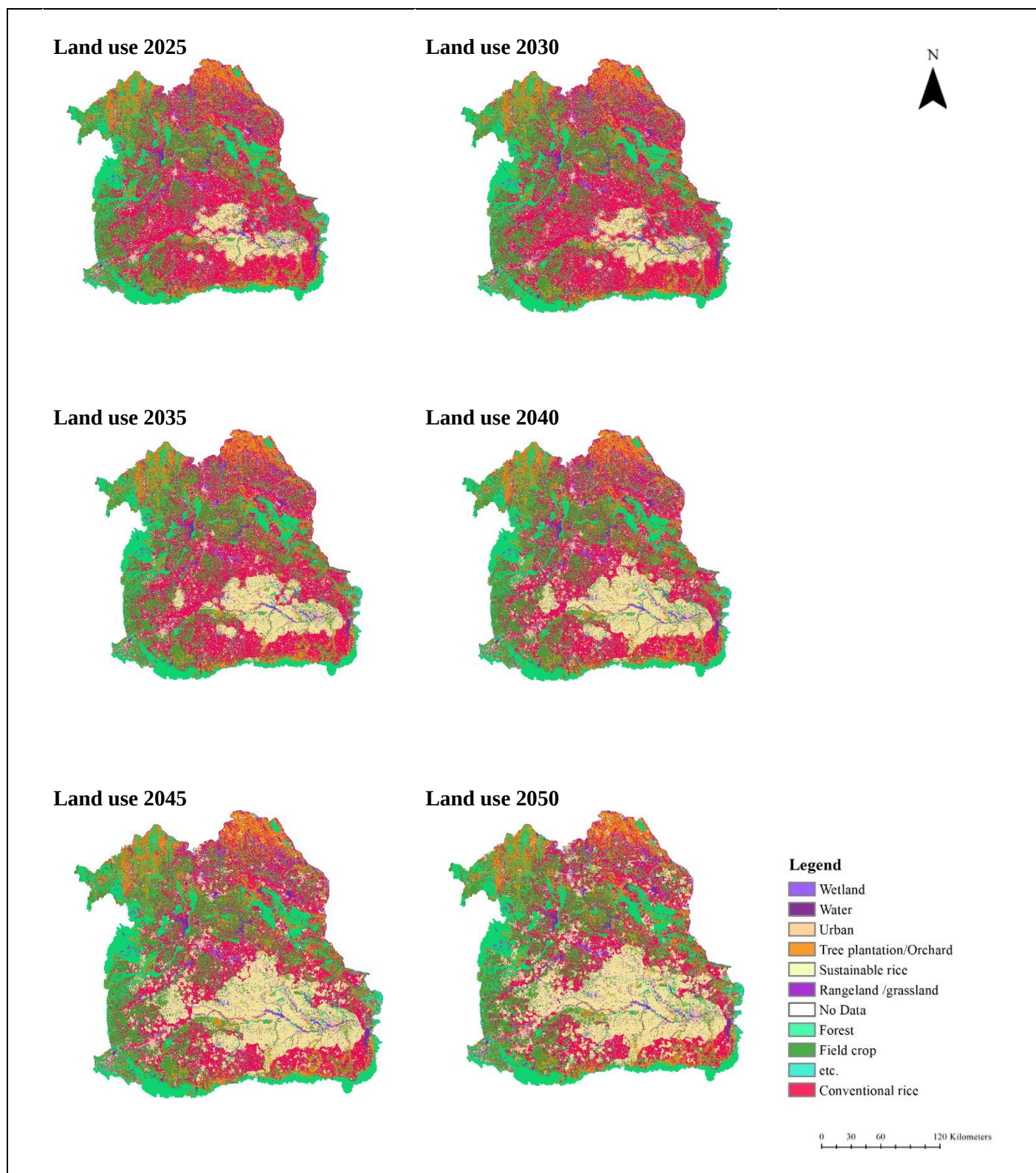


Figure 3.14 The sustainable rice area prediction in the NE under Scenario 3

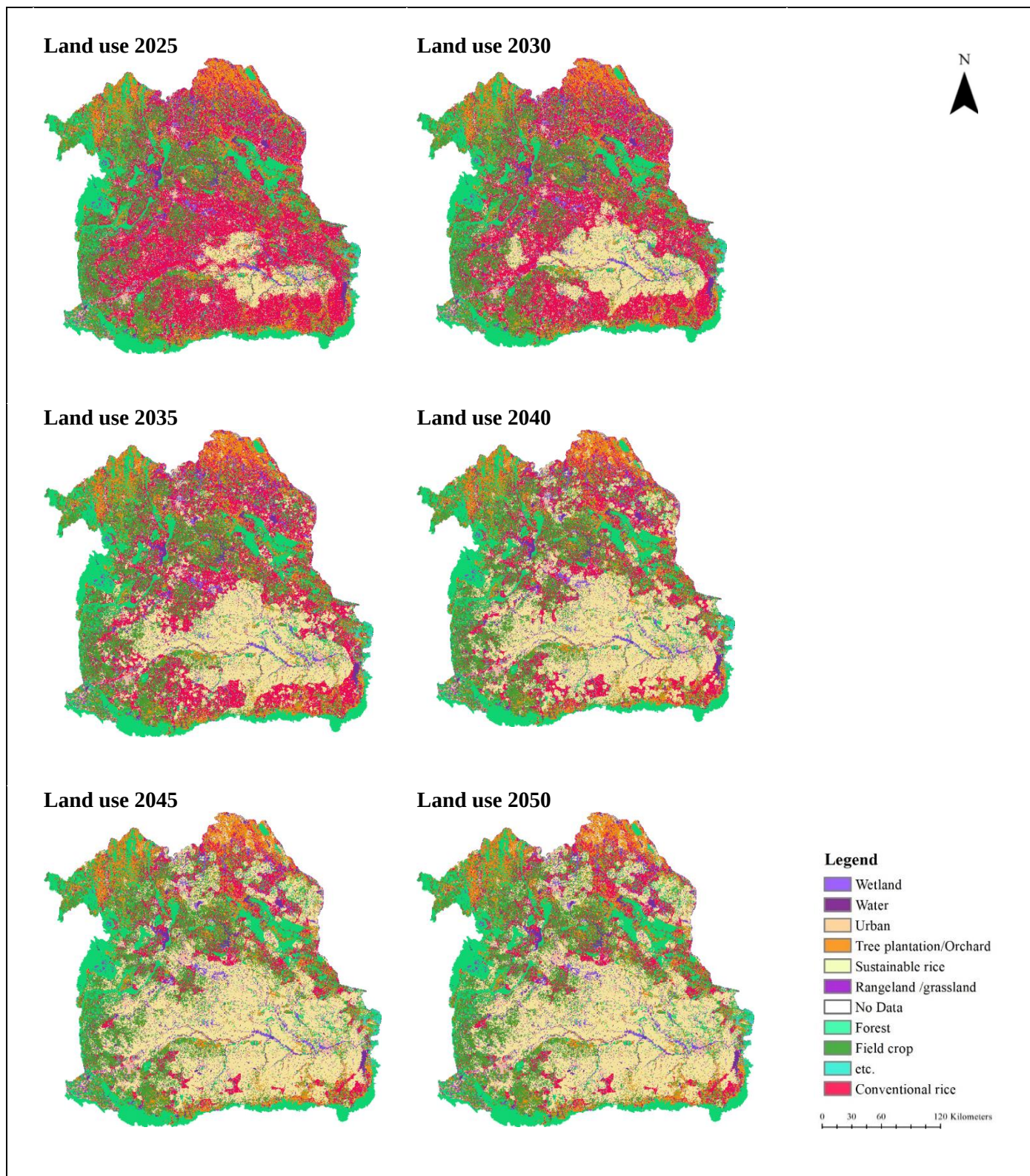


Figure 3.15 The sustainable rice area prediction in the NE under Scenario 4

The land use change analysis for the central region

The study area in the central region of 5,492,895 ha includes fourteen provinces¹⁹. The sample provinces are selected because they have historical data on sustainable rice production.

3.2.8 Geographical characteristics of the central region, Thailand

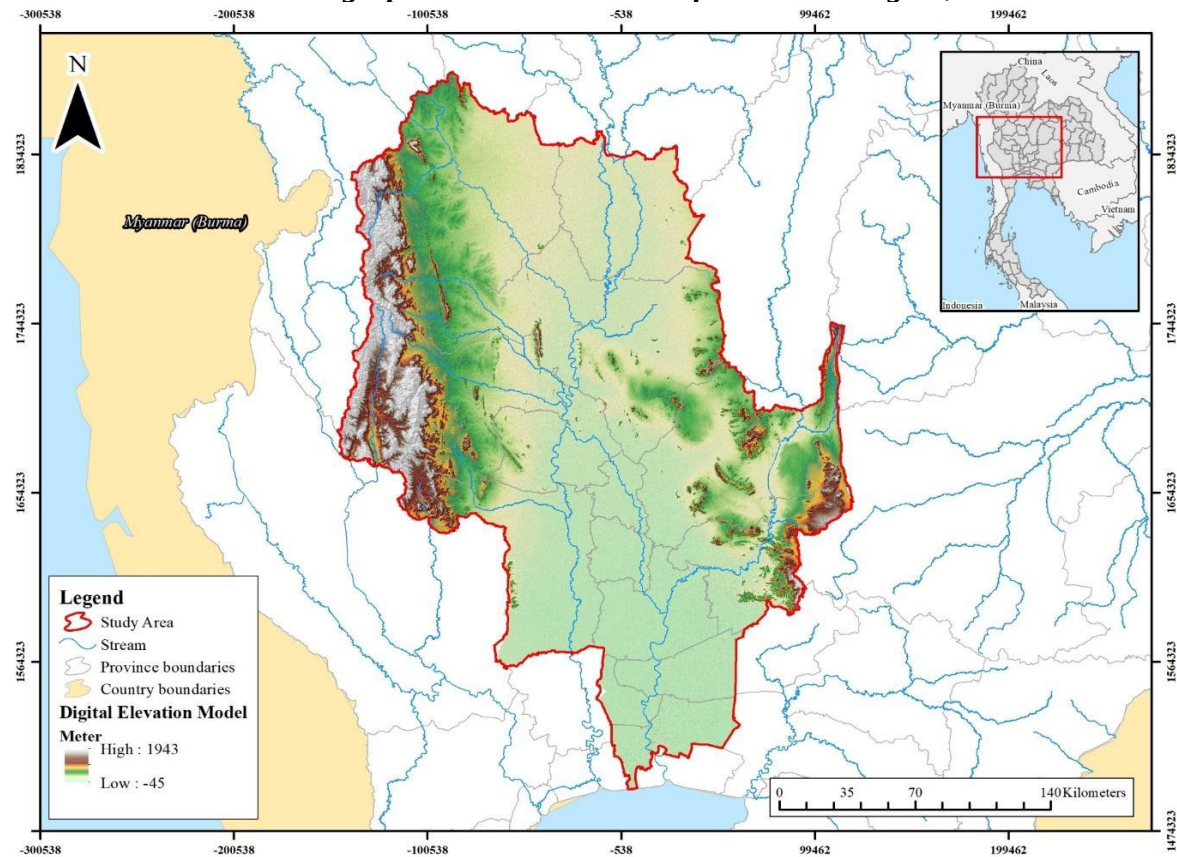


Figure 3.16 The geographical characteristics of the study area in the central region, DEM 30m by 30m

Table 3.6 The elevation of Central region classification

Order	Elevation range (meter)	Area (square meter)	Area Percent
1	0 - 175	46,036.31	83.81
2	175 - 396	4,298.04	7.82
3	396 - 617	2,324.21	4.23
4	617 - 838	1,152.40	2.10
5	838 - 1,059	691.01	1.26
6	1,059 - 1,280	301.22	0.55
7	1,280 - 1,501	89.21	0.16
8	1,501 - 1,722	30.86	0.06
9	1,722 - 1,943	5.68	0.01
Total		54,928.96	100.00

¹⁹ Ang Thong, Bangkok, Chai Nat, Kamphaeng Phet, Lop Buri, Nakhon Sawan, Nonthaburi, Pathum Thani, Phichit, Phra Nakhon Si Ayutthaya, Saraburi, Sing Buri, Suphan Buri, Uthai Thani

3.2.9 Land use Classification of the Central region

According to the Department of Land Development (2022), the land use in the central is mainly categorized into four classes, including

- 1) Agricultural land accounts for 35,555,828 ha (65%) of the total area of the Northeast, which is mainly rice paddy fields, field crops, and orchards.
- 2) Build-up land accounts for 589,828 ha (11%) of the total area of central land. It includes mainly urban land, buildings, roads, and highways.
- 3) Water accounts for 177,049 ha (3%) of the total area of central region where the natural water resources are included.
- 4) Miscellaneous land includes grass land, forest land, and wetland, which account for 1,170,190 ha (21%) of the total Central area.

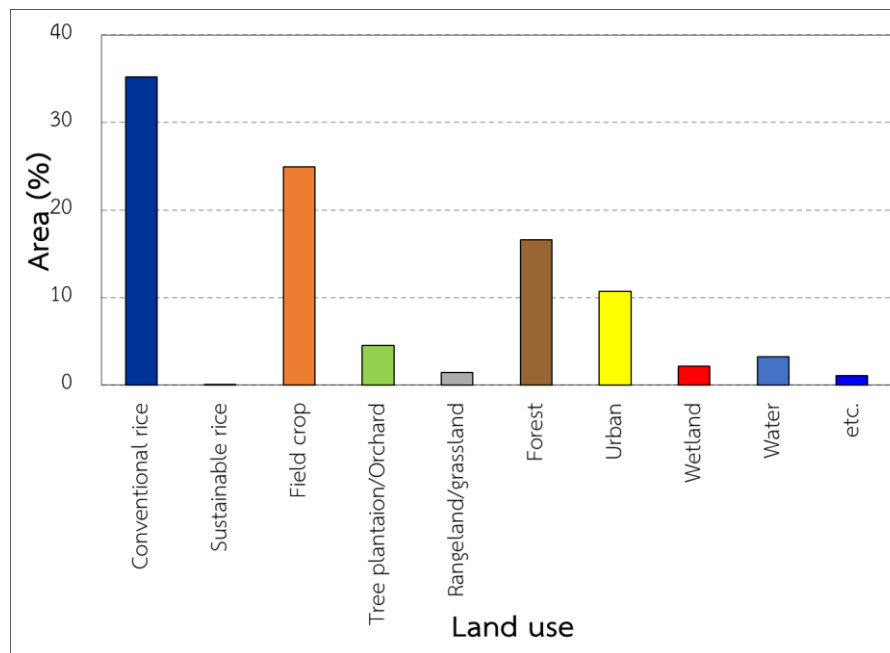


Figure 3.17 Land use classification of the study area in central region Year 2022

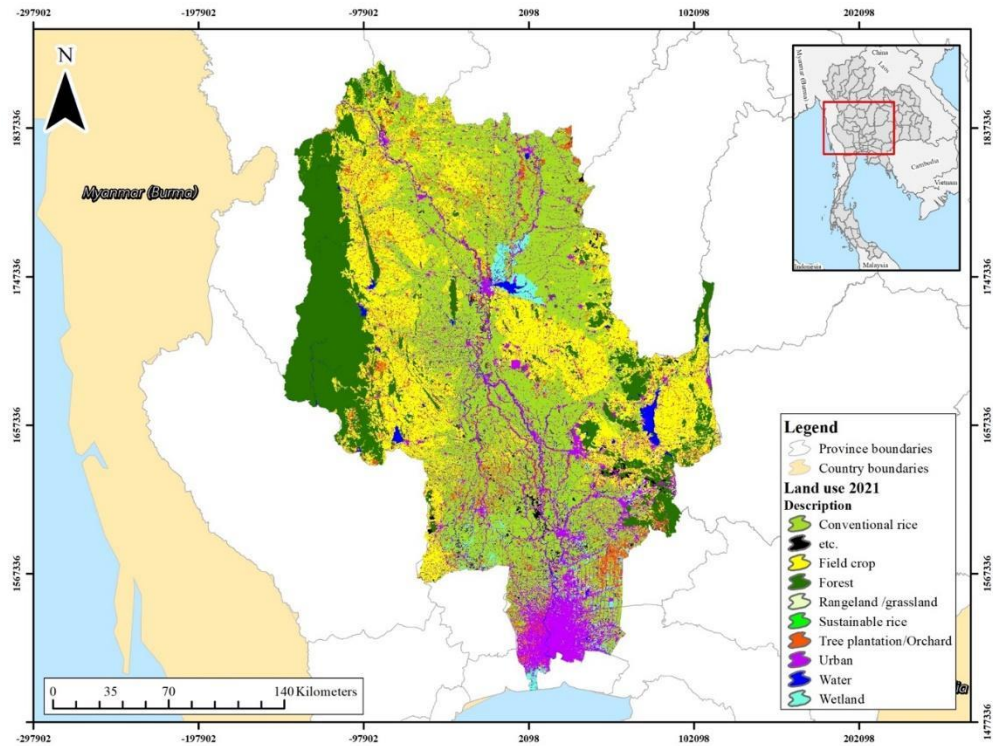


Figure 3.18 Land use classification in Central region Year 2021

3.2.10 Land use change prediction in two-time period (T1 and T2), central region, Thailand

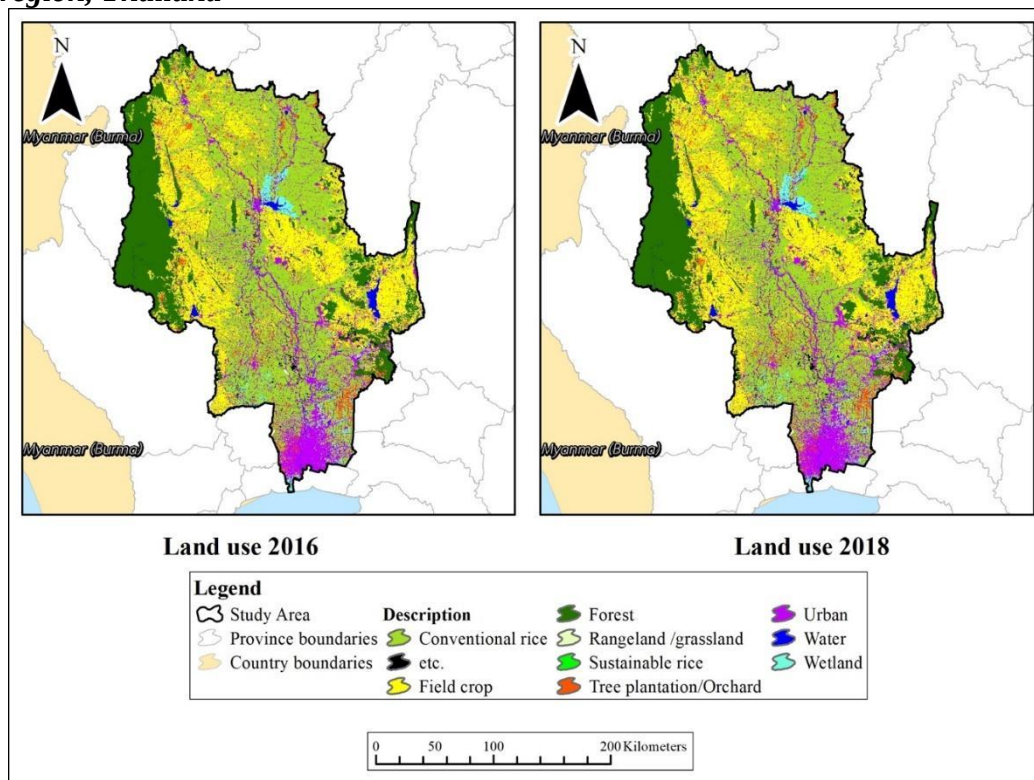


Figure 3.19 Land use two periods of the central region in 2016 (T1) and 2018 (T2)

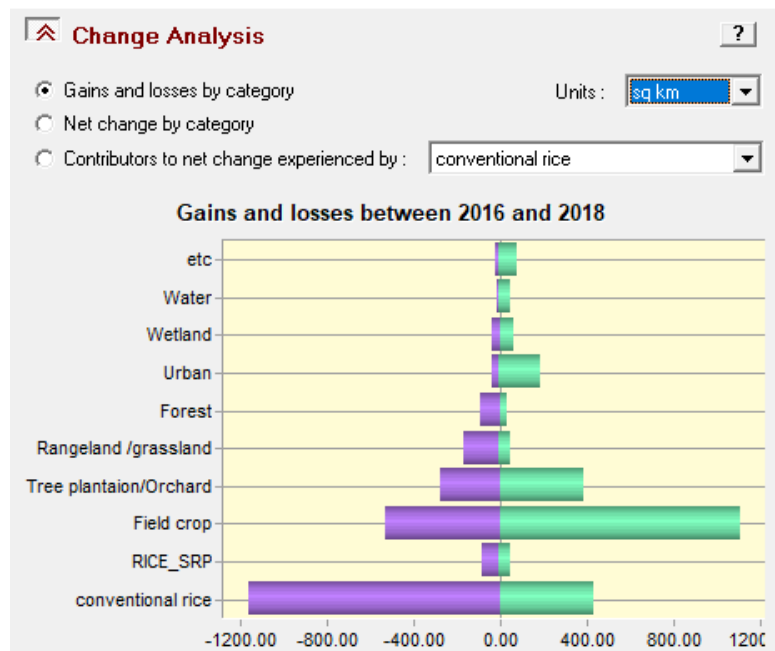
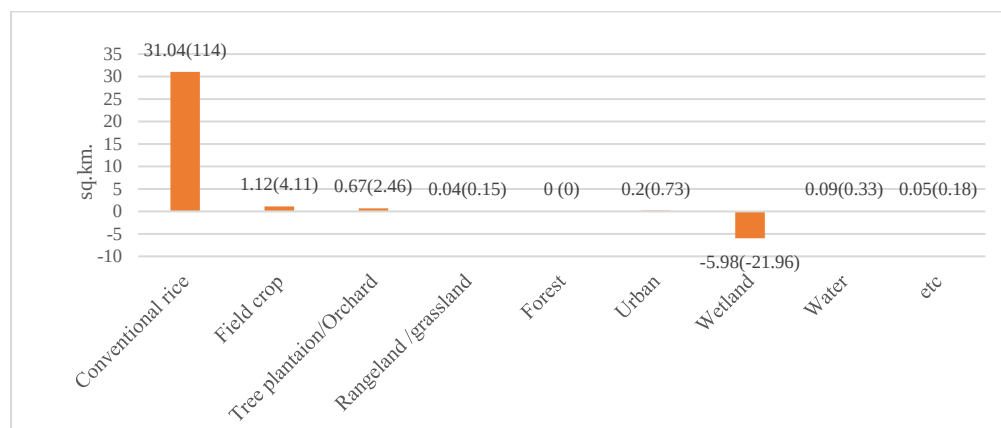


Figure 3.20 Change analysis of land use in central during 2016 and 2018 using Land Change Modeler

Table 3.7 presents the change in the central region land during two periods. Considering within the same class in this region, we found that the majority shift of agricultural land use are the field agriculture and tree plantation or orchard with the most significant net increases of 581.18 square kilometers (4.43%), 103.88 square kilometers (4.33%), respectively. The land use for conventional rice paddy fields and sustainable rice paddy fields has the highest net decrease of 728.36 square kilometers (3.64%) and 27.23 square kilometers (32.88%), respectively. Note that the negative sign of the changes in the last column shows that the relative lower land area in 2018 is less than was in 2016 on its own. In particular, Figure 3.21 illustrates the conversion of sustainable rice area in the central region. A decreasing in the sustainable rice area of 27.23 sq. km. contributes the most of 31.04 sq. km., to conventional rice paddy. And followed by the field crop land (1.12 sq.km.) and the tree plantation land (0.67 sq. km.). However, the majority of the increased sustainable rice area in the central region is converted from a wetland, accounting for 5.98 square kilometers.

Table 3.7 the change analysis of land use in central region each class between 2016 and 2018

Order	Land use category	Area (Sq. meter)		Change	
		2016	2018	Sq. meter	Percent
1	Conventional rice	20,029.81	19,301.44	-728.36	-3.64
2	Sustainable rice	82.82	55.58	-27.23	-32.88
3	Field crop	13,126.98	13,708.17	581.18	4.43
4	Tree plantation/Orchard	2,397.58	2,501.46	103.88	4.33
5	Rangeland /grassland	899.67	783.71	-115.96	-12.89
6	Forest	9,194.30	9,131.94	-62.36	-0.68
7	Urban	5,745.31	5,897.72	152.42	2.65
8	Wetland	1,162.44	1,177.66	15.22	1.31
9	Water	1,732.13	1,770.19	38.06	2.20
10	etc.	542.54	601.09	58.55	10.79



Note: * a percentage is displayed in parenthesis; a positive sign denotes that SRP converted into other LU class, while a negative sign shows that a particular class converted to SRP.

Figure 3.21 LU class contribution to the net change in the SRP rice area, northeast region

3.2.11 Driving variables for land use change in the central region*

After the land use change analysis between two time periods was established, the LCM then conducted a transition potential analysis to determine which driving factors may be significant in future land use change using the multi-layer perceptron method (MLP). The driving factors in this study are slope, average precipitation, maximum temperature, mean temperature, minimum temperature, and distance from an urban area. Figure 3.22 depicts the spatial distribution of all driving factors. Cramer's V statistic was used to determine the significant driving forces to be included in the modeling in order to quantify the relationship between each type of land use and the driving factors. Using Cramer's V, the most offerings that are compatible in two LU maps are identified. If Cramer's V values of 0.15 or higher have a moderately substantial influence on land

use change; if the coefficient values more than 0.4 have a very significant influence on land use change (Eastman, 2012).

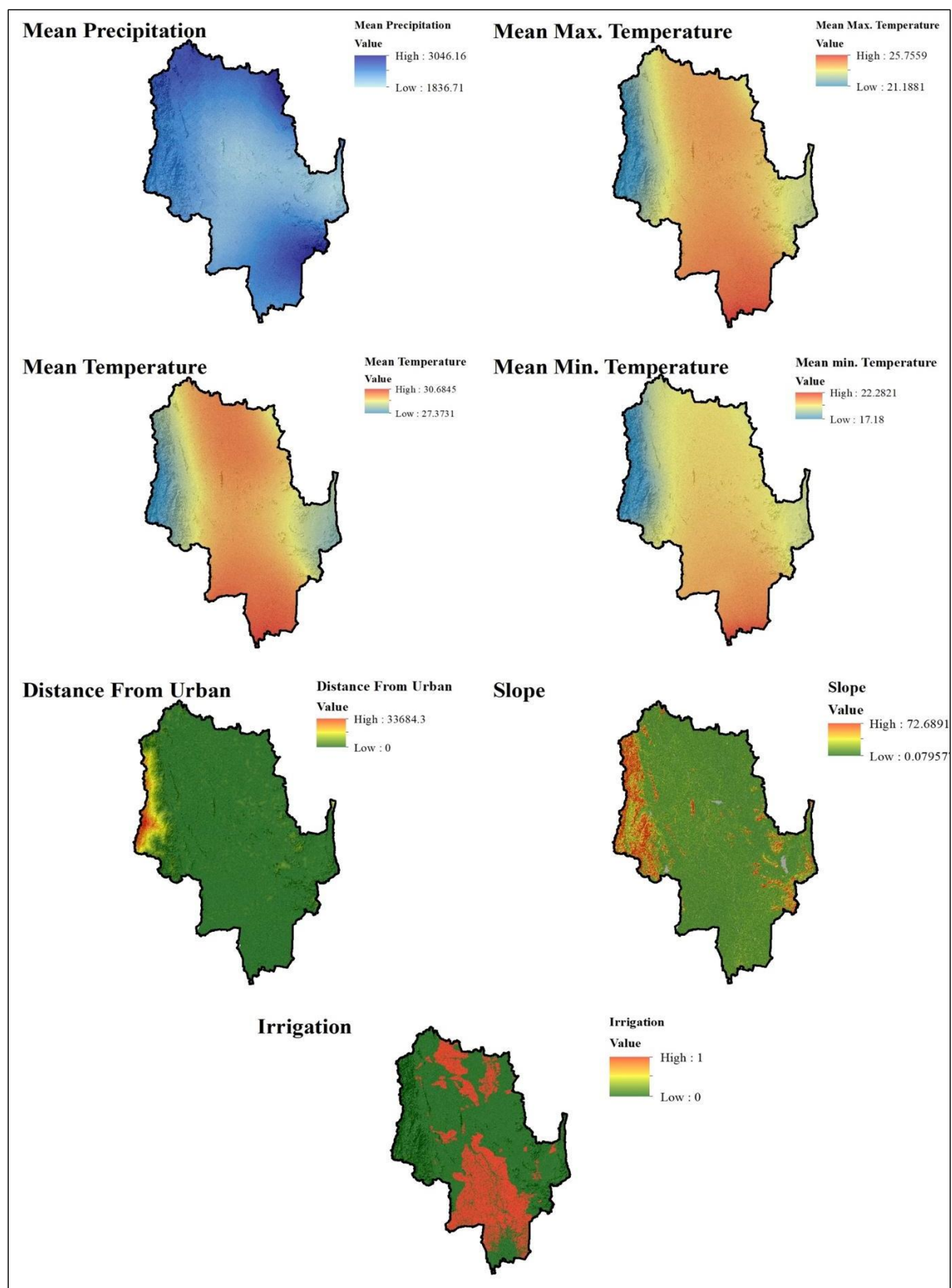
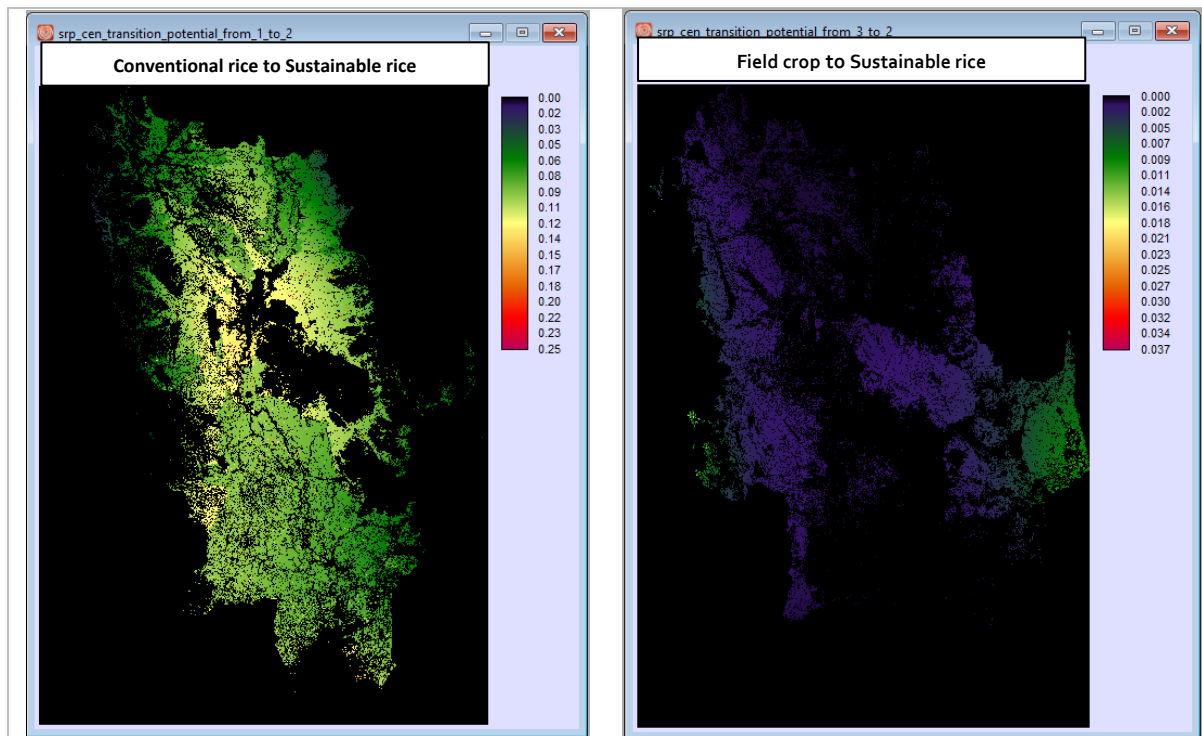


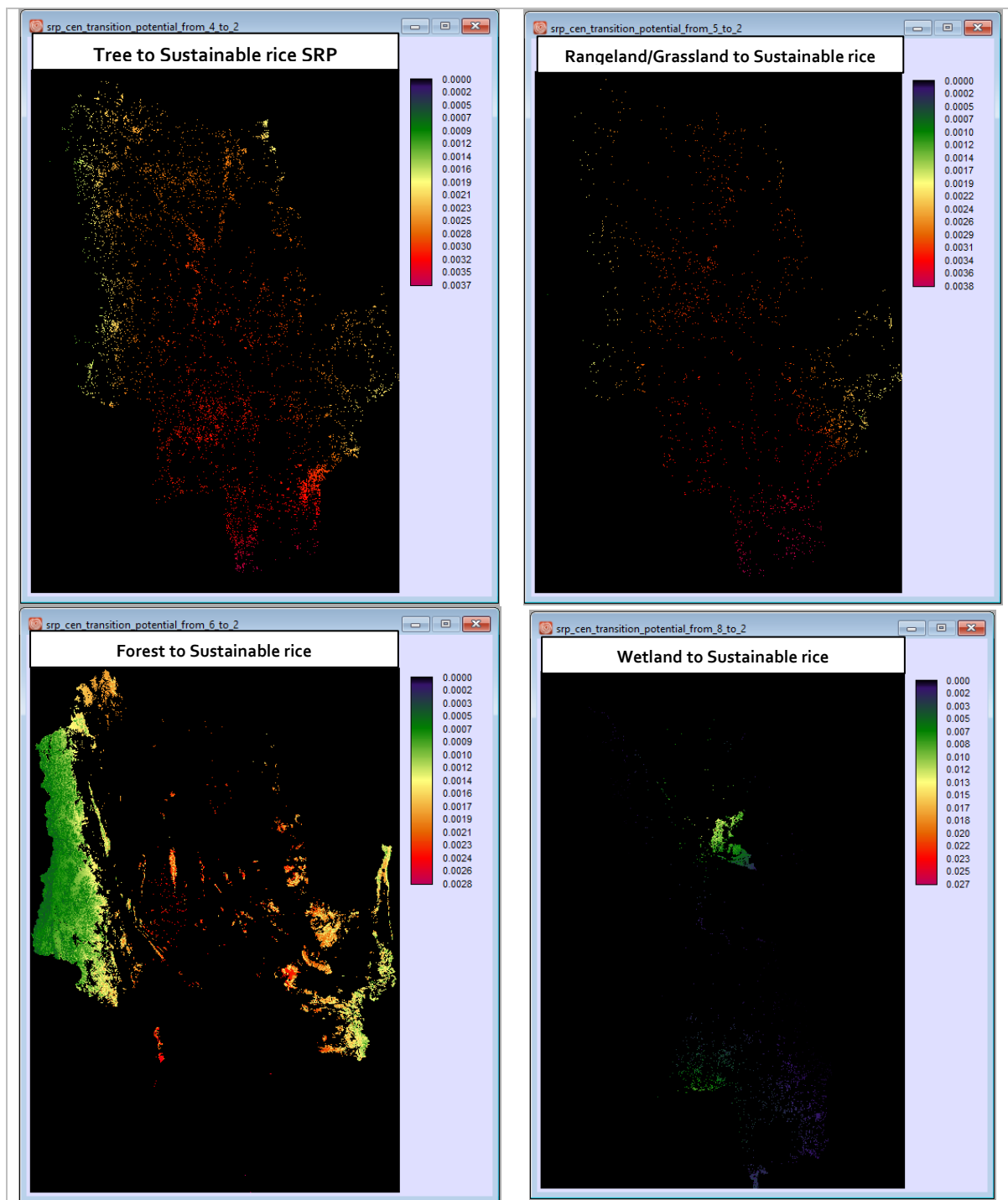
Figure 3.22 Driver variables for transition potential of land-use change analysis in the central region.

Table 3.8 Cramer's V association test of driving factors for the central region

Order	Land use\Variables	Cramer's V						
		Mean precipitation	Mean max. temperature	Mean temperature	Mean min. temperature	Slope	Distance from urban	Irrigated area
1	Overall	0.0141	0.3021	0.2916	0.2921	0.2636	0.2289	0.1540
2	Conventional rice	0.0001	0.0001	0.0001	0.0001	0.0010	0.0001	0.0001
3	Sustainable rice	0.2328	0.4693	0.4851	0.4239	0.3146	0.2306	0.4470
4	Field crop	0.0261	0.0324	0.0300	0.0301	0.0131	0.0108	0.0117
5	Tree/Orchard	0.2532	0.4118	0.3643	0.3863	0.2003	0.1802	0.1804
6	Rangeland/grassland	0.1149	0.0954	0.0864	0.7087	0.0747	0.0782	0.0521
7	Forest	0.0365	0.0552	0.0456	0.0565	0.0453	0.0437	0.0351
8	Urban	0.3175	0.7274	0.7018	0.7078	0.8273	0.7205	0.2685
9	Wetland	0.0904	0.3926	0.3833	0.3921	0.1270	0.1452	0.1165
10	Water	0.0679	0.1970	0.1912	0.2073	0.0588	0.0459	0.0394
11	etc.	0.0541	0.0847	0.0890	0.0738	0.0654	0.0486	0.0743

3.2.12 Transition potential selection of land use in the central region, Thailand.*





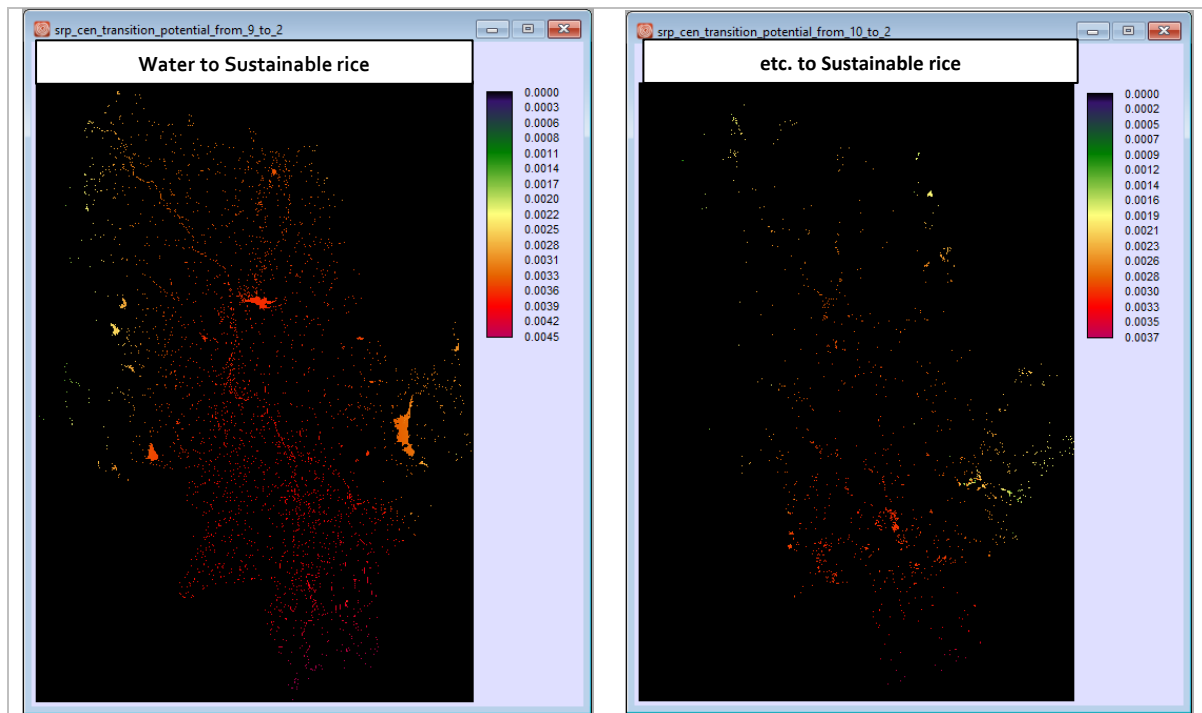


Figure 3.23 Maps of transition potential of SRP rice cultivation area in the central region, Thailand

3.2.13 Validity test of land use change prediction for the central region*

The assessment of land use change prediction for the central region is similar to previous conducted for the northeast region. The overall accuracy and the kappa coefficient are assessed. As a results, the accuracy assessment of land use in the central region shows that the kappa value was 0.91 and the overall assessment was 93.12%. According to Congalton (1991)²⁰, an overall accuracy value greater than 70% is considered as acceptable and with a kappa statistic of 0.4-0.85 is considered as the reliable agreement. Thus, the outcomes of both regions are appropriate for use in the further stage of land use prediction.

²⁰ Congalton, R.G. A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data. Remote Sens. Environ. 1991, 37, 35–46.

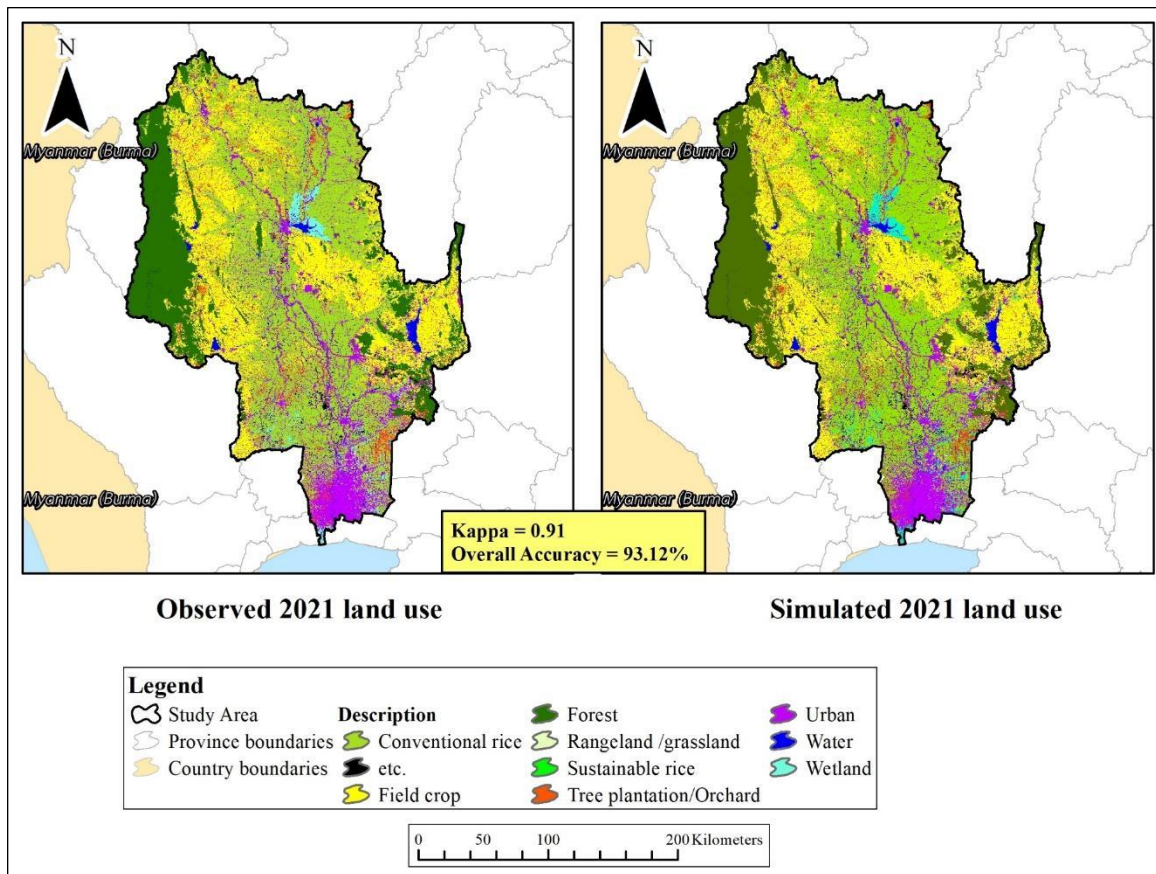


Figure 3.24 Validation of the central land use prediction based on the observed 2021 LU and simulated 2021 LU.

3.2.14 Land use change prediction under future scenarios of the central region

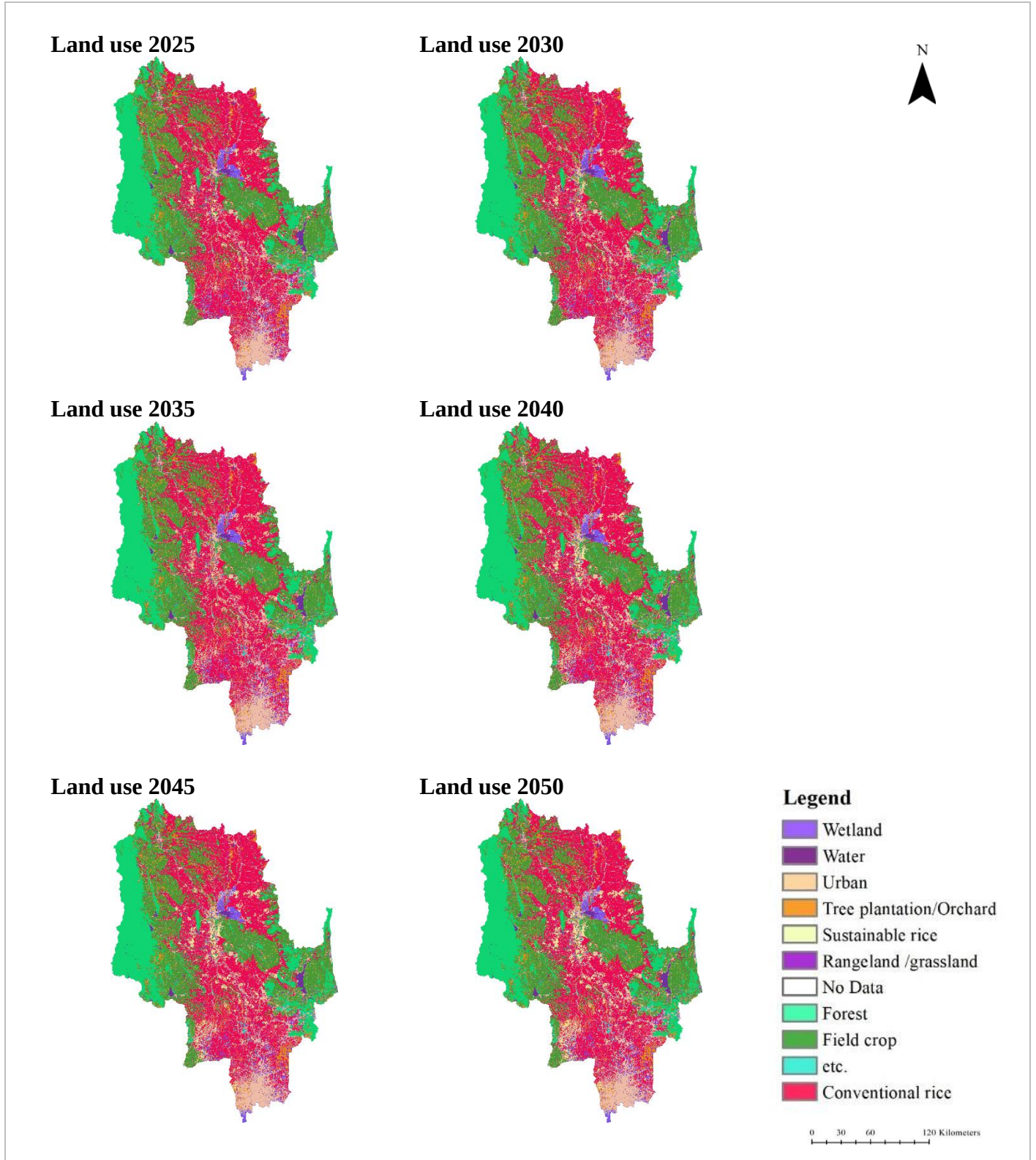


Figure 3.25 The sustainable rice area prediction in the central region under Scenario 1

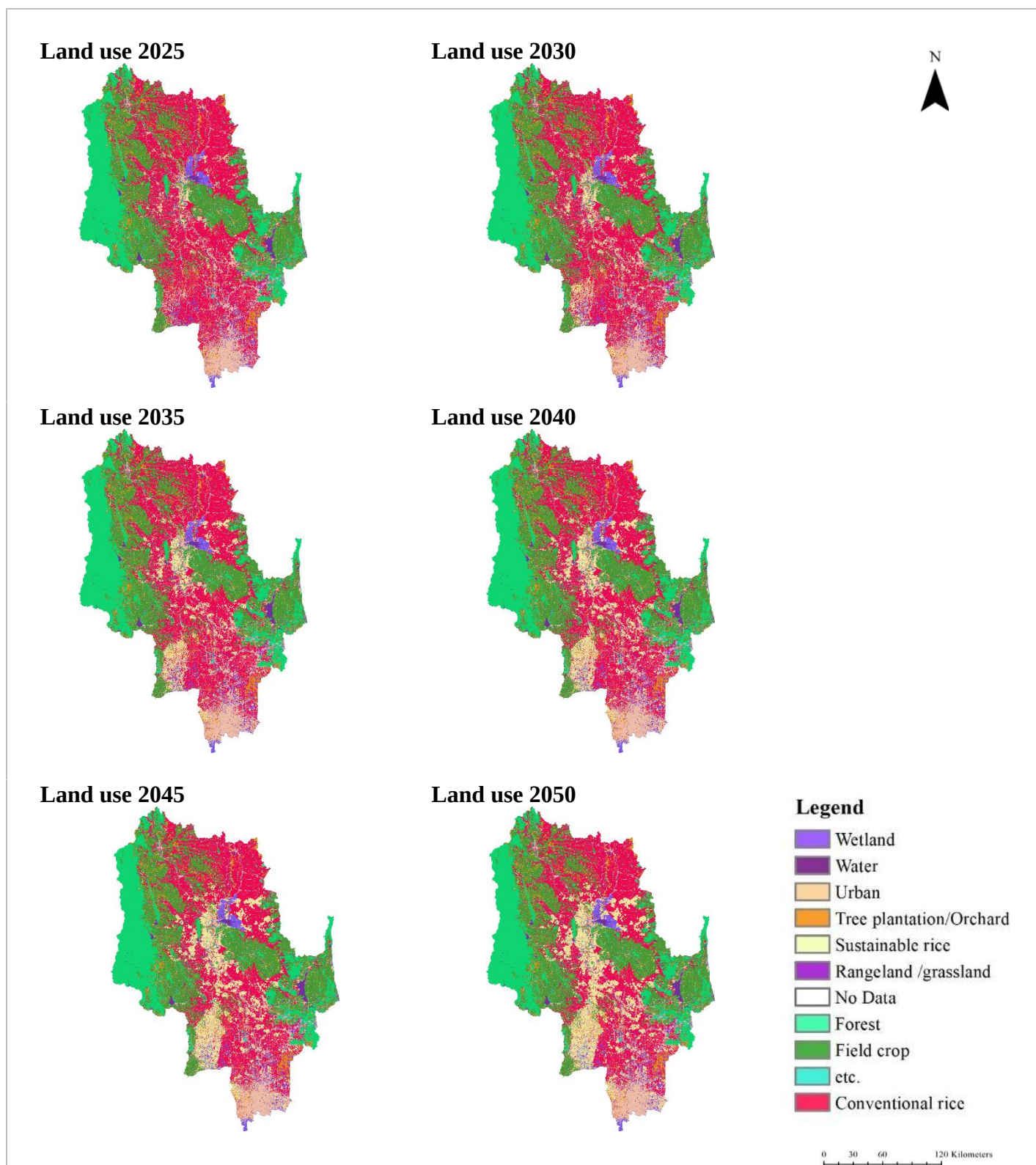


Figure 3.26 The sustainable rice area prediction in the central region under Scenario 2

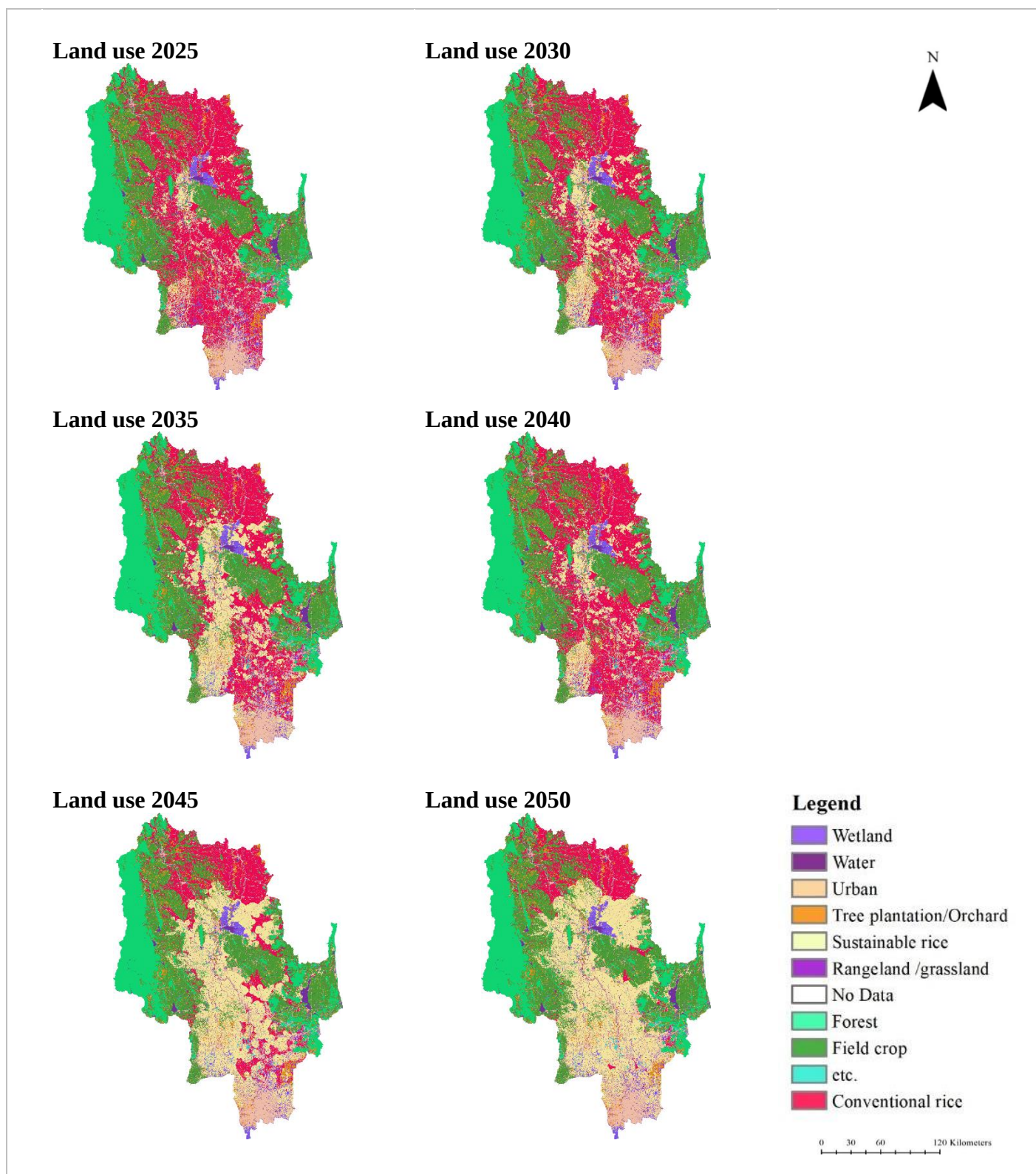


Figure 3.27 The sustainable rice area prediction in the central region under Scenario 3

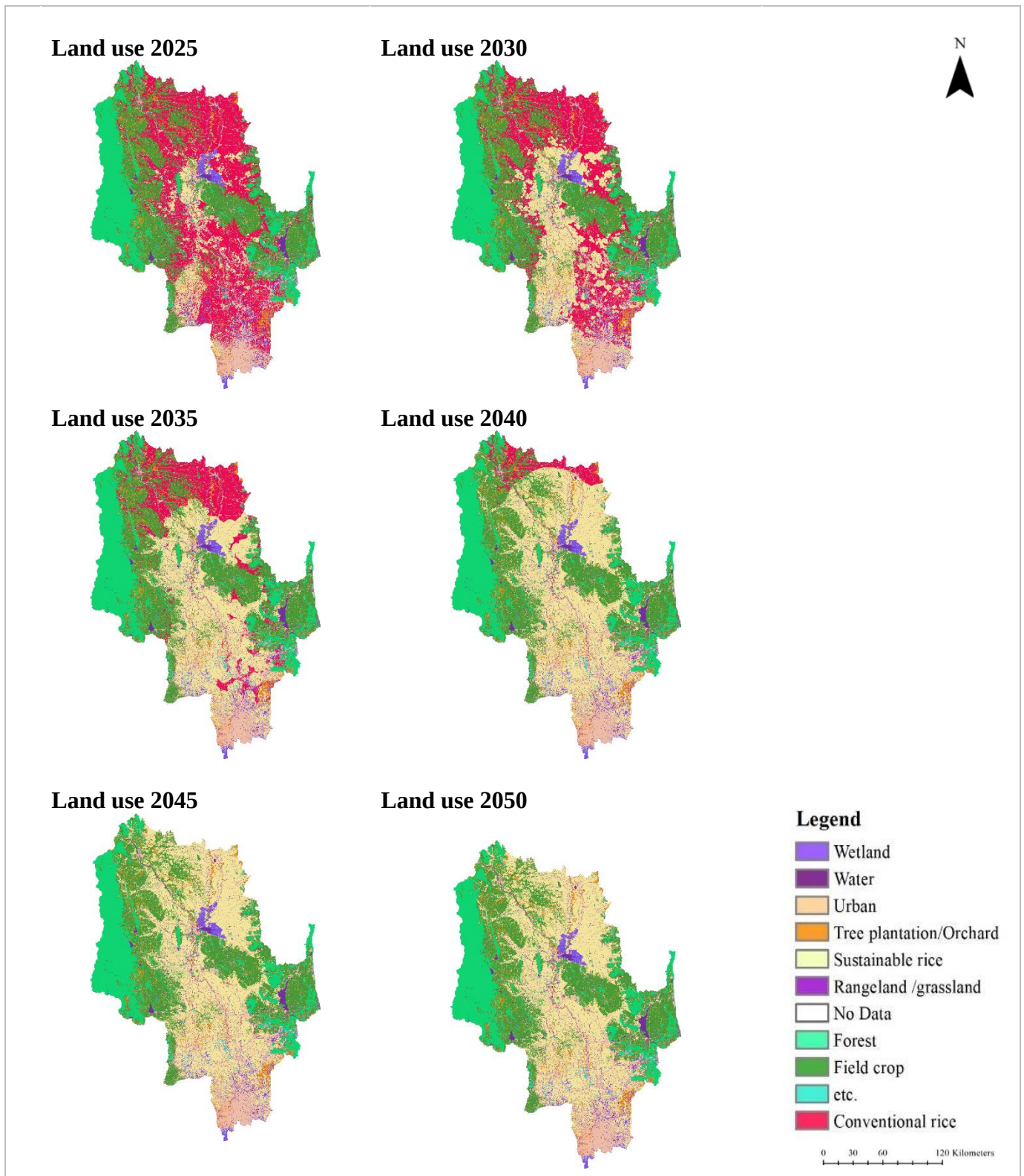


Figure 3.28 The sustainable rice area prediction in the central region under Scenario 4

Figures 3.25-3.28 present the prediction of sustainable rice area for the central region of Thailand. The analysis considers the fourteen provinces where there is a historical record of sustainable rice practice in the area. The irrigation system is very important to rice production in the central region, so it is a key part of the conversion prediction. As a results, as gradually conversion of sustainable rice in BAU, the minimal conversion presents around Phra Nakhon Si Ayutthaya where the clustered of wetland and water area, Cho Phraya river basis, are located. and it is obvious in 2050. Scenario 2 and scenario 3 are aligned together of illustrating a clear vision of sustainable rice area in 2030. Finally, in Scenario 4, the transformational change toward sustainable rice is achieved, as is the government promotion of rice cultivation. Since 2045, the adjacent river plain of the central region has been the main location for sustainable rice paddy fields.

3.3 Spatial analysis integrated with data on farmer adoption of sustainable rice practices.

The second component of spatial analysis is developed to bridge the gap between the land use change model and farmers' adoption of sustainable rice practice. This part incorporates household survey data and the relevant spatial data into the analysis. A farmer's choice is influenced by the qualities of the farmland used for rice cultivation. Growing rice requires a decent amount of land area to achieve sufficient yield. The farmer's choices will have a significant impact on how the land is used. The analysis intends to examine relationships between four parameters, including household characteristics, the farmer's perspectives on sustainable rice practice, field features, and the farmers' geographic location, and how this influences their adoption of sustainable rice practices (Figure 3.29). The results of this section will be used to further present the spatial dependency at the study site and landscape level.

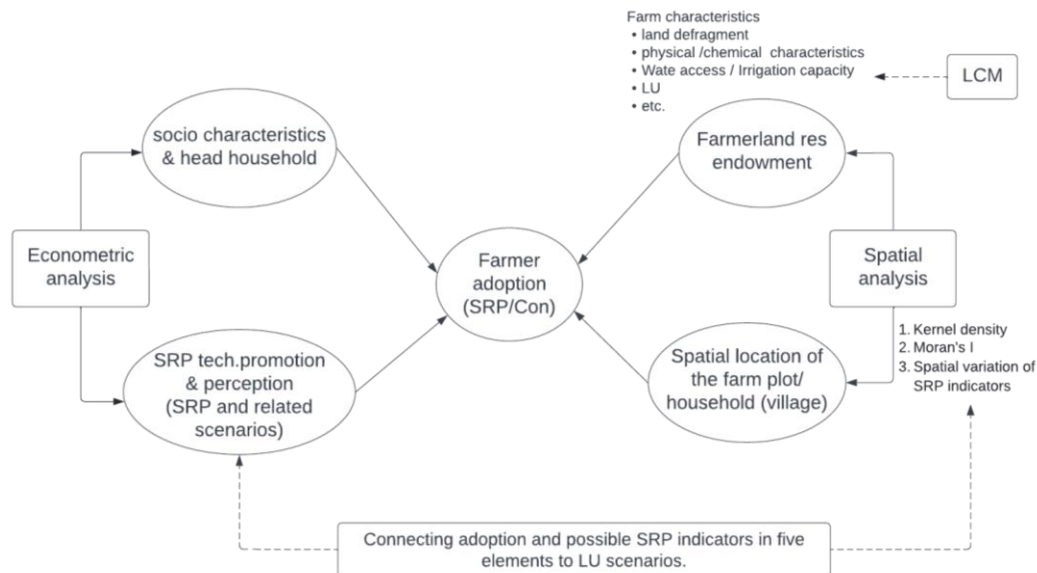


Figure 3.29 Conceptual framework for analysis of farmer adoption of SRP

The land use area changes under each scenario are linked to measurable changes not only to output and revenues from rice (produced capital dimension) but also capital stocks related to two additional dimensions: natural capital, and human capital.

As described in the TEEBAgriFood framework, the outcomes of agricultural production, processing, distribution, and consumption can be understood as changes in natural, human, social, and produced capital. Outcomes related to natural capital stocks that are covered in this study include changes to biodiversity, GHG emissions, air pollution, and water footprint. Outcomes in terms of changes in human capital relate to changes in health of both farmers and the general public are also explored.

TEEBAgriFood analysis in Thailand uses a scenario modelling approach to examine the potential future impacts of land-use changes as a result of current sustainable rice expansion. Impacts are assessed at the landscape level in terms of changes in rice-field biodiversity, the emission of greenhouse gases, air pollution, water footprint, and the health impacts of chemical pesticides. The methodologies applied and results for each measure are presented in part 4 - 9.

3.4 Summary

The study in this section utilizes the Land Change Modeler to analyze both past and future land-use dynamics and further predict the conversion of land for SRP rice production in the northeast and central region of Thailand. The research focuses on a landscape-level analysis that

considers crucial parameters for assessing ecosystem services and biodiversity implications. Based on the land-use data, SRP rice inspection records, and geographical characteristics from 2016 to 2018, an analysis of land-use change in Thailand indicates a noticeable pattern in rice production. Specifically, there has been a decline in the area dedicated to SRP rice compared to conventional rice in both the Northeast and Central regions. The main factors that contribute to changes in land use include geographical features such as slope and elevation, climate variables like average precipitation and temperature, as well as social factors that reflect urbanization, such as distance to a road and village center, and the presence of irrigation zones. Note that the climate variables in this analysis are based on the RCP4.5 emission scenario. The projected conversion of SRP rice area in both regions is outlined across four future scenarios: business as usual, moderate change, enhanced change, and transformational change. According to the study, the Mun River basin in the northeast region has the highest prevalence of rain-fed SRP rice production. In 2045, sustainable rice cultivation shows slight improvements in the southern regions, particularly in the provinces of Surin and Ubon Ratchathani. These improvements are attributed to the enhanced and transformative changes implemented in the conversion of SRP rice production land. In the Central region of the country, there is a significant prediction of SRP conversion. This is particularly prevalent in an irrigated area near Phra Nakhon Si Ayutthaya province, where wetlands and watersheds are concentrated in close proximity to the Cho Phraya river basin. The increasing trend will become apparent by 2050 in scenarios two and three. If the conversion of SRP rice land becomes more aggressive due to the transformative shift, we can expect a similar scenario to occur as early as 2030.

The aim of this section is to estimate and conduct spatial analysis of GHG emissions from conventional rice practice and sustainable rice practice in Central and Northeast regions of Thailand. The three main sources of GHG emissions from rice field are focused. The first source of GHG is directly emitted during rice cultivation. The flooding of rice fields is a major source of methane gas emission. In addition to nitrous oxide emissions, which mainly comes from fertilizer, is also estimate. The second source of GHG emissions from rice field is from the soil, which is related to soil organic carbon stocks that presents the capability of the soils for GHG removal. The third source of GHG emissions is from rice straw burning after harvesting rice gain. The rice straw burning generates not only GHG emissions but also air pollution. The rice straw burning is widely performed by conventional rice practice but is prohibited for sustainable rice practice.

4.1 Greenhouse gas emissions, soil carbon stock and rice grain yields

Rice (*Oryza sativa* L.) is the food staple for half of the world's population (FAO, 2020) and an important economic crop in Thailand. Agriculture is the main source of methane (CH₄) and nitrous oxide (N₂O) emissions. Total greenhouse (GHG) emissions of Thailand from the agriculture sector in 2013 were 50.9 million ton CO₂eq. Rice cultivation was the largest source in this section and was estimated to have emitted 27.9 million ton CO₂eq (54.72%) (ONEP, 2017). Under flooding practices of rice cultivation, CH₄ is produced in anaerobic soil through organic matter fermentation by methanogenic bacteria (Le Mer and Roger, 2001). Moreover, water management, nitrogen fertilizer application, residue return, and matter amendment are also the factors in controlling CH₄ and N₂O emissions (Towprayoon *et al.*, 2005; Cha-un *et al.*, 2017, Chidthaisong *et al.*, 2018; Sriphirom *et al.*, 2020; Arunrat *et al.*, 2021; Cha-un *et al.*, 2021). Especially, organic matter amendment such as crop residue and manure has been practiced to promote soil organic carbon (SOC) stocks, but also enhances CH₄ emissions from rice fields (Cha-un *et al.*, 2017).

The low GHG emission is the one indicator to evaluate the performance of good agricultural practices (GAP) and sustainable rice platform (SRP) standard. The SRP standard provides a framework for advanced farming practices, leading to higher net profits, increased yields, enhanced food safety, and lower GHG emissions. Therefore, in order to achieve this

standard, the finding of sustainable rice field management practices with optimizing the amount of fertilizer and organic matter applied to the soil, residue management, water management such as alternate wetting and drying (AWD) could be one option to reduce CH₄ and N₂O emissions while maintaining or even increasing grain yields and SOC stocks.

The long-term observation of CH₄ and N₂O emissions, grain yields and SOC stocks is difficult due to spatial differences in environmental factors the dynamism of field management practices that are normally changed in every cropping season. Time limitations and expenses are also important factors. Therefore, the modelling approach to realize the long-term variation of rice grain yield, SOC sequestration, and GHG emissions under different environmental factors and field management practices. The Denitrification–Decomposition (DNDC) model is a computer simulation that has been developed for predicting carbon and nitrogen cycling in agroecosystems (Li *et al.*, 1994). The DNDC has well simulated in long-term SOC dynamics and GHG emissions and other related variables such as crop yields from rice cultivation (Shirato, 2005; Babu *et al.*, 2006; Chen *et al.*, 2016; Cha-un *et al.*, 2015; Cha-un *et al.*, 2017; Naher *et al.*, 2020; Cha-un *et al.*, 2021). Therefore, this model is used to simulate the long-term GHG (N₂O and CH₄) emissions, SOC sequestration, and rice grain yield under different field management practices.

This study will use the DNDC model to investigate the emissions of CH₄, N₂O, grain yields, and SOC stocks under different rice management practices in the representative provinces in the Northeast and Central regions of Thailand. After that, the simulated results at the site scale in each province will be used for evaluation at the regional scale, respectively.

4.2 Material and method

4.2.1 Study design

In this project, the Northeast and Central regions of Thailand are the study areas. The DNDC model (version 9.5) will be validated against field observation data from published papers in a Thai rice field, and then will be used to simulate in the long-term (2021-2050) of different rice field management scenarios. The changes in GHG emissions (CH₄ and N₂O), crop yields including rice grain, maize, and mung bean and SOC stocks from rice cultivation with various managements of two regions are simulated as Figure 4.1

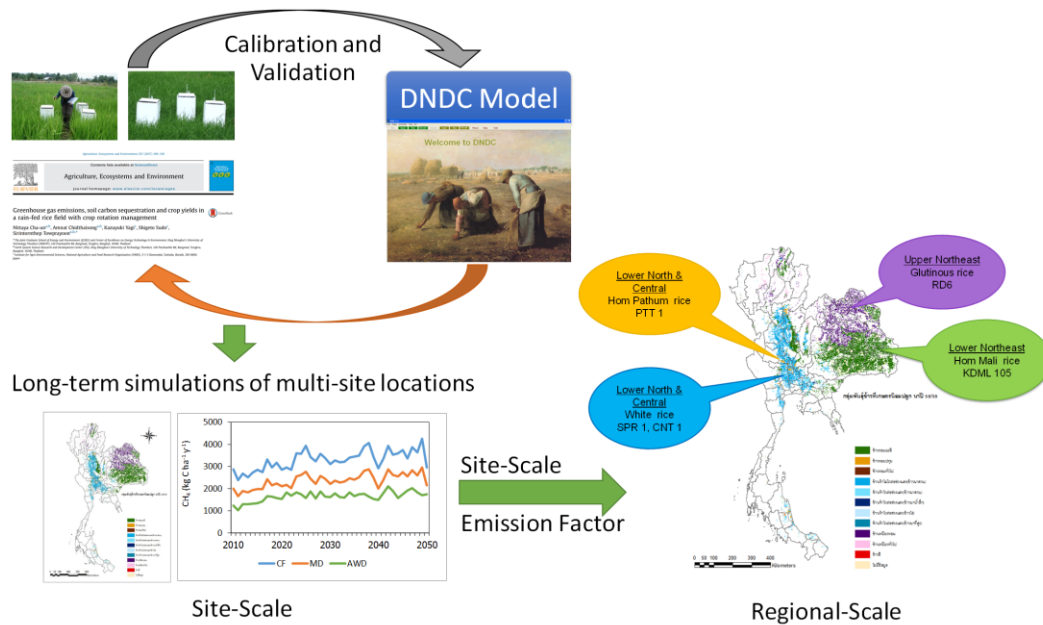


Figure 4.1 Scope of the study

4.2.2 DNDC model description

The Denitrification-Decomposition (DNDC) model is a computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems (Figure 4.2). The model can be used for predicting crop growth, soil temperature and moisture regimes, soil carbon dynamics, nitrogen leaching, and emissions of trace gases such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, 2017). During the last two decades, the DNDC model has been used by researchers throughout the world. As presented in the 9.5 version, DNDC has also been developed and improved in simulations of crop growth, nitrification inhibitor application, slow-release fertilizers, sprinkler and drip irrigation, plastic film mulching, etc., to meet the demand for GHG mitigation studies (Gilhespy *et al.*, 2014; Cha-un *et al.*, 2021). Also, this current version provides an appropriate modeling framework for the long-term simulation of crop yield, SOC stock change and GHG emissions in the rice field ecosystems (Gilhespy *et al.*, 2014). Therefore, the version of DNDC 9.5 (open source, downloaded from <http://www.dndc.sr.unh.edu/>, accessed on 26 December 2021) are used in this study.

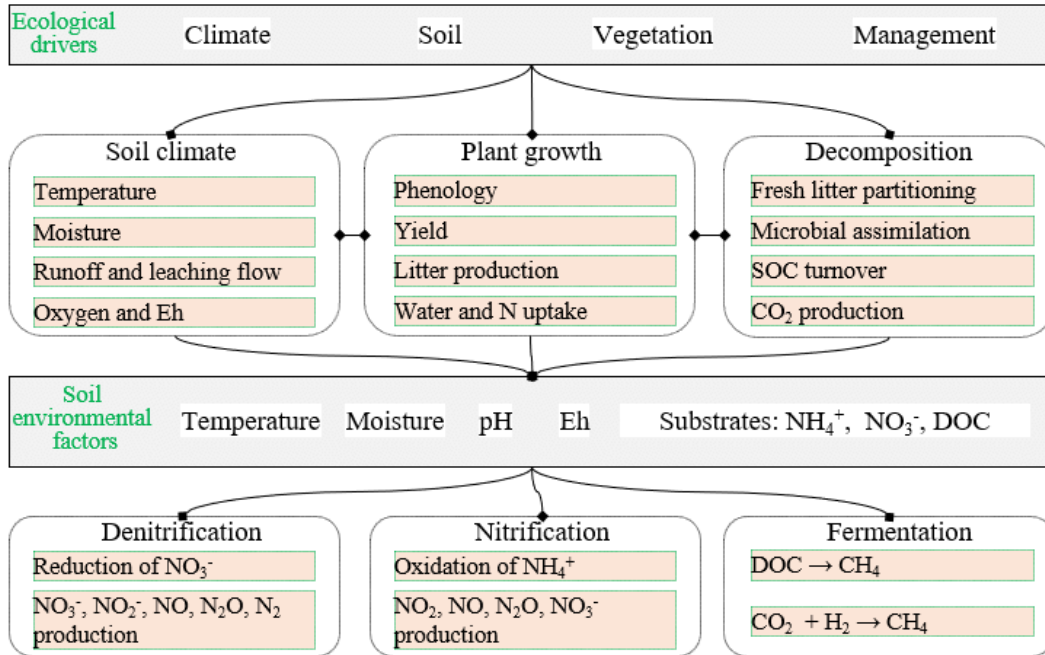


Figure 4.2 Structure of the DNDC Model (Li, 2016, as cited in Yin et al., 2020)

4.2.3 Validation of the model performance

The field observation data from several published papers in a Thai rice field experiment (Table 4.1) and data from the field survey will be used to calibrate and validate the SOC stock, rice grain yield, and emissions of CH₄ and N₂O in order to examine the reliability of model.

Table 4.1 Thai rice field experiment and parameters for model validation

Region	Province	Parameter	Reference
Central	Ratchaburi	SOC stock, grain yield, CH ₄ , N ₂ O	Cha-un <i>et al.</i> , 2017
	Prachinburi	grain yield, CH ₄ , N ₂ O	Chidthaisong <i>et al.</i> , 2018
	Ratchaburi	SOC stock, grain yield, CH ₄ , N ₂ O	Sriphirom <i>et al.</i> , 2020
	Pathum Thani	grain yield, CH ₄ , N ₂ O	Ruensuk <i>et al.</i> , 2021
	Ang Thong	grain yield, CH ₄ , N ₂ O	Ruensuk <i>et al.</i> , 2021
	Chai Nat	grain yield, CH ₄ , N ₂ O	Ruensuk <i>et al.</i> , 2021
Northeast	Khonkaen	grain yield, CH ₄	Saenjan <i>et al.</i> , 2006
			Thammasom <i>et al.</i> , 2016

Region	Province	Parameter	Reference
	Sakon Nakhon	grain yield, CH ₄ , N ₂ O	Ruensuk <i>et al.</i> , 2021
	Ubon Ratchathani	CH ₄	Rossopa <i>et al.</i> , 2013

4.2.4 Study sites

In Thailand, rice cultivation makes up over 60% of agricultural land (OAE, 2019). Over 60% of the major rice cultivation areas are located in the Northeast (NE). The glutinous rice variety RD6 is mainly cultivated in the upper Northeast (U-NE) (64%), whereas Hom Mali or fragrant rice (KDML 105, RD15) (95%) is cultivated in the lower Northeast (L-NE). While, in the Central (C), Western (W) and Eastern (E) regions, double-cropping of rice per year is usually found in these regions due to the availability of water from irrigation networks. These regions produce white rice with various rice varieties. The common varieties are Patum Thani 1 (PTT 1), Suphan Buri 1 (SPR 1), and Chainat 1 (CNT 1) (Varinruk, 2017) as Figure 4.3.

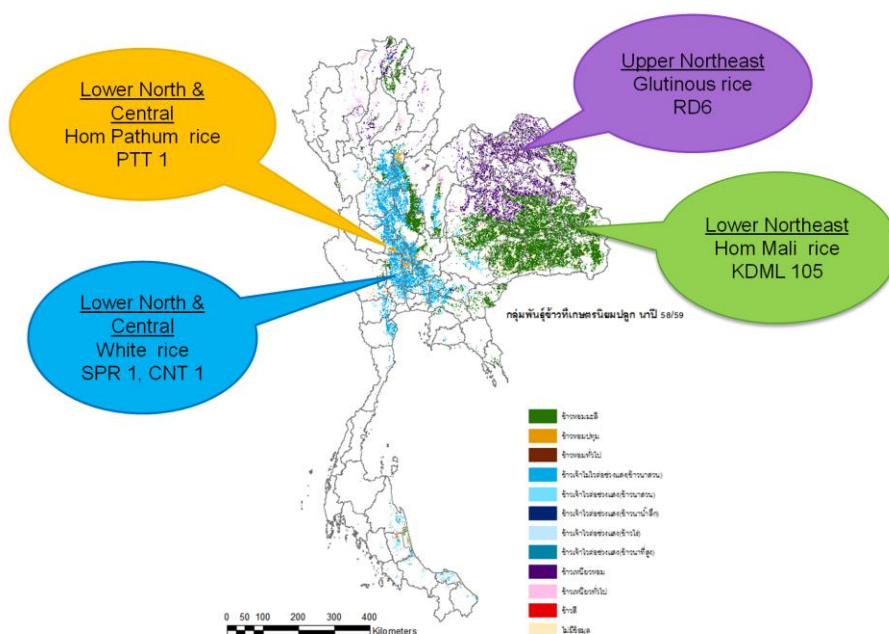


Figure 4.3 Rice varieties in different rice sub-ecosystem (DOAE, 2017; Varinruk, 2017)

In this project, the five provinces in Central region and seven provinces in Northeast region were selected to be representative study sites for each region. The represent provinces were selected from the provinces where the cumulative harvested area was more than 50% of the total harvested area of each region. The selected study sites were listed in Table 4.2.

Table 4.2 Study sites in Central and Northeast regions, Thailand

No.	Region	Province
1	Central	Suphanburi
2	Central	Phranakornsri Ayuthaya
3	Central	Chainat
4	Central	Angthong
5	Central	Pathumthani
1	Northeast	Khonkane
2	Northeast	Sakonnakorn
3	Northeast	Udon Thani
4	Northeast	Ubon Ratchathani
5	Northeast	Roi-et
6	Northeast	Nakorn Ratchasima
7	Northeast	Surin

4.2.5 Long-term simulations of multi-site location

The data sets of daily climates, soil properties, and rice management practices were required as inputs in the model. The model requires climate data such as daily maximum and minimum air temperatures, and rainfall. The climate data from 2001-2020 are obtained from the observation stations of Thai Meteorological Department (TMD) and the climate data for the future simulation (2021-2050) obtained from the Regional Climate Model Version 4.3.7, CNRM-CM5 Model, Resolution 25 x 25 km, assuming the emissions scenario on the Representative Concentration Pathways (RCP) 4.5 which refer to climate scenarios of the Intergovernmental Panel on Climate Change (IPCC) (Ramkhamhaeng University Center of Regional Climate Change and Renewable Energy: RU-CORE, 2020). RCP 4.5 is described by IPCC as a moderate scenario with intermediate greenhouse gas emissions. Mean temperature and total precipitation over 2021-2050 of the studied sites obtained from the model RCP 4.5 were presented in Figures 4.4 and 4.5. Mean temperatures under RCP 4.5 are between 24 – 25 °C in the lower northeast region, 23 – 25 °C in the upper northeast region and 25 – 26 °C in the central region. Annual precipitations under RCP 4.5 are within the ranges of 1700 – 2900 mm in the lower northeast region, 1400 – 2500 mm in the upper northeast region, and 1700 – 3100 mm in the central region.

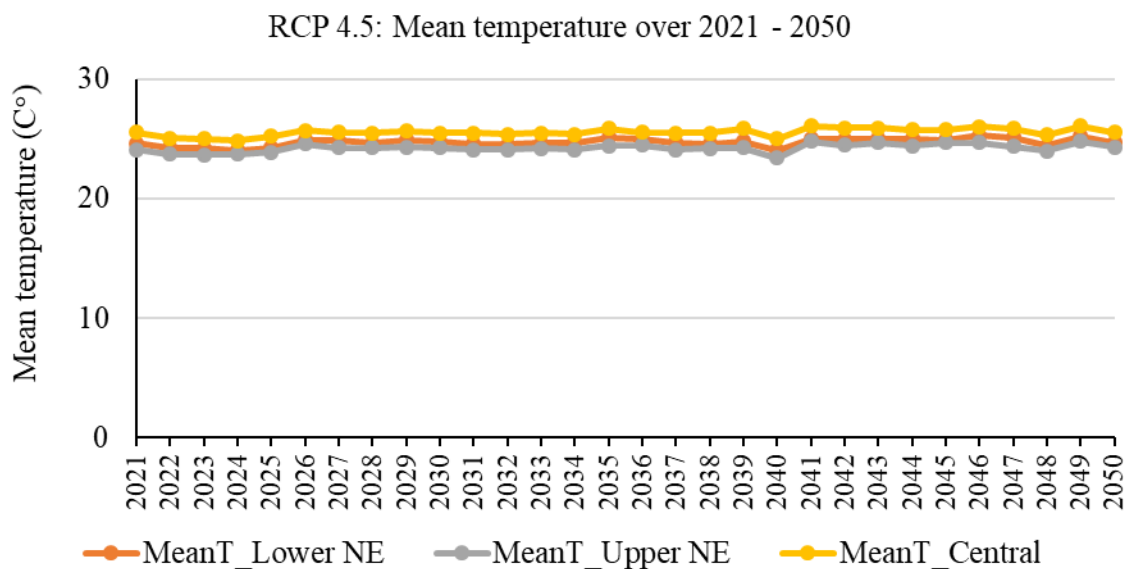


Figure 4.4 Mean daily temperature over 2021-2050 of the studied sites

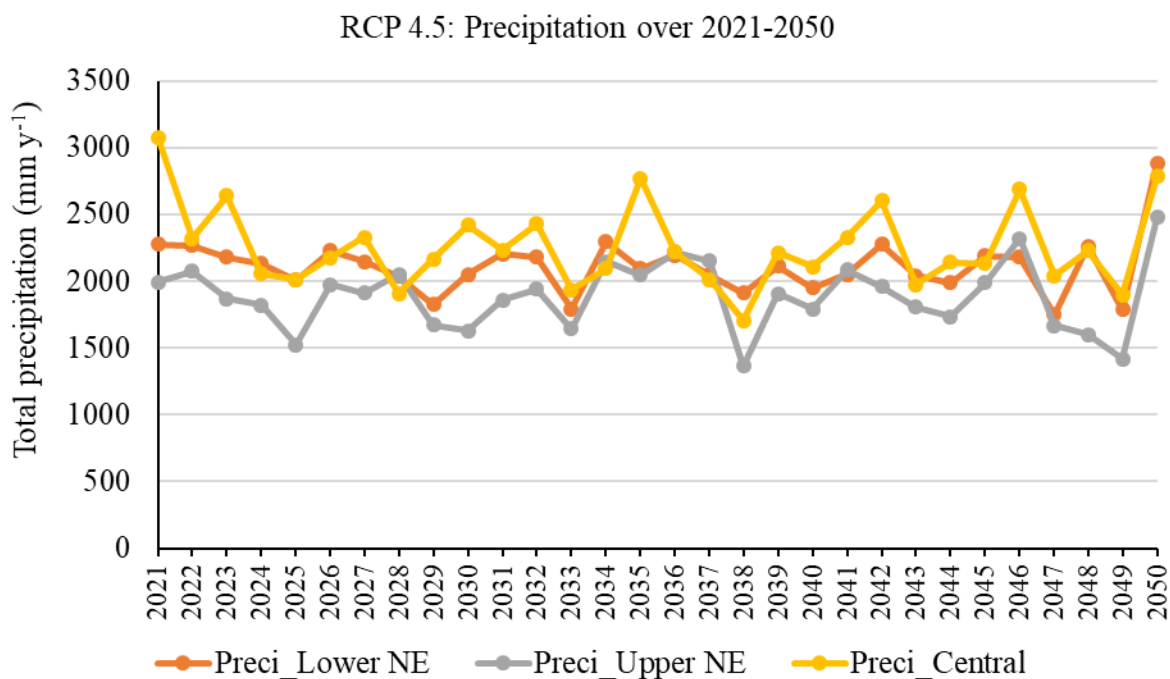


Figure 4.5 Total precipitation over 2021-2050 of the studied sites

The soil data of each site are compiled from the database of the Land Development Department of Thailand (Table 4.3). The crop calendar and field management practices (Figure 4.6) (Cha-un *et al.*, 2021) for each site were compiled from the government published reports, supplemented data from the Rice Department (Varinruk, 2017; RD, 2019), the Office of Agricultural Eco-nomics, Ministry of Agriculture and Cooperatives (OAE, 2019) and data from the field survey.

Table 4.3 Soil properties in the study sites

No.	Provinces	Region	Soil texture	BD (g/cm ³)	pH	% OM	%OC	SOC
					(1:1 water)			(g C kg ⁻¹)
1	Suphan Buri	Central	clay	1.16	5.57	3.89	2.26	22.582
2	Ayuthaya	Central	clay	0.93	5.42	2.82	1.64	16.362
3	Chainat	Central	clay	1.22	5.79	2.34	1.36	13.562
4	Angthong	Central	clay	0.81	5.51	2.26	1.31	13.085
5	Pathumthani	Central	clay	0.86	5.96	3.39	1.97	19.662
6	Khon Kaen	Northeast	sandy loam	1.35	5.07	1.03	0.60	5.975
7	Sakon Nakhon	Northeast	sandy loam	1.35	4.55	1.54	0.89	8.927
8	Udon Thani	Northeast	sandy loam	1.35	4.45	1.11	0.65	6.455
9	Ubon Ratchathani	Northeast	sandy loam	1.35	5.03	0.53	0.31	3.084
10	Roi-et	Northeast	sandy loam	1.35	4.94	0.70	0.41	4.086
11	Nakhon Ratchasima	Northeast	sandy loam	1.35	6.28	1.04	0.60	6.004
12	Surin	Northeast	sandy loam	1.35	5.05	0.76	0.44	4.408

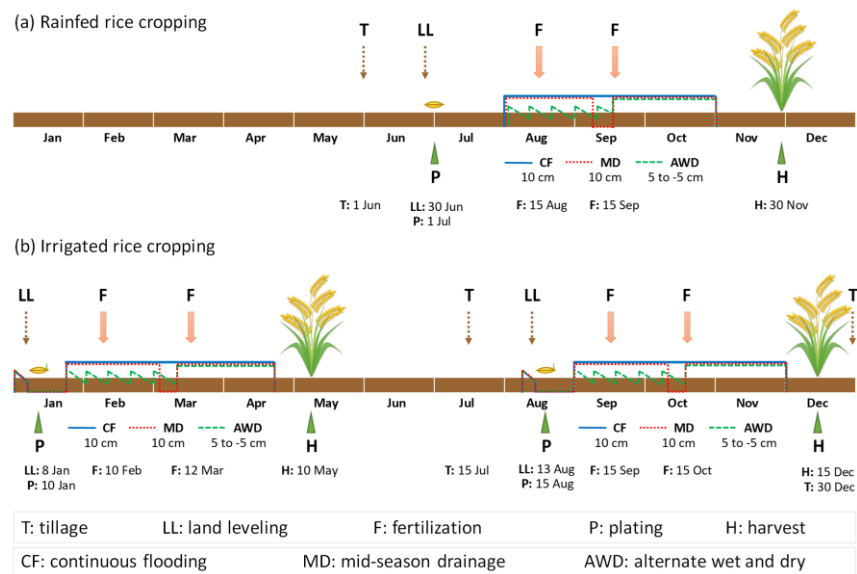


Figure 4.6 Schematic illustrations of the crop calendar and field management practices (Cha-un *et al.*, 2021).

4.2.6 Rice field management practices

The conditions of rice field management practices with cropping system, crop residue management, fertilizers and water management for the simulation in each study site (Figure 4.7) are showed as following list:

- Condition 1 (C1): conventional practice with single rice cultivations in the wet season, burnt crop residue, chemical fertilizer application, and continuous flooding
- Condition 2 (C2): conventional practice with double rice cultivations in the dry and wet seasons, burnt crop residue, chemical fertilizer application, and continuous flooding
- Condition 3 (C3): suitable rice cultivation with double rice cultivation in the dry and wet seasons, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry (AWD) irrigation
- Condition 4 (C4): suitable rice practice with single rice cultivation in the wet season, crop rotation with maize in the dry season, un- burnt crop residue, recommended fertilizer application, and AWD irrigation
- Condition 5 (C5): suitable rice practice with single rice cultivation in the wet season, crop rotation with mung bean in the dry season, un-burnt crop residue, recommended fertilizer application, and AWD irrigation
- Condition 6 (C6): suitable rice practice with single rice cultivation in the wet season, crop rotation with mung bean in the dry season, un-burnt crop residue, recommended fertilizer application, and continuous flooding
- Condition 7 (C7): suitable rice practice with single rice cultivation in the wet season, un-burnt crop residue, recommended fertilizer application, and continuous flooding

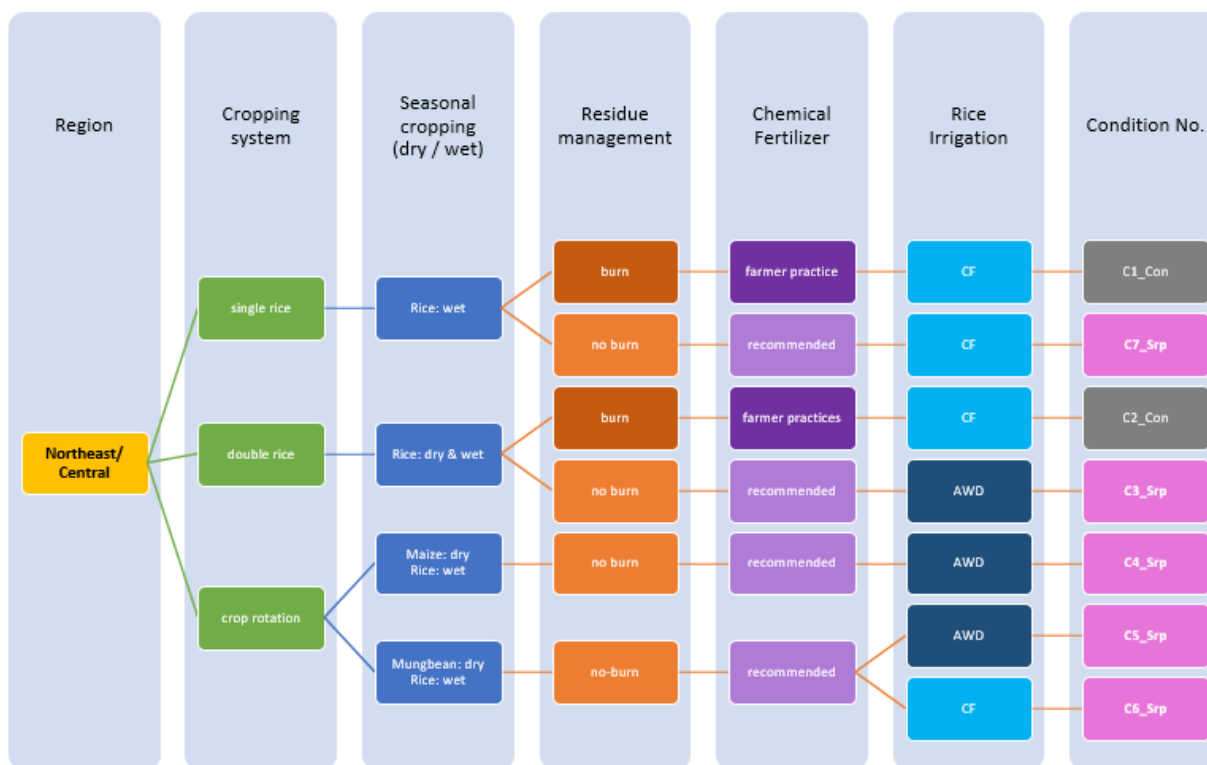


Figure 4.7 Schematic illustrations of the seven conditions

Note: Single rice = fallow+rice in dry and wet seasons, Double rice= rice+rice in dry and wet seasons; CON= conventional rice practice; SRP= sustainable rice practice; CF=continuous flooding; and AWD=alternate wet and dry irrigation

Based on conditions 5 and 6, the DNDC model is unable to utilize sunn hemp data due to limitations in available information. The DNDC model requires comprehensive physiological and phenological parameters for plants. Due to limited data available for sunn hemp, a similar leguminous plant, namely mung bean, have been instead utilized to supplement the DNDC model.

The GHG emissions, SOC stock, and rice yield of each study site will be simulated. The simulated results from many study sites of each region will be averaged. Then, the average results of each region are used for estimate the GHG emissions, SOC stock, and rice yield in the whole region.

4.2.6.1 Crop calendar and field management practices for 7 cropping conditions

The crop calendar and field management practices with 7 cropping conditions for model simulation were compiled from the government published reports and the field survey, which are provided in Table 4.4. The baseline of farmer yield data for each cropping season were also needed to input and run the model (Table 4.5 and 4.6). The rates and modes of chemical fertilizer applications based on farmer practices and the recommendation of the Rice Department (RD, 2019) are provided in Table 4.7 and 4.8, respectively.

Table 4.4 Crop calendar and field management practices for 7 cropping conditions

Season	Management practices	Cropping conditions						
		C1 Fallow-Rice	C2 Rice-Rice	C3 Rice-Rice	C4 Maize-Rice	C5 Bean-Rice	C6 Bean-Rice	C7 Fallow-Rice
Dry	Tillage (incorporation)	-	30 Dec (burn)	30 Dec (no-burn)	30 Dec (no-burn)	30 Dec (no-burn)	30 Dec (no-burn)	-
	Land levelling	-	8 Jan	8 Jan	8 Jan	8 Jan	8 Jan	-
	Planting	-	10 Jan	10 Jan	10 Jan	10 Jan	10 Jan	-
	Fertilization	-	1 st : 10 Feb 2 nd : 25 Feb 3 rd : 12 Mar	1 st : 10 Feb 2 nd : 12 Mar	1 st : 10 Jan 2 nd : 20 Feb	1 st : 20 Jan	1 st : 20 Jan	-
	Flooding	-	1 st : 2-9 Jan AWD: -5 to 5 cm 2 nd : 25 Jan-25 Apr CF: 10 cm	1 st : 2-9 Jan AWD: -5 to 5 cm 2 nd : 25 Jan-25 Feb AWD: -5 to 5 cm 3 rd : 26 Feb-25 Apr CF: 10 cm	-	-	-	-
	Irrigation	-	-	-	1 st : 11 Jan	1 st : 11 Jan	1 st : 11 Jan	-

Season	Management practices	Cropping conditions						
		C1	C2	C3	C4	C5	C6	C7
		Fallow-Rice	Rice-Rice	Rice-Rice	Maize-Rice	Bean-Rice	Bean-Rice	Fallow-Rice
					2 nd : 21 Jan 3 rd : 31 Jan 4 th : 21 Feb 5 th : 15 Mar	2 nd : 21 Jan 3 rd : 31 Jan 4 th : 15 Feb 5 th : 15 Mar	2 nd : 21 Jan 3 rd : 31 Jan 4 th : 15 Feb 5 th : 15 Mar	
	Harvest	-	10 May	10 May	10 May	5 Apr	5 Apr	-
Wet	Tillage (incorporation)	1 Jun (burn)	15 Jul (burn)	15 Jul (no-burn)	15 Jul (no-burn)	15 Jul (no-burn)	15 Jul (no-burn)	1 Jun (no-burn)
	Land levelling	30 Jun	13 Aug	13 Aug	13 Aug	13 Aug	13 Aug	30 Jun
	Planting	1 Jul	15 Aug	15 Aug	15 Aug	15 Aug	15 Aug	1 Jul
	Fertilization	1 st : 15 Aug 2 nd : 30 Aug 3 rd : 15 Sep	1 st : 15 Sep 2 nd : 30 Sep 3 rd : 15 Oct	1 st : 15 Sep 2 nd : 15 Oct	1 st : 15 Sep 2 nd : 15 Oct	1 st : 15 Sep 2 nd : 15 Oct	1 st : 15 Sep 2 nd : 15 Oct	1 st : 15 Aug 2 nd : 15 Sep
	Flooding	1 st : 1 Aug-1 Nov CF: 10 cm	1 st : 7-14 Aug AWD: -5 to 5 cm 2 nd : 30 Aug-1 Dec CF: 10 cm	1 st : 7-14 Aug AWD: -5 to 5 cm 2 nd : 30 Aug-30 Sep AWD: -5 to 5 cm	1 st : 7-14 Aug AWD: -5 to 5 cm 2 nd : 30 Aug-30 Sep AWD: -5 to 5 cm	1 st : 7-14 Aug AWD: -5 to 5 cm 2 nd : 30 Aug-30 Sep AWD: -5 to 5 cm	1 st : 7-14 Aug AWD: -5 to 5 cm 2 nd : 30 Aug-1 Dec CF: 10 cm	1 st : 1 Aug-1 Nov CF: 10 cm

Season	Management practices	Cropping conditions						
		C1	C2	C3	C4	C5	C6	C7
		Fallow-Rice	Rice-Rice	Rice-Rice	Maize-Rice	Bean-Rice	Bean-Rice	Fallow-Rice
				3 rd : 1 Oct-1 Dec CF: 10 cm	3 rd : 1 Oct-1 Dec CF: 10 cm	3 rd : 1 Oct-1 Dec CF: 10 cm		
	Harvest	15 Nov	15 Dec	15 Dec	15 Dec	15 Dec	15 Dec	15 Nov

C1 and C2 are conventional rice practices (CON). C3 to C7 conditions are sustainable rice practices (SRP). C1 = single rice_CF (CON), C2 = double rice_CF (CON), C3 = double rice_AWD (SRP), C4 = Maize-Rice_AWD (SRP), C5 = Mungbean -Rice_AWD (SRP), C6 = Mungbean -Rice_CF (SRP), C7 = single rice_AWD (SRP). Crop residue fraction for burning and no-burn practices are 0.2 and 1.0, respectively.

Table 4.5 Rice yields (kg C/ha/y) from farmer practice and recommended yield from Rice Department

No.	Province	Rain-fed Rice (Wet season)	Irrigated-Rice	
			Dry season	Wet season
1	Suphan Buri	2,023	2,400	2,274
2	Ayuthaya	2,093	2,651	2,512
3	Chainat	2,121	2,470	2,456
4	Angthong	2,121	2,470	2,553
5	Pathumthani	2,121	2,470	2,553
6	Khon Kaen	977	1,116	979
7	Sakon Nakhon	1,060	1,116	921
8	Udon Thani	1,046	1,116	1,381
9	Ubon Ratchathani	1,060	1,116	1,060
10	Roi-et	1,060	1,116	1,060
11	Nakhon Ratchasima	1,102	1,116	1,245
12	Surin	1,186	1,116	1,206
13	RD's Rec_ Northeast	1,256	2,009	2,009
14	RD's Rec_ Central	2,651	2,651	2,651

Remark: %C in rice grain is 44.65.

Table 4.6 Averaged yields of mung bean and maize in Northeast and Central regions

Region	Mung bean yield		Maize yield	
	kg/rai	kg C/ha	kg/rai	kg C/ha
Northeast	200	563	1,000	2,817
Central	230	647	1,500	4,225

Remark: %C in mung bean and maize grains are 45.00 and 45.07, respectively.

Table 4.7 Compound fertilizer application rates from farmer practice

No.	Provinces	Rain-fed area (Wet season) (kg N/ha and kg P/ha)*			Irrigated area (Dry season) (kg N/ha and kg P/ha)			Irrigated area (Wet season) (kg N/ha and kg P/ha)		
		1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
1	Suphan Buri	40 N, 20 P	U. 14 N	28 N, 12.5 P	U. 57.5 N	45 N, 56.5 P	40 N, 20 P	U. 57.5	40 N, 20 P	30 N, 37.5 P
2	Ayuthaya	50 N, 62.5 P	U. 50 N	S. 62.5 N	45 N, 56.3 P	U. 57.5 N	50 N, 25 P	45 N, 56.3 P	30 N, 15 P	U. 86.3 N
3	Chainat	U. 100.6 N	15 N, 18.8 P	50 N, 25 P	U. 100.6 N	35 N, 43.8 P	40 N, 20 P	U. 86.3 N	25 N, 31.5 P	30 N, 16 P
4	Angthong	U. 100.6 N	15 N, 18.8 P	50 N, 25 P	U. 100.6 N	35 N, 43.8 P	40 N, 20 P	U. 100.6 N	15 N, 18.8 P	50 N, 25 P
5	Pathumthani	U. 100.6 N	15 N, 18.8 P	50 N, 25 P	U. 100.6 N	35 N, 43.8 P	40 N, 20 P	U. 100.6 N	15 N, 18.8 P	50 N, 25 P
6	Khon Kaen	20 N, 25 P	25 N, 12.5 P	25 N, 25 P	U. 28.8 N	20 N, 20 P	25 N, 25 P	25 N, 12.5 P	30 N, 37.5 P	25 N, 25 P
7	Sakon Nakhon	20 N, 10 P	18.7 N, 18.7 P	15 N, 15 P	U. 71.9 N	18.8 N, 18.8 P	20 N, 10 P	U. 43.1 N	18.8 N, 18.8 P	20 N, 10 P
8	Udon Thani	U. 86.2 N	14 N, 14 P	20 N, 25 P	U. 28.8 N	20 N, 20 P	25 N, 12.5 P	30 N, 30 P	18.8 N, 18.8 P	25 N, 12.5 P
9	Ubon Ratchathani	U. 86.2 N	18.7 N, 18.8 P	25 N, 25 P	U. 28.8 N	20 N, 20 P	25 N, 25 P	U. 86.3 N	18.8 N, 18.8 P	25 N, 25 P

10	Roi-et	U. 86.2 N	18.7 N, 18.8 P	25 N, 25 P	U. 28.8 N	20 N, 20 P	25 N, 25 P	U. 86.3 N	18.8 N,18.8 P	25 N, 25 P
11	Nakhon Ratchasima	25 N, 25 P	U. 71.8 N	25 N, 31.2 P	U. 28.8 N	20 N, 20 P	25 N, 31.3 P	45 N, 22.5 P	22.5 N, 10 P	25 N, 31.3 P
12	Surin	30 N, 30 P	30 N, 15 P	U. 57.5 N	U. 28.8 N	20 N, 20 P	18.8 N,18.8 P	U. 43.1 N	30 N, 30 P	18.8 N,18.8 P

Note: U=Urea fertilizer, S = Ammonium Sulfate; * N from kg N/ha as a form of ammonium and P from kg P/ha as a form of phosphate

Table 4.8 Compound fertilizer application rates from RD's recommendation and secondary data

Soil texture	1st apply (30 DAS)	2nd apply (60 DAS)
Clay	N = 53 kg N/ha P = 30 kg P/ha	N = 53 kg N/ha
Loam or Sand	N = 30 kg N/ha P = 30 kg P/ha	N = 43.13 kg N/ha

Note: N from kg N/ha as a form of ammonium and P from kg P/ha as a form of phosphate; the secondary data refers from a research of Laywisadkul and Yingjajaval (2019)

4.3 Results

4.3.1 Long-term GHG emission estimations under different rice field management practices

The main sources of GHG emissions in the study are focused from rice field throughout the entire year. In addition, soil carbon stock (SOC), which is the capability of GHG removal, of the field is also estimated in this section. To calculate GHG emissions including CH₄ and N₂O from the rice field, Global Warming Potential (GWP) values from the IPCC Fifth Assessment Report (AR5) were used to convert their units to CO₂ equivalent. The GWP value of methane (CH₄) is 28 and for nitrous oxide (N₂O) is 265.

4.3.2 CH₄ emissions from the rice fields

Annual CH₄ emissions from conventional and sustainable rice practice over 2021-2050 under different managements are shown in Figure 4.8

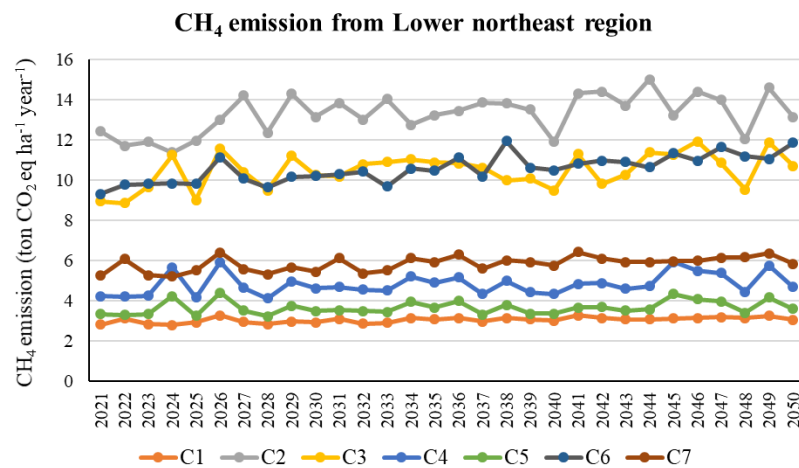
Comparing among annual CH₄ emissions under RCP 4.5 from the different management practices can lead to varying patterns and ranges of annual CH₄ emissions. This highlights the importance of considering the specific management practices in place when assessing CH₄ emissions. Condition 2 (a conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding) has the highest trend of CH₄ emissions. On the other hand, Condition 1 (a conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding) has the lowest trend of CH₄ emissions.

Within the sustainable rice practice (SRP), the highest trend of CH₄ emissions are observed from Condition 3 and 6 in the northeast region and in Condition 3 in the central region, while the lowest trend of CH₄ emissions is observed from Condition 5 in both regions. Condition 3 involves a sustainable rice cultivation practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation. Condition 6 involves single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding. In contrast, Condition 5 involves single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation. The findings indicate that within the sustainable rice practice, different management practices can still lead to varying patterns and ranges of CH₄ emissions. The highest trend of CH₄ emissions is observed in Condition 3 and 6, which both involve either double rice cultivation or continuous flooding. Meanwhile, the lowest trend of CH₄ emissions is observed in Condition 5, which involves single rice cultivation and alternate wet and dry irrigation. The results indicate that the presence of high residue left in the field or water management practices can enhance the emission of CH₄ from the rice field.

The water management may play a significant role in determining CH₄ emissions from rice cultivation. This is highlighted by comparing the CH₄ emissions from Condition 5 and 6, which involve similar management practices but different water management approaches. Specifically, both conditions involve the same practices, including recommended fertilizer application, un-burnt crop residue, and crop rotation with mung bean. However, in Condition 6, continuous flooding is used, while in Condition 5, alternate wet and dry irrigation is employed. The results show that Condition 5 has a lower trend of CH₄ emissions than Condition 6. Same as the comparison of Condition 2 and Condition 3, both of which involve double rice cultivation but with different water management approaches, it can be observed that Condition 3, which utilizes alternate wet and dry irrigation, has a lower trend of CH₄ emissions compared to Condition 2, which involves continuous flooding. This difference may be attributed to the water management practices employed in each condition. The continuous flooding in Condition 6 may have led to a higher amount of water use and prolonged flooding, which could promote CH₄ emissions from the field. In contrast, the alternate wet and dry irrigation in Condition 5 may have helped to reduce CH₄ emissions by limiting the amount of water in the field and the anaerobic condition to generate CH₄. The study by Thuy *et al.* (2018) provides evidence that water management practices such as alternate wet

and dry irrigation can be an effective way to mitigate CH₄ emissions from rice cultivation. The study found that CH₄ emissions from paddy fields with alternate wetting and drying conditions decreased by 59.1% compared to continuous flooding conditions. Also, Setyanto et al. (2018) presents that the use of alternate wetting and drying (AWD) resulted in 35% smaller CH₄ emission compared to continuous flooding (CF) without yield loss. This suggests that the alternate wet and dry irrigation approach may be a more sustainable option for rice cultivation, as it leads to lower greenhouse gas emissions while still maintaining yields. Therefore, water management is a key factor that should be considered when developing sustainable rice cultivation practices aimed at reducing greenhouse gas emissions.

Comparing the emission between the regions, the central region of Thailand exhibits lower CH₄ emissions compared to the northeast region. This difference in emissions may be attributed to the soil texture, with the central region having lower sand content than the northeast. Sass *et al.* (2021) and Sukdanont *et al.* (2021) found a positive correlation between CH₄ emissions and sand content in the soil, supporting this relationship.



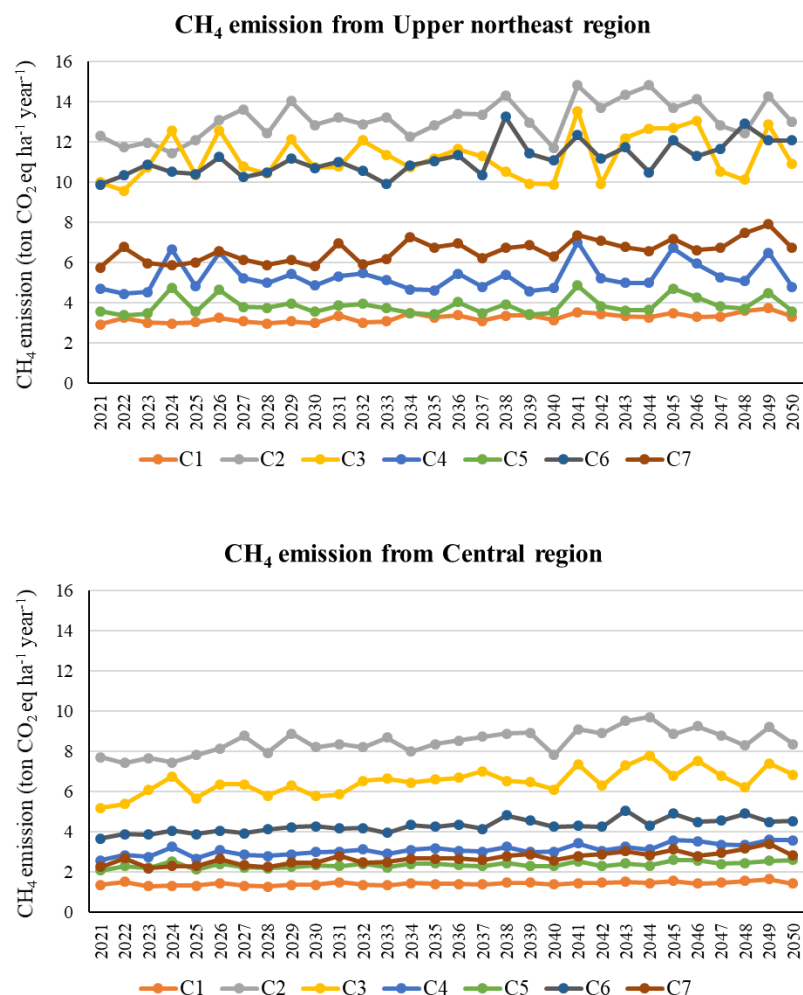


Figure 4.8 Annual CH₄ emissions from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions

4.3.3 N₂O emissions from the rice fields

Nitrogen plays a crucial role in the production of N₂O emissions from soil microorganisms, particularly through nitrification and denitrification processes. Chemical fertilizers and manure are common sources of nitrogen for soil microorganisms, whereas soil organic matter (SOM) is also a significant source of nitrogen in the production of N₂O (Aguilera *et al.*, 2013; Yin *et al.*, 2020; Guenet *et al.*, 2020) as Figure 4.9 If these nitrogen sources remain in the soil, the environment may be conducive to nitrification or denitrification, leading to N₂O production. On the other hand,

if the nitrogen substrate is lost from the soil through leaching or plant uptake, the production of N_2O will decrease.

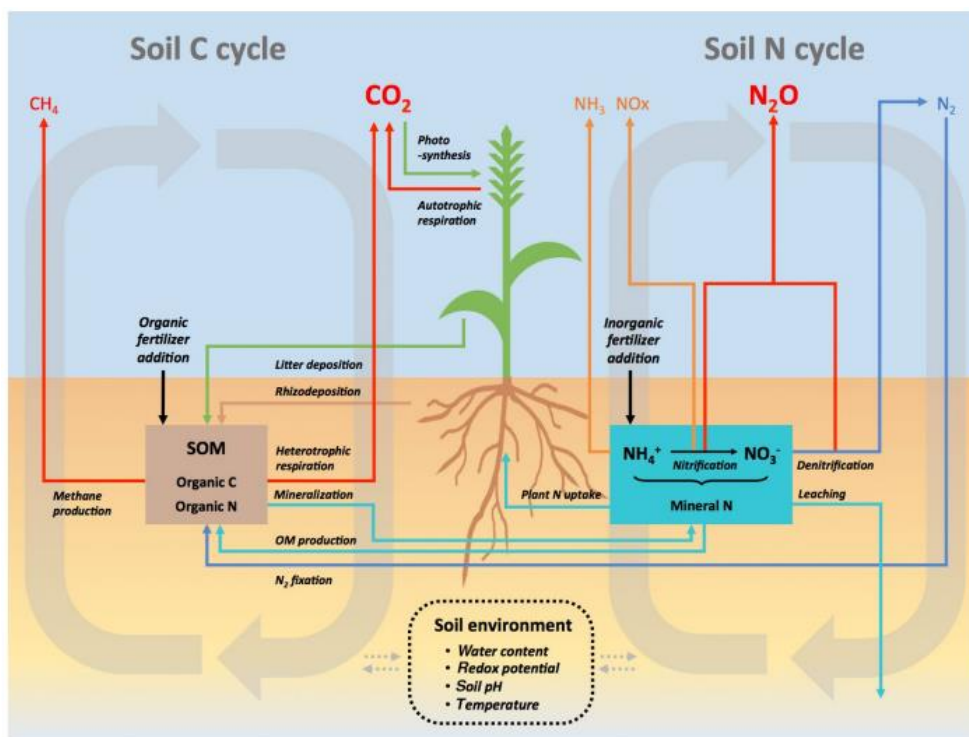


Figure 4.9 A schematic representation of C–N interactions in the terrestrial ecosystem (Guenet *et al.*, 2020)

Annual N_2O emissions from conventional and sustainable rice practice over 2021-2050 under different managements are shown in Figure 4.10. The study compared seven management conditions in rice fields and found that those involving crop rotation (Conditions 4, 5, and 6) resulted in higher N_2O emissions. The addition of nitrogen (N) fertilizer for crop rotation may have provided a greater N source for N_2O production compared to conditions involving double or single rice cultivation. Based on the findings, it can be inferred that the application of the fertilizer for single rice cultivation in Condition 1 and 7 resulted in lower N_2O emissions compared to other conditions. The N provided in this condition may be sufficient for rice growth, applied once a year and may not remain in the soil for long, thereby limiting the availability of N as a source for N_2O production.

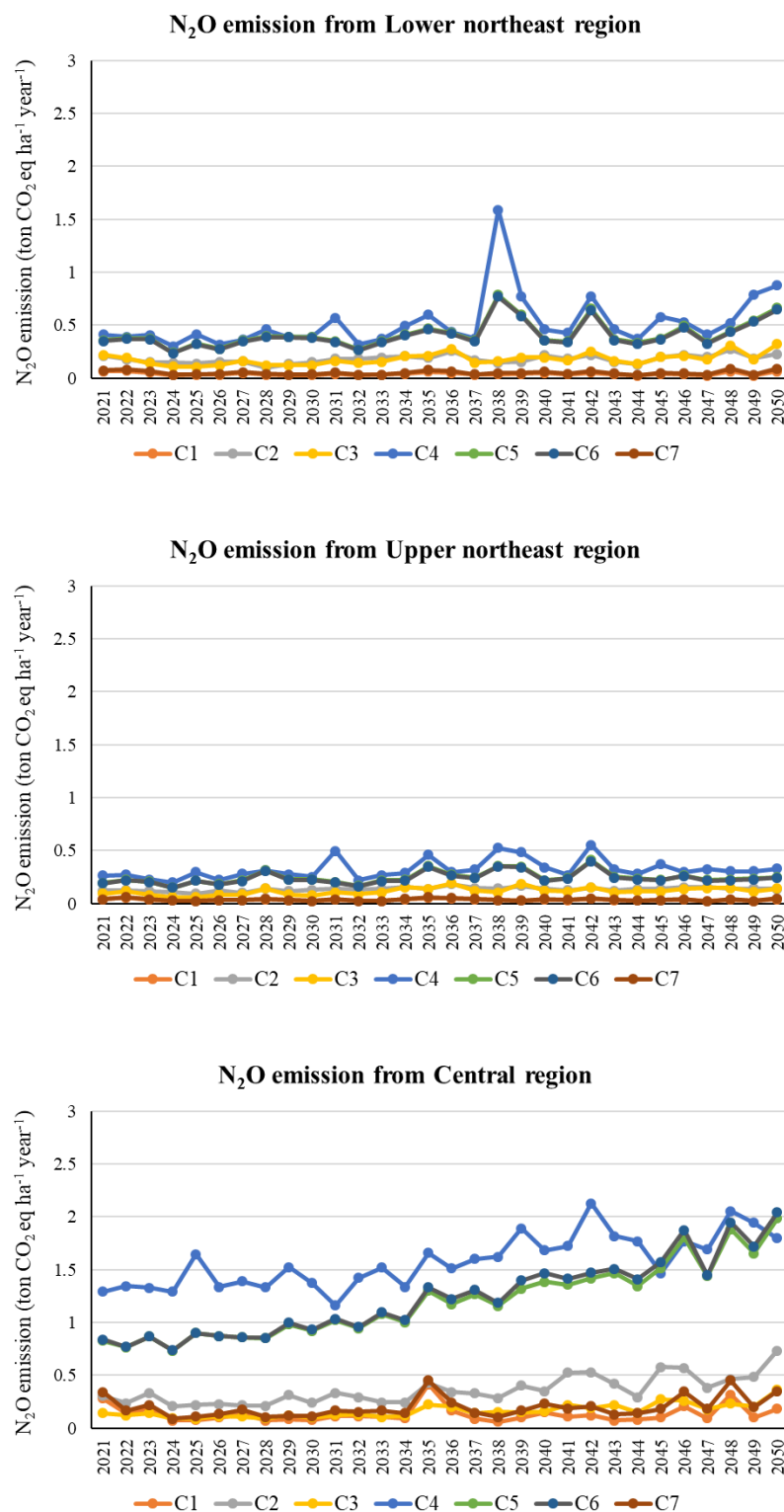
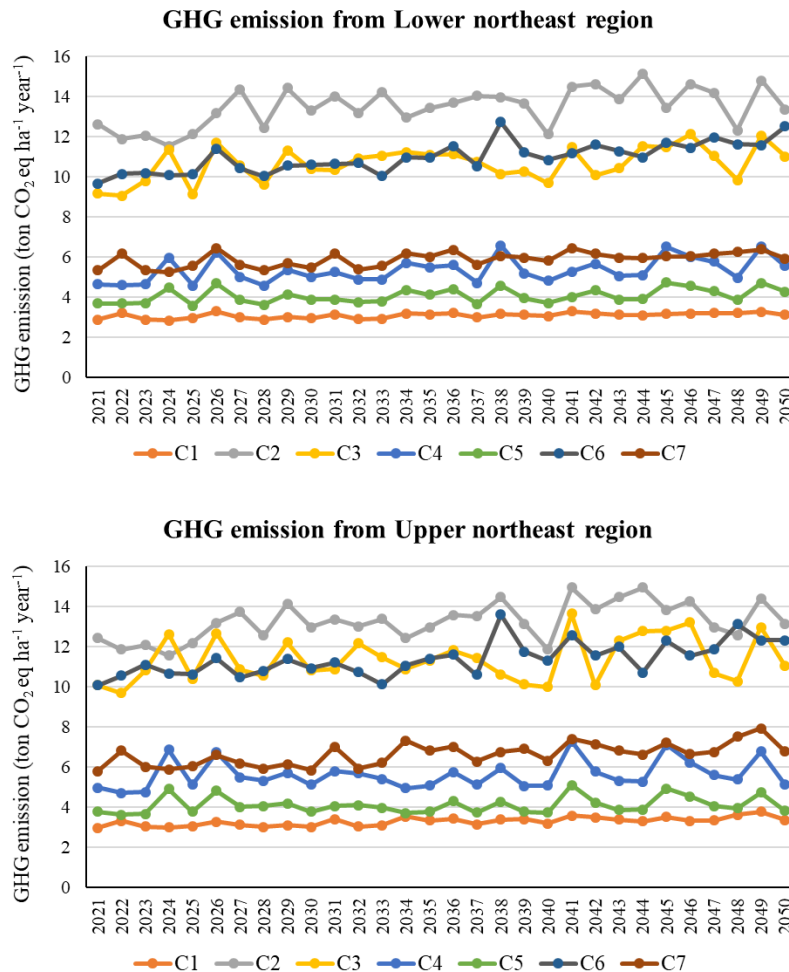


Figure 4.10 Annual N₂O emissions from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions

4.3.4 Total GHG emissions (CH_4 and N_2O emissions)

Total greenhouse gas (GHG) emissions in this study are a combination of projected CH_4 and N_2O emissions. As CH_4 emissions dominate in paddy rice fields, the trend of the GHG graph (Figure 4.11) closely follows the projected CH_4 emission graph (Figure 4.7). This aligns with previous research indicating that paddy rice fields are significant contributors to soil CH_4 emissions (IPCC, 2002). As CH_4 is the dominant greenhouse gas emitted from rice fields, controlling its production should be a priority. Methanogenesis, the process that produces CH_4 , occurs under anaerobic or flooded conditions. Hence, reducing the duration of flooding periods can help inhibit CH_4 production as the comparison between C2 and C3, and the comparison between C5 and C6. Similarly, Thuy *et al.* (2018) demonstrated that CH_4 emissions from paddy fields managed using alternate wetting and drying conditions decreased by 59.1% compared to those under continuous flooding. Therefore, water management practices are key to mitigating CH_4 emissions.



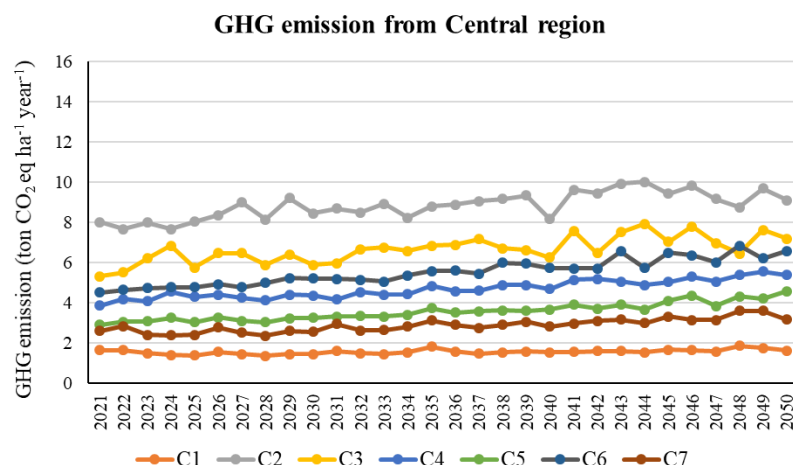


Figure 4.11 Annual total GHG emissions from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions

4.3.5 Long-term SOC stocks estimations under different rice field management practices

The SOC stocks of topsoil (0-30 cm in depth) over 2021-2050 from all seven conditions (Figure 4.7) are shown in Figure 4.12. The study shows that different management practices can result in diverse patterns and ranges of annual SOC stocks. The carbon comprises approximately 50%-58% of organic matter (Pribyl, 2010). Therefore, increasing the amount of organic matter in soil leads to an increase in SOC. Double cultivations per year, such as Condition 2, 3, 4, 5, and 6, result in more crop residues being incorporated into the soil, leading to a greater increase in SOC compared to single cultivation such as Condition 1 and 7. High SOC stocks are found in soil under the SRP condition, particularly in Condition 3, which involves double rice cultivation per year, and Condition 4, which involves rice and maize cultivation per year. As maize residues contribute more organic matter to the soil than other crops used in rotation, the SOC levels in this condition are higher compared to other crop rotation conditions. Therefore, cultivation management plays a crucial role in promoting SOC. Upon comparing the central and northeast regions of Thailand, it was observed that the former has higher SOC stocks than the latter. The variation in SOC stocks could potentially be linked to the soil texture, as suggested by Kuśmierz *et al.* (2023). The study indicates that clay-rich soils have longer turnover times and slower decomposition rates, which could result in the preservation of SOC in the central region with high clay content. On the other hand, the northeast region with sand-rich soil might have a lower SOC stock due to a faster

decomposition rate. However, it is important to note that decomposition rates can be influenced by several other factors such as soil moisture, nutrient availability, and microbial communities, which may affect the observed relationship.

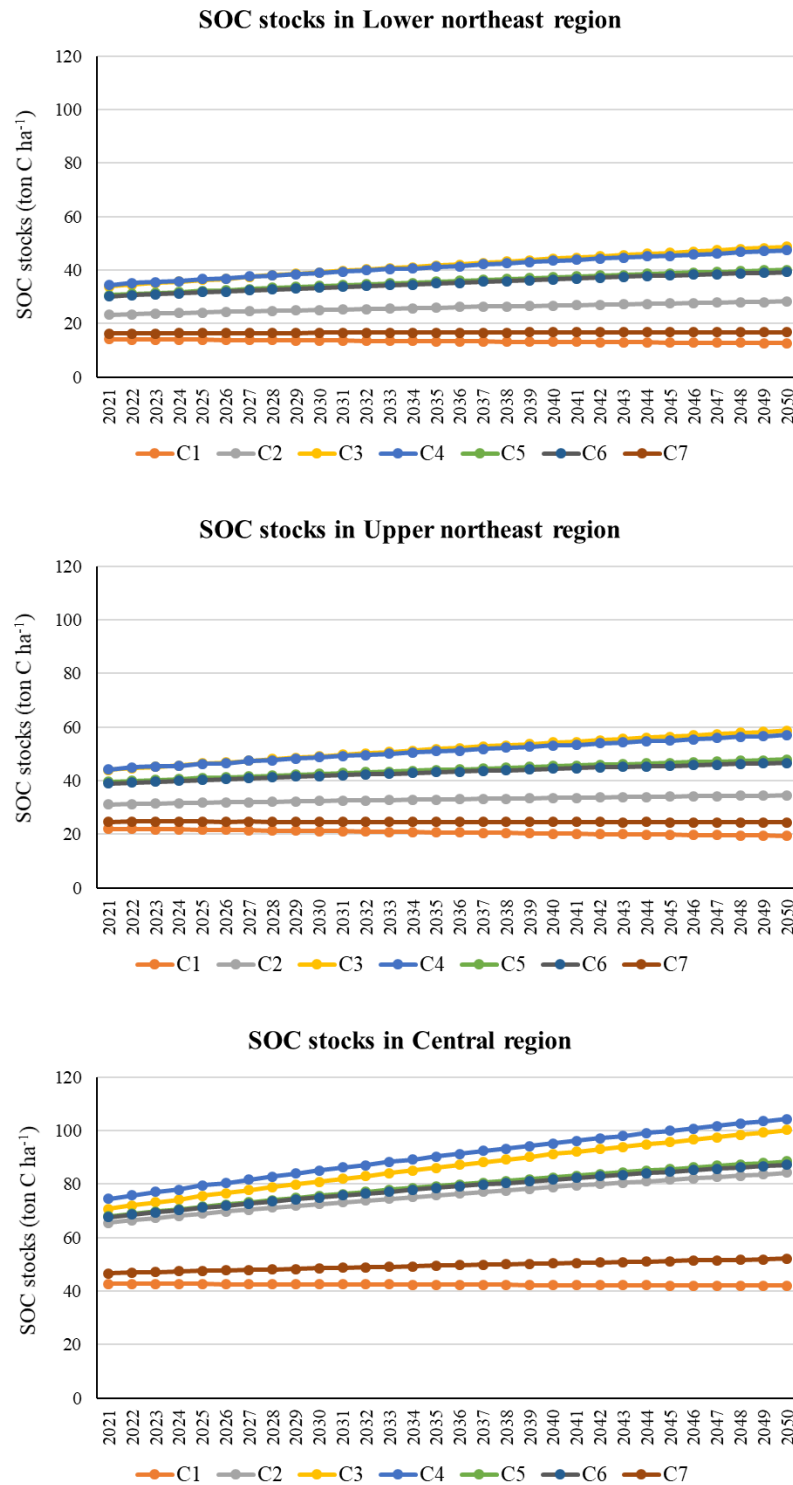


Figure 4.12 SOC stocks of topsoil (0-30 cm in depth) from different rice practices over 2021-2050 in lower northeast, upper northeast, and central regions

4.4 Greenhouse gas emissions, soil carbon stock and rice grain yields from cultivation based on scenario analysis

As described earlier in this report, seven managements including 1) a conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding (C1), 2) a conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding (C2), 3) a sustainable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation (C3), 4) a sustainable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation (C4), 5) a sustainable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation (C5), 6) a sustainable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding (C6), and 7) a sustainable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding (C7) under RCP 4.5 have been put forward for assessing in four scenarios. Additionally, the land use in each scenario was classified to 4 areas including 1) conventional rice practice in the irrigation area, 2) conventional rice practice in the non-irrigation area, 3) sustainable rice practice in the irrigation area, and 4) sustainable rice practice in the non-irrigation area. Therefore, the seven conditions (C1 to C7) were grouped to be six situations based on the land use areas and the corresponding opportunities that can arise within each classified area. Results from these assessments are summarized for the years 2025, 2030, 2035, 2040, 2045, and 2050 (Table 4.9 – 4.11).

Considering GHG emissions from the rice fields (Table 4.9), CH₄ is the largest contributor to GHG emissions in the northeast and central parts of Thailand. The analysis of various scenarios revealed that Scenario 4 presented the highest CH₄ emissions in the northeast region, whereas the Business as Usual (BAU) scenario showed the lowest levels. In the central region, the BAU scenario mostly recorded the highest CH₄ emissions, whereas Scenario 4 had the lowest emissions.

Among the six possible situations analyzed, those involving C1, C2, C3, and C6 (a) had the highest GHG emissions in both regions, while those involving C1, C2, C5, and C7 (f) had the lowest GHG emissions in both regions. The high GHG emissions may be the impact of double crop cultivation from C3 and C6. However, the study also found that an increase in the area of SRP positively affected GHG reduction in the central region but had a negative effect on GHG reduction in the northeast region.

Table 4.9 Accumulated CH₄, N₂O, and total emissions in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050

a) Situation involving C1, C2, C3, and C6 under RCP 4.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.77	0.28	25.05	25.34	0.30	25.65	26.78	0.37	27.15	28.82	0.45	29.28
2030	154.10	1.84	155.94	158.68	2.05	160.73	170.04	2.57	172.61	186.53	3.32	189.85
2035	287.34	3.77	291.11	300.65	4.38	305.04	333.68	5.90	339.58	382.90	8.11	391.02
2040	424.51	5.96	430.47	451.65	7.40	459.05	520.64	10.98	531.62	623.67	16.07	639.74
2045	568.92	8.00	576.92	614.73	10.34	625.06	732.25	16.19	748.43	907.73	24.40	932.13
2050	714.50	10.41	724.91	785.92	14.19	800.11	967.66	23.33	990.99	1225.76	35.20	1260.96

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.27	0.32	9.59	9.27	0.33	9.60	9.25	0.35	9.60	9.18	0.38	9.57
2030	58.78	2.12	60.90	58.75	2.19	60.94	58.49	2.35	60.85	57.92	2.58	60.49
2035	108.26	4.65	112.91	108.16	4.85	113.01	107.55	5.31	112.86	106.48	6.01	112.49
2040	159.13	7.23	166.36	158.95	7.71	166.66	157.76	8.83	166.59	157.27	10.98	168.26
2045	213.63	10.47	224.10	213.19	11.32	224.51	211.25	13.40	224.65	213.97	18.29	232.26
2050	266.07	14.51	280.57	265.54	15.92	281.45	263.84	19.71	283.54	270.51	27.67	298.18

b) Situation involving C1, C2, C3, and C7 under RCP 4.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.11	0.24	24.34	24.32	0.24	24.56	24.84	0.24	25.08	25.56	0.24	25.80
2030	149.64	1.56	151.19	151.31	1.56	152.87	155.29	1.57	156.85	160.99	1.58	162.57
2035	277.96	3.15	281.11	282.93	3.16	286.09	294.89	3.20	298.09	312.76	3.24	316.00
2040	408.33	4.78	413.11	418.20	4.82	423.02	442.60	4.91	447.50	479.23	5.02	484.25
2045	544.68	6.25	550.93	561.31	6.32	567.63	603.12	6.46	609.58	666.68	6.64	673.33
2050	680.54	7.93	688.46	706.19	8.05	714.24	770.45	8.30	778.75	864.43	8.59	873.02

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.21	0.29	9.50	9.19	0.29	9.48	9.11	0.28	9.39	8.96	0.27	9.23
2030	58.39	1.93	60.32	58.16	1.92	60.08	57.44	1.87	59.31	56.20	1.78	57.98
2035	107.48	4.25	111.72	106.87	4.18	111.05	105.02	4.00	109.02	102.07	3.71	105.78
2040	157.84	6.49	164.32	156.61	6.35	162.96	152.89	5.95	158.85	148.00	5.42	153.42
2045	211.76	9.26	221.02	209.61	8.96	218.58	203.40	8.15	211.55	197.90	7.30	205.21
2050	263.57	12.71	276.28	260.55	12.21	272.76	252.31	10.93	263.23	247.40	9.95	257.35

c) Situation involving C1, C2, C4, and C6 under RCP 4.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.70	0.28	24.98	25.27	0.31	25.58	26.65	0.37	27.03	28.58	0.47	29.05
2030	153.63	1.86	155.49	158.12	2.08	160.20	168.92	2.62	171.55	184.39	3.42	187.80
2035	286.38	3.81	290.18	299.24	4.45	303.69	330.32	6.06	336.39	375.98	8.45	384.43
2040	423.03	6.05	429.07	449.12	7.56	456.68	513.95	11.44	525.39	609.47	17.02	626.49
2045	566.80	8.12	574.92	610.59	10.60	621.19	720.63	16.92	737.55	883.03	25.90	908.94

2050	711.69	10.57	722.26	779.73	14.58	794.31	949.54	24.46	974.00	1188.85	37.38	1226.23
------	--------	-------	--------	--------	-------	--------	--------	-------	--------	---------	-------	---------

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.16	0.38	9.54	9.11	0.42	9.52	8.91	0.53	9.44	8.57	0.70	9.27
2030	58.06	2.42	60.48	57.54	2.70	60.24	55.93	3.45	59.37	53.13	4.62	57.75
2035	106.68	5.28	111.97	104.96	6.13	111.09	99.91	8.36	108.27	91.87	11.83	103.70
2040	156.39	8.37	164.75	152.75	10.29	163.04	142.18	15.31	157.50	128.10	23.08	151.18
2045	209.37	12.23	221.59	202.71	15.65	218.36	184.17	24.61	208.78	166.07	38.11	204.17
2050	260.15	17.03	277.18	250.17	22.50	272.67	223.80	36.88	260.68	204.57	55.81	260.37

d) Situation involving C1, C2, C4, and C7 under RCP 4.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.038	0.243	24.280	24.25	0.24	24.49	24.71	0.25	24.96	25.32	0.25	25.58
2030	149.161	1.576	150.737	150.76	1.58	152.34	154.17	1.62	155.79	158.84	1.68	160.52
2035	276.991	3.190	280.182	281.52	3.23	284.75	291.54	3.36	294.90	305.84	3.58	309.42
2040	406.850	4.866	411.717	415.67	4.99	420.65	435.91	5.37	441.27	465.03	5.97	471.00
2045	542.562	6.373	548.934	557.18	6.58	563.76	591.50	7.20	598.70	641.98	8.15	650.13
2050	677.732	8.084	685.816	700.00	8.44	708.44	752.33	9.43	761.77	827.52	10.77	838.29

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.11	0.35	9.45	9.02	0.37	9.40	8.77	0.46	9.23	8.34	0.59	8.93
2030	57.66	2.24	59.90	56.96	2.43	59.38	54.87	2.96	57.83	51.41	3.82	55.23
2035	105.90	4.88	110.78	103.66	5.46	109.13	97.39	7.04	104.43	87.46	9.53	96.99
2040	155.09	7.62	162.71	150.41	8.92	159.34	137.31	12.44	149.75	118.83	17.52	136.35

2045	207.49	11.03	218.52	199.13	13.30	212.43	176.33	19.36	195.68	150.00	27.12	177.12
2050	257.65	15.23	272.88	245.18	18.80	263.97	212.26	28.10	240.37	181.46	38.09	219.55

e) Situation involving C1, C2, C5, and C6 under RCP 4.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.69	0.28	24.97	25.26	0.31	25.56	26.63	0.37	27.00	28.53	0.46	29.00
2030	153.52	1.86	155.38	158.00	2.07	160.08	168.69	2.62	171.31	183.94	3.41	187.35
2035	286.18	3.80	289.97	298.96	4.43	303.39	329.65	6.02	335.67	374.60	8.36	382.96
2040	422.72	6.02	428.74	448.61	7.50	456.11	512.61	11.27	523.88	606.60	16.67	623.28
2045	566.35	8.08	574.42	609.73	10.51	620.23	718.18	16.66	734.84	877.76	25.37	903.13
2050	711.08	10.52	721.60	778.41	14.45	792.85	945.62	24.07	969.69	1180.73	36.61	1217.33

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.14	0.35	9.49	9.08	0.38	9.45	8.85	0.44	9.30	8.46	0.55	9.01
2030	57.92	2.30	60.22	57.30	2.50	59.80	55.41	3.02	58.43	52.16	3.82	55.98
2035	106.36	5.07	111.43	104.29	5.72	110.01	98.32	7.40	105.71	88.82	10.00	98.82
2040	155.82	8.02	163.84	151.46	9.53	160.99	138.92	13.45	152.37	121.99	19.59	141.58
2045	208.45	11.75	220.20	200.44	14.51	214.95	178.30	21.71	200.00	155.75	32.87	188.62
2050	258.77	16.50	275.28	246.53	21.24	267.77	214.30	33.65	247.95	189.23	50.05	239.28

f) Situation involving C1, C2, C5, and C7 under RCP 4.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.02	0.24	24.27	24.24	0.24	24.48	24.68	0.24	24.93	25.27	0.25	25.52
2030	149.06	1.57	150.63	150.64	1.58	152.22	153.94	1.61	155.55	158.40	1.67	160.06

2035	276.79	3.18	279.97	281.23	3.21	284.44	290.86	3.32	294.18	304.45	3.49	307.94
2040	406.54	4.84	411.38	415.16	4.93	420.08	434.57	5.20	439.76	462.16	5.62	467.78
2045	542.11	6.33	548.44	556.31	6.49	562.80	589.06	6.94	595.99	636.72	7.61	644.33
2050	677.12	8.03	685.15	698.68	8.30	706.98	748.41	9.04	757.45	819.39	10.00	829.39

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.09	0.32	9.41	8.99	0.33	9.33	8.71	0.37	9.08	8.24	0.44	8.67
2030	57.52	2.12	59.64	56.72	2.22	58.94	54.36	2.53	56.89	50.45	3.02	53.47
2035	105.57	4.67	110.24	103.00	5.05	108.05	95.79	6.08	101.88	84.41	7.70	92.11
2040	154.52	7.28	161.80	149.12	8.17	157.29	134.05	10.58	144.62	112.72	14.03	126.75
2045	206.58	10.54	217.12	196.86	12.16	209.03	170.45	16.46	186.91	139.69	21.88	161.56
2050	256.27	14.70	270.98	241.54	17.53	259.08	202.77	24.87	227.64	166.12	32.34	198.46

The model projections (Table 4.10) suggest that the expansion of the SRP area leads to an increase in annual SOC stocks in both regions. This is because more residues are returned to the soil as a source of SOC compared to conventional practices. Therefore, the quantity of organic matter input, such as crop residues or organic fertilizer, and land management practices such as residue management, will play a crucial role in determining the amount of SOC.

Table 4.10 The annual SOC stocks in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050

a) Situation involving C1, C2, C3, and C6 under RCP 4.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	114.55	116.06	120.02	125.73
2030	114.41	118.87	130.09	147.40
2035	114.40	122.05	142.37	173.18
2040	114.96	126.23	156.58	203.14

2045	114.87	130.84	172.22	230.59
2050	115.50	136.56	189.71	237.03

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	111.05	111.64	113.11	115.15
2030	115.34	117.01	113.74	127.72
2035	119.40	122.57	115.09	143.24
2040	123.32	128.09	117.03	163.84
2045	126.97	133.64	119.46	175.22
2050	130.55	139.41	122.48	182.30

b) Situation involving C1, C2, C3, and C7 under RCP 4.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	112.20	112.43	113.11	114.15
2030	110.82	111.62	113.74	117.16
2035	109.58	111.04	115.09	121.68
2040	108.51	110.75	117.03	127.25
2045	107.22	110.54	119.46	132.51
2050	106.25	110.66	122.48	133.14

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4

2025	110.18	110.39	110.94	111.80
2030	114.05	114.78	116.66	119.63
2035	117.75	119.19	122.91	128.53
2040	121.17	123.54	129.66	138.33
2045	124.38	127.83	136.63	145.27
2050	127.51	132.26	144.50	150.71

c) Situation involving C1, C2, C4, and C6 under RCP 4.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	114.55	116.06	120.03	125.74
2030	114.41	118.86	130.07	147.38
2035	114.39	122.03	142.32	173.05
2040	114.94	126.19	156.45	202.85
2045	114.84	130.76	171.97	230.08
2050	115.46	136.45	189.34	236.44

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	111.20	111.86	113.51	115.94
2030	115.54	117.47	122.35	129.94
2035	119.67	123.24	132.14	146.59
2040	123.63	128.95	142.71	167.72
2045	127.35	134.75	154.35	179.47
2050	130.99	140.73	167.96	186.52

d) Situation involving C1, C2, C4, and C7 under RCP 4.5

Year	Soil Organic Carbon Stock (Mt C yr⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	112.20	112.43	113.12	114.16
2030	110.82	111.62	113.72	117.13
2035	109.57	111.02	115.03	121.55
2040	108.49	110.71	116.90	126.97
2045	107.19	110.46	119.21	132.00
2050	106.22	110.55	122.11	132.55

Year	Soil Organic Carbon Stock (Mt C yr⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	110.32	110.61	111.38	112.60
2030	114.25	115.24	117.80	121.85
2035	118.02	119.86	124.69	131.88
2040	121.48	124.40	131.98	142.21
2045	124.76	128.94	139.58	149.51
2050	127.95	133.58	147.99	154.93

e) Situation involving C1, C2, C5, and C6 under RCP 4.5

Year	Soil Organic Carbon Stock (Mt C yr⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	114.49	115.99	119.91	125.53

2030	114.32	118.73	129.74	146.68
2035	114.28	121.81	141.68	171.63
2040	114.80	125.86	155.45	200.64
2045	114.68	130.32	170.53	227.14
2050	115.27	135.83	187.32	233.19

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	110.91	111.42	112.63	114.33
2030	115.09	116.44	119.79	124.92
2035	118.96	121.45	127.41	137.71
2040	122.65	126.22	135.35	155.39
2045	126.04	130.90	144.12	164.72
2050	129.28	135.57	154.36	170.08

f) Situation involving C1, C2, C5, and C7 under RCP 4.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	112.14	112.37	113.00	113.95
2030	110.73	111.48	113.39	116.44
2035	109.46	110.80	114.40	120.13
2040	108.35	110.38	115.90	124.75
2045	107.03	110.02	117.77	129.05
2050	106.02	109.93	120.09	129.30

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	110.03	110.17	110.50	110.99
2030	113.80	114.21	115.23	116.83
2035	117.30	118.08	119.97	123.01
2040	120.50	121.67	124.62	129.88
2045	123.44	125.09	129.35	134.76
2050	126.25	128.42	134.39	138.49

4.5 Post-harvest GHG from rice residue burning

Rice residue burning is a significant source of air pollution including Greenhouse Gases. Paddy fields are mostly located in the central and northeastern regions of Thailand, which has the peak season of residue burning around January to April as shown in the total particulate matter emission maps in Figure 4.13 (Garivait, S., Bonnet, S., & Kamnoed, O., 2008). Residue burning is prohibited in sustainable rice practices promoted by Organic Thailand, GAP++ and the SRP Standard.

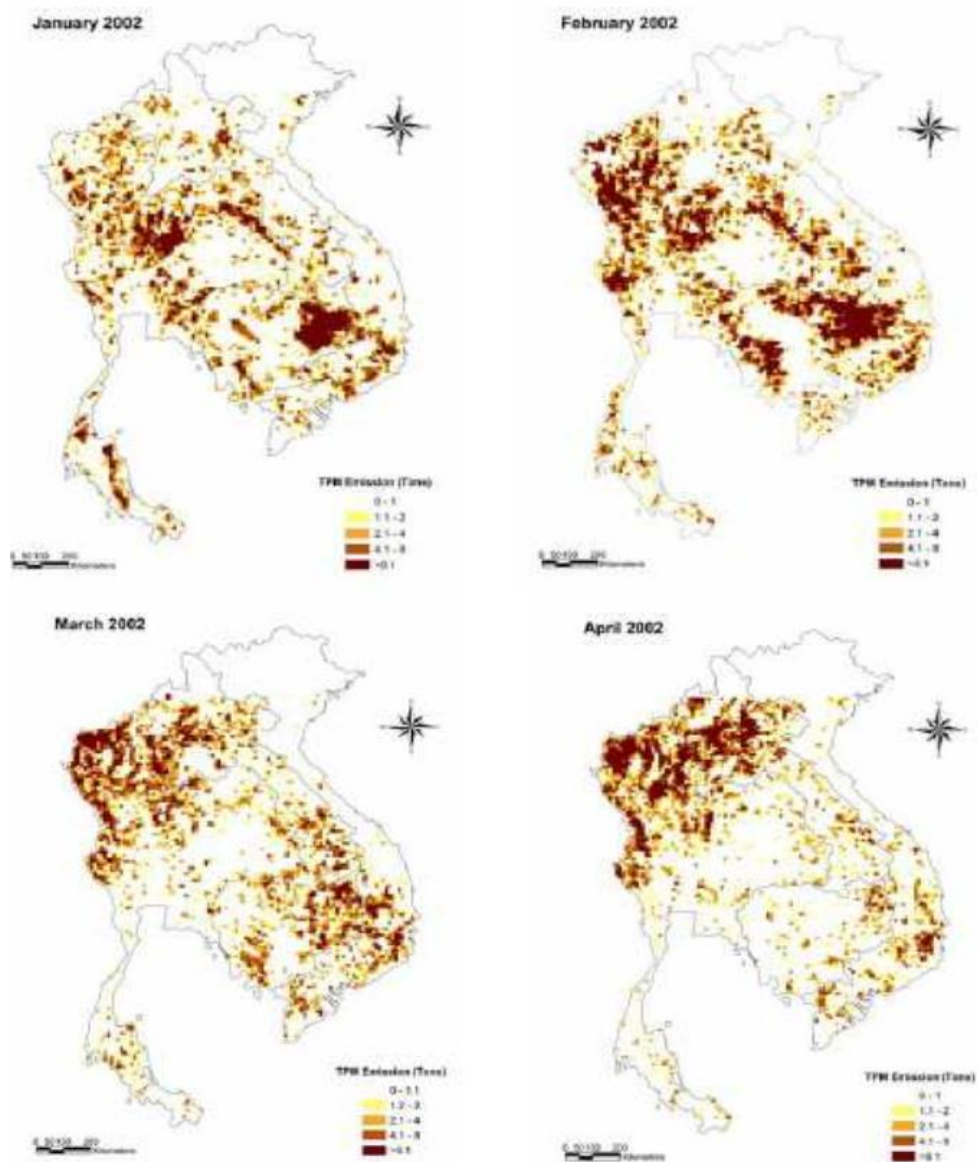


Figure 4.13 Monthly total particulate matter emission from rice residue burning in 2002
Source: Garivait, S., Bonnet, S., & Kamnoed, O., 2008

Greenhouse gas (GHG) emissions from rice straw burning in this analysis focus on emissions of Methane (CH_4) and Nitrogen oxides (NO_x). GHG emissions from rice stubble burning are calculated based on chapter 2 of 2006 IPCC guidelines for national greenhouse gas

inventories. CO₂ emissions from rice burning are excluded from these calculations (Eggleston, H. S., et al., 2006),²¹.

The method applied for calculating the level of GHG emissions from rice residue burning, is explained in the following section. The same method is used to calculate PM_{2.5} emissions from rice residue burning. The PM_{2.5} data is applied in the health costs analysis later in this assessment.

4.5.1 Method for calculation of emissions of GHG and PM 2.5 from rice residue burning

The GHG inventory are estimated including changes in biomass and soil carbon stocks, CH₄ emissions from rice cultivation and from direct and indirect N₂O emissions from soils. The DNDC model is used for inventory calculations. However, the DNDC software package does not cover a burning process that also releases GHG as well as particulate matter (PM) that significantly impact environment and human health.

For the greenhouse gas emission and air pollution from burning of rice residues in paddy fields, the Carbon monoxide (CO), Carbon dioxide (CO₂), Methane (CH₄), Nitrogen oxides (NO_x), Sulfur dioxide (SO₂), Black carbon (BC), Organic carbon (OC), PM₁₀, and PM_{2.5} were estimated on the basis of the available literature on the emission of air pollutants from the study of emission of air pollutants from rice residue open burning in Thailand, 2018 (Junpen, et al., 2018). In this analysis, calculations of emissions from burning are only carried out for conventional paddy fields areas, as burning residues is not a permitted practice in the organic rice system. The relevant air pollution emissions are estimated by the formula:

$$E_{sti} = EF_i \times M_{st} \times 10^{-3}$$

where E_i is emission of air pollutant i (tons).

M is the mass of burned dry matter (tons of dry matter).

EF_i is the emission factor of the air pollutant i (grams per kilogram of burned dry matter).

s, t are scenario and year of the study (year).

²¹ other negative impacts from rice straw burning include fine particulate emissions, in particular PM 2.5. This has important impacts on public health. The method to be applied for analyzing this in terms of health cost will be presented in the next section.

A number of studies have measured the emission factors. This section of the study transfers selected values from Junpen, et al., (2018), based on nine types of greenhouse gas and air pollution emissions. The value of selected emission factors is shown in Table 4.11

Table 4.11 Value of emission factors

Gases	Emission factor (EF) (gram per kilogram of burned dry matter)
CO ₂	1177
CO	93
CH ₄	9.6
NO _x	0.49
SO ₂	0.51
BC	0.53
OC	3.1
PM _{2.5}	8.3
PM ₁₀	9.4

Source: Junpen, et al., (2018)

The mass of burned dry matter was estimated based on Intergovernmental Panel on Climate Change (IPCC) guidelines for national Greenhouse Gas Inventories (Junpen, et al., 2018).

$$M_{st} = \alpha \times RRB_{st}$$

where RRB is quantity of rice residue in the burned field (tons of dry matter)

α is the combustion factor (unitless).

s, t are scenario and year of the study (year).

The combustion factor was studied by Cheewaphongphan and Garivait (2013) based on field experiments to show the fraction of burned rice residue combusted by fire distinguishing each region of Thailand. The average combustion factors in the northeast and central are 0.52 and 0.12 respectively, while the average for the whole country is 0.34. The quantity of rice residue in the burned field, RRB , is estimated by the fraction of rice residue subjected to open burning, FB , and the amount of residue, straw and stubble, generated in the field, RRG . Meanwhile the amount of residue in the field is estimated by burn area, HA , and the density of residue in that area, RD as follows:

$$RRB_{st} = (RRG_t \times FB)$$

$$RRG_{st} = (HA_{st} \times RD_t)$$

where FB is the fraction of rice residues subject to open burning (unitless).

RRG is the amount of rice residues generated in the field (tons).

HA is the rice harvest area in the study year (hectares).

RD is average amount of rice residue density per unit area, biomass load (tons per hectare).

s, t are scenario and year of the study (year).

The rice harvest area, *HA*, is estimated by the conventional rice area based on four scenarios. For the first Scenario, BAU, it is assumed that 5.31 % of the rice area in northeast and 2.27% of the rice area in central are conventional rice, and would be subject to burning, while in Scenario 4, the transformational change towards sustainability scenario, 59.95 % of the rice area in northeast and 22.91 % of the rice area in central will be considered as area subject to rice residue burning.

The rice residue density, *RD*, for Khao Dawk Mali 105, represented to rice variety in the northeast is reported to be about 4.80 tonnes per hectare, and 5.63 tonnes per hectare from Patum Thani 1 as rice variety in central (Cheewaphongphan et al., 2018). Meanwhile throughout the whole country, different rice varieties range from 4.18 to 8.02 tonnes per hectare. It is clear that Khao Dawk Mali 105 are used from most of the northeast farmers. In the central area, more rice varieties are applied, but the five main varieties are Phatum Thani, Suphan buri, Pitch Nu Lok, Chai nat, and RD series which provide *RD* around 5.63 as Phatum Thani 1.

The fraction of rice residues subject to open burning studied in 2015/2016, surveyed in the whole Thai regions, showed that in the rain-fed fields, the fraction of rice residues subject to open burning was about 21 percent and 36 percent of all rice residue in the field in northeast and central areas, respectively (Cheewaphongphan et al., 2018).

4.5.2 Results of GHG from residue burning

The result of the calculation was determined step by step. Firstly, the conventional rice area from 2021 to 2050 in each scenario was calculated by subtracting the projected sustainable rice area from the total rice area of 6,533,707 and 2,004,640 hectares in northeast and central respectively. Then, the amount of rice residue generated in the field, *RRG*, was calculated by multiplying the area by the average rice residue density, *RD*, which is assumed to be 4.80 and 5.63

tons per ha. After that, the quantity of rice residue in the burned field, RRB, according to the fraction burned, FB, which was assessed to be 21 and 36 percent. Next, the mass of burned dry matter, M, was computed by multiplying by the average combustion factor, α , or 0.52 and 0.12 (Junpen, et al., 2018). Finally, the emissions of each air pollutant, E , in each year of the four scenarios were calculated by multiplying the kilograms of burned dry matter by the emission factors, EF, set out above. The results of this analysis are presented in Table 4.12.

The amount of rice residues generated in the field, RRG, in this section of our study was focused only on the conventional rice area, due to the fact that burning residues in the field are prohibited in the SRP practice. Analysis from Junpen et al (2018) showed that there were about 61.87 million tons of RRG for the whole country, 31.14 million tons in northeast, and 13.04 million tons in central in 2018.

Table 4.12 Amount of rice residues generated (RRG) from conventional rice fields in the Northeast region

Years	RRG (Million tons)						
	BAU	Scenario 2	%Change	Scenario 3	%Change	Scenario 4	%Change
2021	31.292	31.292	0.0	31.292	0.0	31.292	0.0
2025	30.562	30.157	-1.3	29.068	-4.9	27.492	-10.0
2030	30.266	29.174	-3.6	26.389	-12.8	22.086	-27.0
2035	30.018	28.304	-5.7	23.698	-21.1	16.736	-44.2
2040	29.699	27.363	-7.9	21.026	-29.2	11.362	-61.7
2045	29.513	26.427	-10.5	18.353	-37.8	7.052	-76.1
2050	29.257	25.404	-13.2	15.659	-46.5	7.052	-75.9

Note: Percent change is compared to BAU

Table 4.13 Amount of rice residues generated (RRG) from conventional rice fields in the Central region

Years	RRG (Million tons)						
	BAU	Scenario 2	%Change	Scenario 3	%Change	Scenario 4	%Change
2021	10.896	10.896	0.0	10.896	0.0	10.896	0.0
2025	10.489	10.291	-1.9	9.766	-6.9	8.957	-14.6
2030	10.361	9.821	-5.2	8.415	-18.8	6.252	-39.7
2035	10.219	9.339	-8.6	7.057	-30.9	3.538	-65.4
2040	10.082	8.874	-12.0	5.711	-43.4	0.850	-91.6
2045	9.945	8.398	-15.6	4.360	-56.2	0.004	-100.0
2050	9.813	7.927	-19.2	2.998	-69.4	0.004	-100.0

Note: Percent change is compared to BAU

Next, the quantity of rice residues subjected to open burning, RRB, and the mass of burned dry matter, M, were estimated. The results presented in Table 4.14 and 4.17 show that RRB in northeast was about 6.57 million tons in 2021 and varied from 1.48 to 6.14 million tons in 2050 in BAU and scenario 4. Meanwhile, in the central range from 0.002 to 3.53 million tons in 2050. The mass of burned dry matter in 2050, calculated by using an average combustion factor, α , of 0.52, varied from 0.77 to 3.19 million tons for northeast, and α of 0.12, varied from 0 to 0.42 million tons. The previous study was showed about 3 and 0.53 million tons of M in northeast and central respectively (Junpen, et al., 2018).

Table 4.14 Quantity of rice residues subjected to open burning (RRB) in the Northeast region

Years	RRB (Million tons)						
	BAU	Scenario 2	%Change	Scenario 3	%Change	Scenario 4	%Change
2021	6.571	6.571	0.0	6.571	0.0	6.571	0.0
2025	6.418	6.333	-1.3	6.104	-4.9	5.773	-10.0
2030	6.356	6.127	-3.6	5.542	-12.8	4.638	-27.0
2035	6.304	5.944	-5.7	4.976	-21.1	3.515	-44.2
2040	6.237	5.746	-7.9	4.415	-29.2	2.386	-61.7
2045	6.198	5.550	-10.5	3.854	-37.8	1.481	-76.1
2050	6.144	5.335	-13.2	3.288	-46.5	1.481	-75.9

Note: Percent change is compared to BAU

Table 4.15 Quantity of Rice residues subjected to open burning (RRB) in the Central region

Years	RRB (Million tons)						
	BAU	Scenario 2	%Change	Scenario 3	%Change	Scenario 4	%Change
2021	3.923	3.923	0.0	3.923	0.0	3.923	0.0
2025	3.776	3.705	-1.9	3.516	-6.9	3.224	-14.6
2030	3.730	3.535	-5.2	3.029	-18.8	2.251	-39.7
2035	3.679	3.362	-8.6	2.541	-30.9	1.274	-65.4
2040	3.630	3.194	-12.0	2.056	-43.4	0.306	-91.6
2045	3.580	3.023	-15.6	1.570	-56.2	0.002	-100.0
2050	3.533	2.854	-19.2	1.079	-69.4	0.002	-100.0

Note: Percent change is compared to BAU

Table 4.16 Mass of burned dry matter in the Northeast region

Years	M (Million tons)
-------	------------------

	BAU	Scenario 2	%Change	Scenario 3	%Change	Scenario 4	%Change
2021	3.417	3.417	0.0	3.417	0.0	3.417	0.0
2025	3.337	3.293	-1.3	3.174	-4.9	3.002	-10.0
2030	3.305	3.186	-3.6	2.882	-12.8	2.412	-27.0
2035	3.278	3.091	-5.7	2.588	-21.1	1.828	-44.2
2040	3.243	2.988	-7.9	2.296	-29.2	1.241	-61.7
2045	3.223	2.886	-10.5	2.004	-37.8	0.770	-76.1
2050	3.195	2.774	-13.2	1.710	-46.5	0.770	-75.9

Note: Percent change is compared to BAU

Table 4.17 Mass of burned dry matter in the Central region

Years	M (Million tons)						
	BAU	Scenario 2	%Change	Scenario 3	%Change	Scenario 4	%Change
2021	0.471	0.471	0.0	0.471	0.0	0.471	0.0
2025	0.453	0.445	-1.9	0.422	-6.9	0.387	-14.6
2030	0.448	0.424	-5.2	0.364	-18.8	0.270	-39.7
2035	0.441	0.403	-8.6	0.305	-30.9	0.153	-65.4
2040	0.436	0.383	-12.0	0.247	-43.4	0.037	-91.6
2045	0.430	0.363	-15.6	0.188	-56.2	0.000	-100.0
2050	0.424	0.342	-19.2	0.130	-69.4	0.000	-100.0

Note: Percent change is compared to BAU

Finally, the emission of air pollutants, E_i , were calculated based on the emission factor presented earlier in Table 4.11. Tables 4.18 – 4.25 show the amount of air pollution generated in each scenario from 2021 to 2050. The results show that the greatest amount of air pollution is from CO₂, while NO_x, SO₂, and BC are small amounts. The emissions of PM_{2.5} are in direct correlation with PM₁₀.

Table 4.18 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, BAU scenario

Year	CO ₂	CO	CH ₄	NO _x	SO ₂	BC	OC	PM _{2.5}	PM ₁₀
2021	4,021,931	317,791	32,804	1,674	1,743	1,811	10,593	28,362	32,121
2025	3,928,091	310,376	32,039	1,635	1,702	1,769	10,346	27,700	31,371
2030	3,890,010	307,367	31,728	1,619	1,686	1,752	10,246	27,432	31,067

2035	3,858,229	304,856	31,469	1,606	1,672	1,737	10,162	27,208	30,813
2040	3,817,182	301,613	31,134	1,589	1,654	1,719	10,054	26,918	30,486
2045	3,793,252	299,722	30,939	1,579	1,644	1,708	9,991	26,749	30,294
2050	3,760,314	297,119	30,670	1,565	1,629	1,693	9,904	26,517	30,031

Table 4.19 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, Scenario 2

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	4,021,931	317,791	32,804	1,674	1,743	1,811	10,593	28,362	32,121
2025	3,876,034	306,263	31,614	1,614	1,680	1,745	10,209	27,333	30,956
2030	3,749,701	296,281	30,584	1,561	1,625	1,688	9,876	26,442	29,947
2035	3,637,922	287,448	29,672	1,515	1,576	1,638	9,582	25,654	29,054
2040	3,516,960	277,891	28,685	1,464	1,524	1,584	9,263	24,801	28,088
2045	3,396,648	268,384	27,704	1,414	1,472	1,530	8,946	23,953	27,127
2050	3,265,199	257,998	26,632	1,359	1,415	1,470	8,600	23,026	26,077

Table 4.20 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, Scenario 3

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	4,021,931	317,791	32,804	1,674	1,743	1,811	10,593	28,362	32,121
2025	3,736,092	295,205	30,473	1,555	1,619	1,682	9,840	26,346	29,838
2030	3,391,718	267,995	27,664	1,412	1,470	1,527	8,933	23,918	27,088
2035	3,045,813	240,663	24,843	1,268	1,320	1,372	8,022	21,479	24,325
2040	2,702,387	213,528	22,042	1,125	1,171	1,217	7,118	19,057	21,582
2045	2,358,839	186,382	19,239	982	1,022	1,062	6,213	16,634	18,839
2050	2,012,681	159,031	16,416	838	872	906	5,301	14,193	16,074

Table 4.21 Projected emissions of each air pollutant (tons) due to rice residue burning in the northeast of Thailand, Scenario 4

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	4,021,931	317,791	32,804	1,674	1,743	1,811	10,593	28,362	32,121
2025	3,533,464	279,195	28,820	1,471	1,531	1,591	9,306	24,917	28,220

2030	2,838,720	224,300	23,154	1,182	1,230	1,278	7,477	20,018	22,671
2035	2,151,081	169,966	17,545	896	932	969	5,666	15,169	17,179
2040	1,460,301	115,385	11,911	608	633	658	3,846	10,298	11,663
2045	906,379	71,617	7,393	377	393	408	2,387	6,392	7,239
2050	906,379	71,617	7,393	377	393	408	2,387	6,392	7,239

Table 4.22 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, BAU scenario

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	554,038	43,777	4,519	231	240	249	1,459	3,907	4,425
2025	533,307	42,139	4,350	222	231	240	1,405	3,761	4,259
2030	526,810	41,626	4,297	219	228	237	1,388	3,715	4,207
2035	519,596	41,056	4,238	216	225	234	1,369	3,664	4,150
2040	512,638	40,506	4,181	213	222	231	1,350	3,615	4,094
2045	505,660	39,954	4,124	211	219	228	1,332	3,566	4,038
2050	498,956	39,425	4,070	208	216	225	1,314	3,519	3,985

Table 4.23 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, Scenario 2

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	554,038	43,777	4,519	231	240	249	1,459	3,907	4,425
2025	523,266	41,346	4,268	218	227	236	1,378	3,690	4,179
2030	499,340	39,455	4,073	208	216	225	1,315	3,521	3,988
2035	474,853	37,520	3,873	198	206	214	1,251	3,349	3,792
2040	451,189	35,650	3,680	188	196	203	1,188	3,182	3,603
2045	426,989	33,738	3,483	178	185	192	1,125	3,011	3,410

2050	403,041	31,846	3,287	168	175	181	1,062	2,842	3,219
-------------	---------	--------	-------	-----	-----	-----	-------	-------	-------

Table 4.24 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, Scenario 3

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	554,038	43,777	4,519	231	240	249	1,459	3,907	4,425
2025	496,565	39,236	4,050	207	215	224	1,308	3,502	3,966
2030	427,884	33,809	3,490	178	185	193	1,127	3,017	3,417
2035	358,835	28,353	2,927	149	155	162	945	2,530	2,866
2040	290,361	22,943	2,368	121	126	131	765	2,048	2,319
2045	221,685	17,516	1,808	92	96	100	584	1,563	1,770
2050	152,447	12,045	1,243	63	66	69	402	1,075	1,218

Table 4.25 Projected emissions of each air pollutant (tons) due to rice residue burning in the central of Thailand, Scenario 4

Year	CO2	CO	CH4	NOx	SO2	BC	OC	PM2.5	PM10
2021	554,038	43,777	4,519	231	240	249	1,459	3,907	4,425
2025	455,427	35,985	3,715	190	197	205	1,200	3,212	3,637
2030	317,885	25,117	2,593	132	138	143	837	2,242	2,539
2035	179,901	14,215	1,467	75	78	81	474	1,269	1,437
2040	43,218	3,415	353	18	19	19	114	305	345
2045	216	17.09	1.76	0.09	0.09	0.10	0.57	1.53	1.73
2050	216	17.09	1.76	0.09	0.09	0.10	0.57	1.53	1.73

To compare the GHGs emission from burning in each scenario, the global warming potential values, GWP, are calculated based on the IPCC's fifth assessment report (AR5). The GWP 100 years value of CH4 and NOx are 28, and 265 respectively. Given that rice residue burning is banned in organic rice fields, a change in patterns of rice cultivation from conventional

to SRP would reduce air pollution emissions from burning, especially in GHGs, and particulate matter (PM2.5 and PM10) as shown in figures 4.14-4.15, 4.16-4.17, and 4.18-4.19

Figure 4.14 GWP from burning rice residues according to each scenario (million tons of CO2eq) northeast

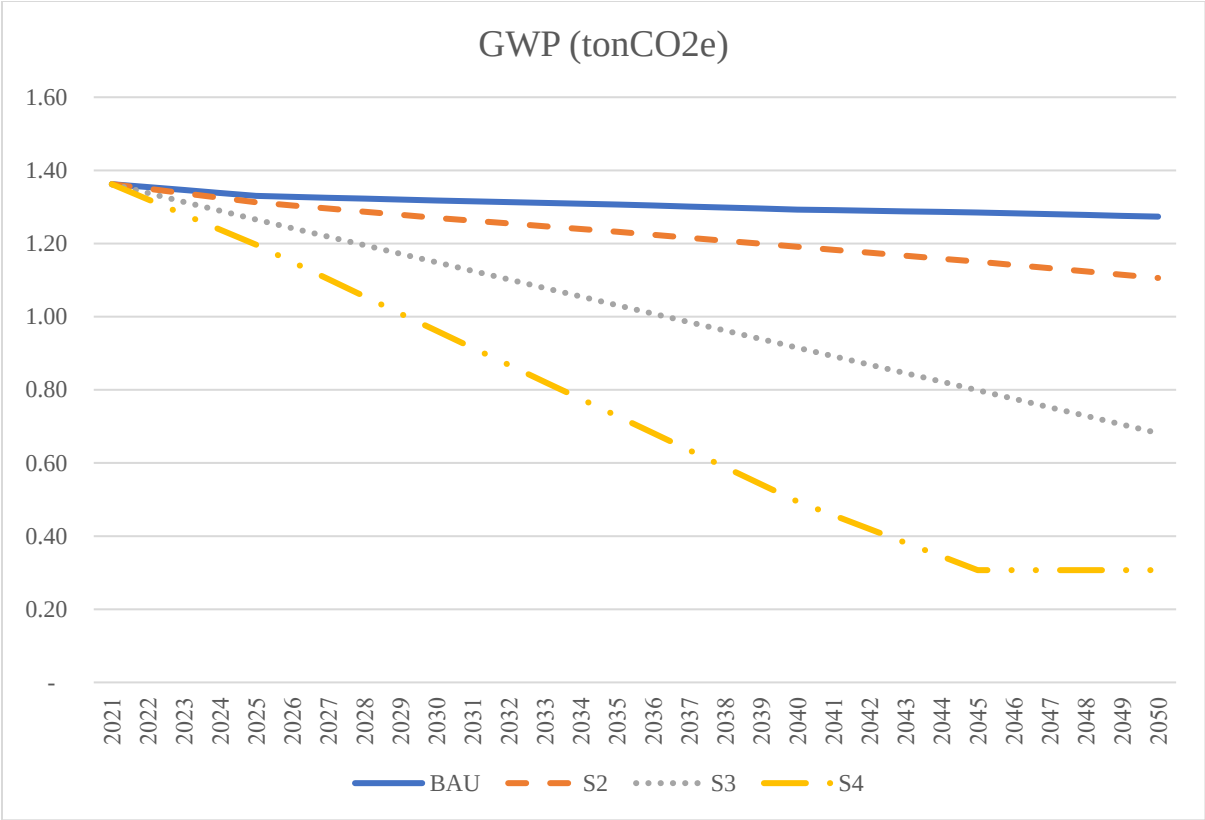


Figure 4.15 GWP from burning rice residues according to each scenario (million tons of CO2eq) central

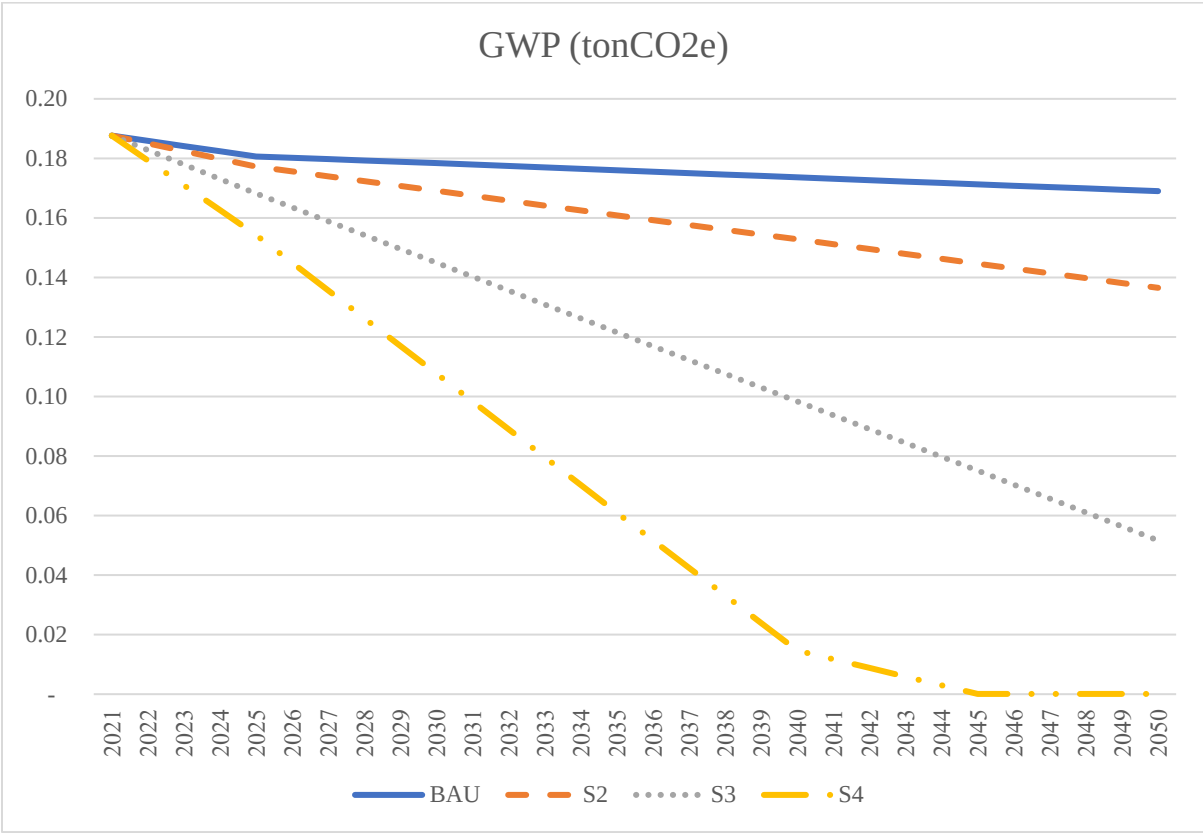


Figure 4.16 Particulate emissions (PM2.5) from burning rice residues in each Scenario (tons) northeast

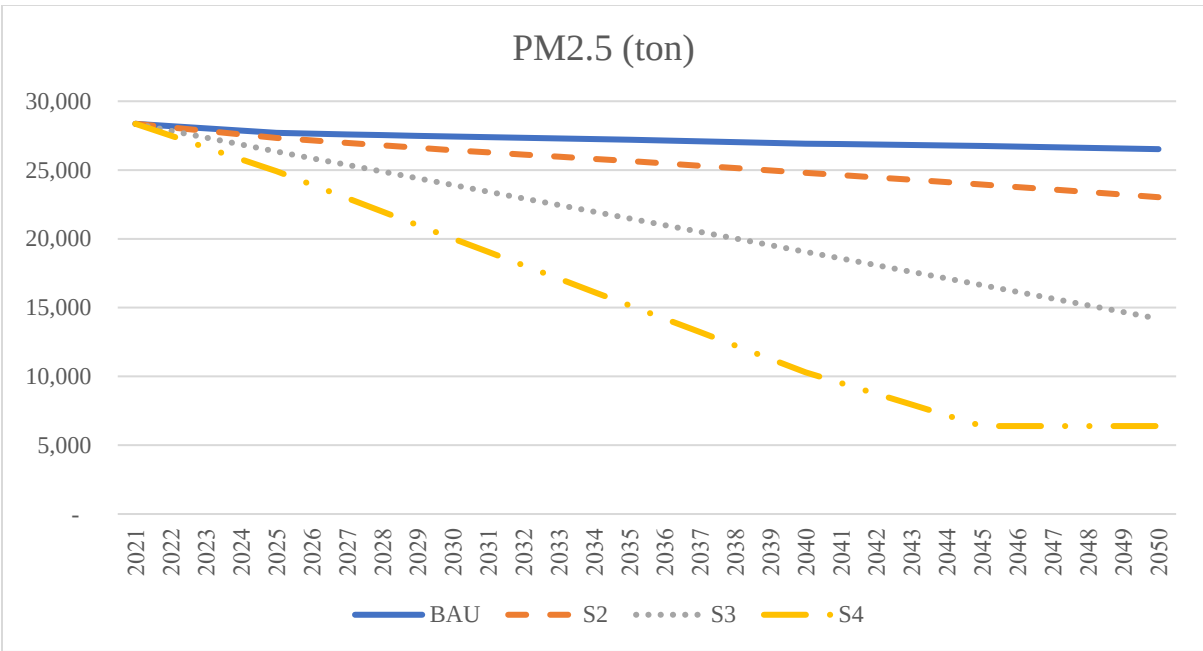


Figure 4.17 Particulate emissions (PM2.5) from burning rice residues in each Scenario (tons) central

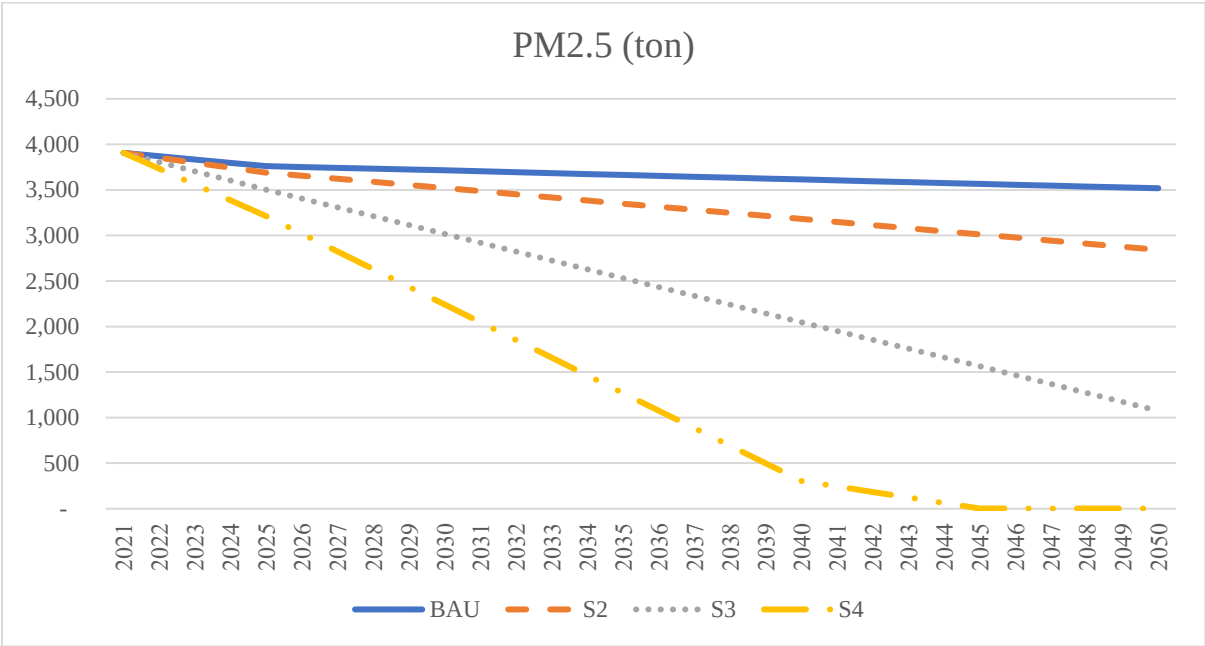


Figure 4.18 Particulate emissions (PM10) from burning rice residues in each Scenario (tons) northeast

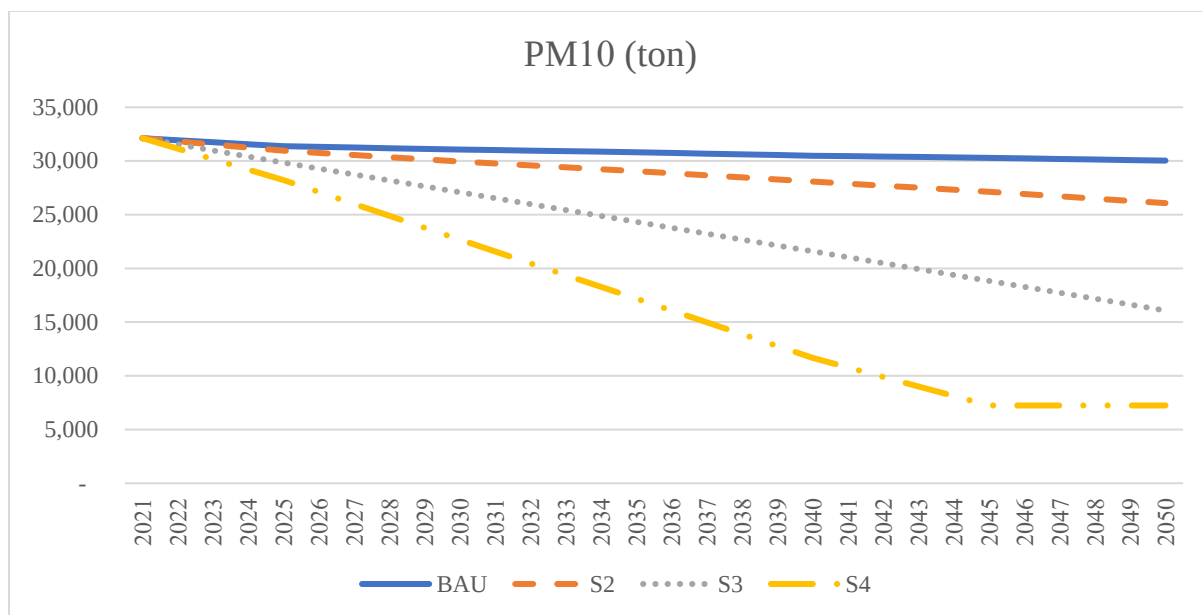
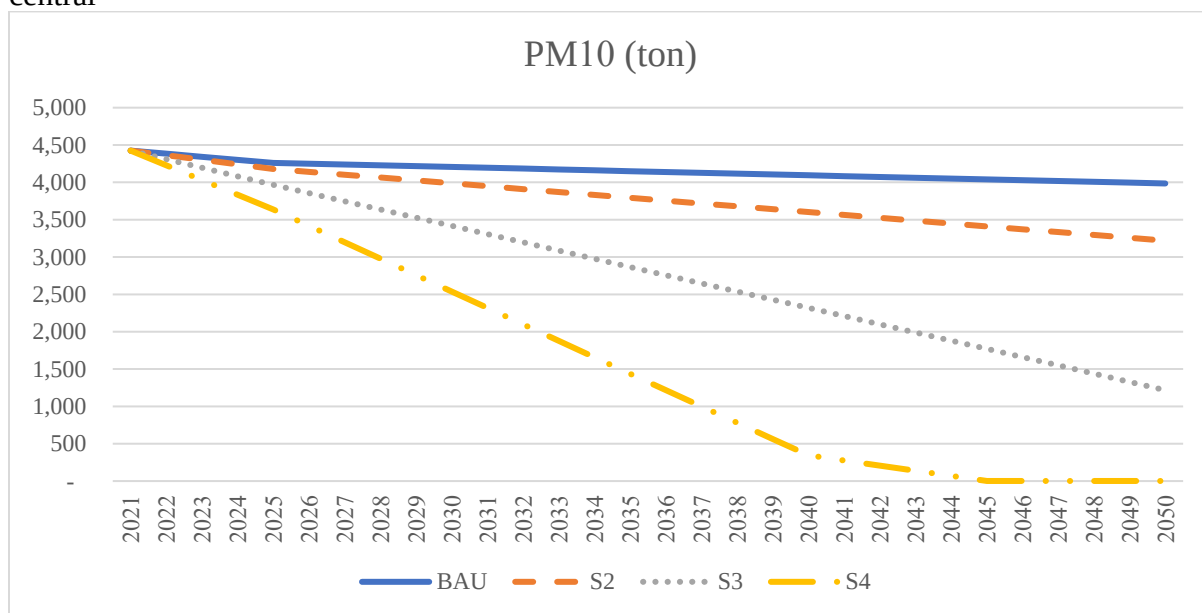


Figure 4.19 Particulate emissions (PM10) from burning rice residues in each Scenario (tons) central



The results show that the cumulative reduction of GHGs emission relative to the BAU scenario were reduced in the second, third, and fourth scenario, respectively.

Figure 4.20 Cumulative reduction of GHGs (CH4 and NOx) from residue burning in terms of GWP emission relative to BAU scenario (MTCO2eq) in the Northeast region

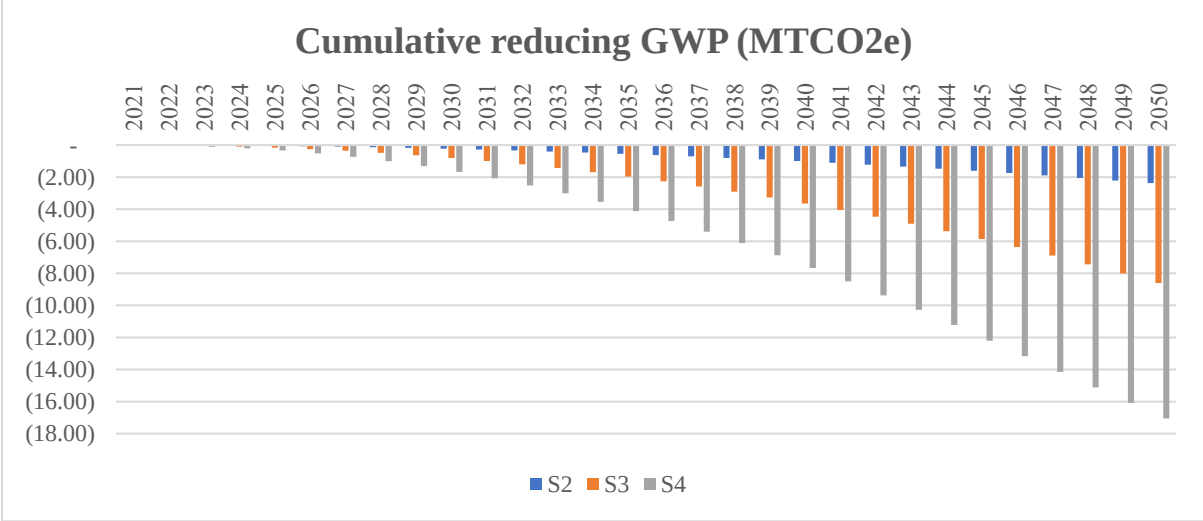
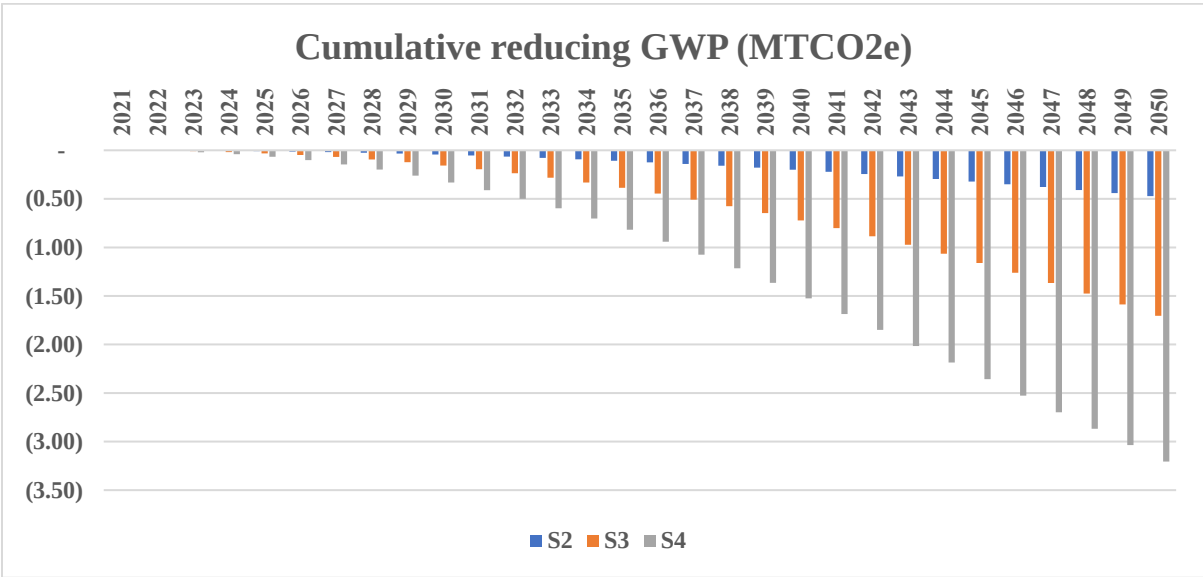


Figure 4.21 Cumulative reduction of GHGs (CH4 and NOx) from residue burning in terms of GWP emission relative to BAU scenario (MTCO2eq) in the Central region



Summary

Summarily, a study conducted in Northeast and Central regions of Thailand compared greenhouse gas (GHG) emissions from different rice field management practices. The study analyzed seven management practices labeled Condition 1 (C1) to Condition 7 (C7), focusing on GHG emissions, soil organic carbon (SOC) stocks, and crop yields. The seven conditions of rice management practices are described below.

- Condition 1 (C1): conventional practice with single rice cultivations in the wet season, burnt crop residue, chemical fertilizer application, and continuous flooding
- Condition 2 (C2): conventional practice with double rice cultivations in the dry and wet seasons, burnt crop residue, chemical fertilizer application, and continuous flooding
- Condition 3 (C3): suitable rice cultivation with double rice cultivation in the dry and wet seasons, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry (AWD) irrigation
- Condition 4 (C4): suitable rice practice with single rice cultivation in the wet season, crop rotation with maize in the dry season, un- burnt crop residue, recommended fertilizer application, and AWD irrigation
- Condition 5 (C5): suitable rice practice with single rice cultivation in the wet season, crop rotation with mung bean in the dry season, un-burnt crop residue, recommended fertilizer application, and AWD irrigation
- Condition 6 (C6): suitable rice practice with single rice cultivation in the wet season, crop rotation with mung bean in the dry season, un-burnt crop residue, recommended fertilizer application, and continuous flooding
- Condition 7 (C7): suitable rice practice with single rice cultivation in the wet season, un-burnt crop residue, recommended fertilizer application, and continuous flooding

Regarding methane (CH₄) emissions, the study found that different management practices led to varying patterns and ranges of annual CH₄ emissions. Condition 2 had the highest trend of

CH₄ emissions, while Condition 1 had the lowest trend. Within the suitable rice practice (SRP), Condition 3 and Condition 6 had the highest trend of CH₄ emissions, while Condition 5 had the lowest trend. A large amount of water for double rice cultivation in Condition 3 and high soil organic carbon with continued flooding practice in Condition 6 may enhance CH₄ production. Alternate wet and dry irrigation (used in Condition 5) resulted in lower CH₄ emissions compared to continuous flooding (used in Condition 6). Comparing emissions between regions, the central region of Thailand exhibited lower CH₄ emissions compared to the northeast region, potentially due to differences in soil texture, with the central region having lower sand content.

For nitrous oxide (N₂O) emissions, the results indicated that conditions involving crop rotation (Conditions 4, 5, and 6) showed higher N₂O emissions compared to other conditions. The addition of nitrogen (N) fertilizer during crop rotation likely contributed to increased N₂O production compared to double or single rice cultivation. Conversely, the application of fertilizer for single rice cultivation in Condition 1 and 7 resulted in lower N₂O emissions. In these conditions, the provided N was sufficient for rice growth, applied once a year, and didn't persist in the soil for long, thus limiting its availability as a source for N₂O production.

The study also found that increasing the amount of organic matter in soil leads to an increase in SOC. Double crop cultivations per year, as seen in Conditions 2, 3, 4, 5, and 6, result in more crop residues being incorporated into the soil, leading to a greater increase in SOC compared to single cultivation, represented by Conditions 1 and 7. The sustainable rice practice (SRP) condition, particularly Conditions 3 and 4 involving double rice cultivation per year and rice-maize cultivation per year, respectively, demonstrates high SOC stocks. This is attributed to the contribution of rice residues applied twice a year and maize residues, which contain more organic matter than other crops used in rotation.

The adoption of SRP, such as retaining crop residues in the soil, helps maintain a source of soil organic matter. This practice may lead to decreased nutrient loss and runoff, which is particularly beneficial for the northeast region, characterized by sandy soil. Notably, the utilization of SRP management combined with mung bean incorporation (C5 and C6) has resulted in increased yields in both the central and northeast regions, even with reduced fertilizer application.

As described earlier in this report, seven conditions have been put forward for assessing in 4 scenarios including the Business as Usual (BAU) scenario, Scenario 2, Scenario 3, and Scenario 4. In the assessment, four scenarios were considered, and a total of seven conditions were proposed. The land use in each scenario was classified to four areas, namely: 1) conventional rice practice in the irrigation area, 2) conventional rice practice in the non-irrigation area, 3) sustainable rice practice in the irrigation area, and 4) sustainable rice practice in the non-irrigation area. The seven conditions were grouped based on land use classification; for example, Condition 6 and 7 were in the sustainable rice practice in the non-irrigation area. Then, the six situations were developed based on the land use areas and the corresponding opportunities that can arise within each classified area.

Among the scenarios studied, Scenario 4 showed the highest CH₄ emissions in the northeast region, while the Business as Usual (BAU) scenario had the lowest CH₄ emissions. In the central region, the BAU scenario had the highest CH₄ emissions, while Scenario 4 had the lowest. When comparing the six situations analyzed, practices involving C1, C2, C3, and C6 resulted in the highest GHG emissions in both regions, while practices involving C1, C2, C5, and C7 had the lowest GHG emissions in both regions. However, the study also revealed that increasing the area of SRP management positively affected GHG reduction in the central region but had a negative effect on GHG reduction in the northeast region.

Moreover, GHG emission and pollutions from rice residual burning were estimated and the result stated that the GHG emission and PM_{2.5} and other pollution could reduce due to the fact that rice stubble burning is prohibited in the sustainable rice practice. The impact directly related to areas. Even though the central region has more burning proportion than that in the northeast region, the northeast showed more deduction of GHG and pollutions due to the bigger areas.

The SRP area results in an increase in annual soil organic carbon (SOC) stocks in both regions. This is primarily due to the greater incorporation of crop residues into the soil, serving as a source of SOC compared to conventional practices.

Part 5 Production Economy and Livelihood

One of purposes of sustainable rice practice is to improve livelihoods among resource-poor small-scale farmers. To our knowledge, there is no evidence of whether sustainable rice practice would improve livelihoods of farmers who adopt this practice. Further evidence is needed to demonstrate experience of sustainable rice farmers compared to conventional farmers. Therefore, in this part, we present the analysis that focuses on comparing the livelihoods of sustainable rice farmers and conventional rice farmers using household survey data. This analysis covers household economic situation such as sources of household incomes, saving, and debt. In addition, the information of rice production such as rice yield, cost of cultivation, and income from rice are highlighted in details in this part. Furthermore, this part describes the projection of rice yield between conventional and sustainable rice practices between 2021 to 2050 based on the scenarios presented in section 3. The factors that would induce conventional farmers to adopt the sustainable rice practice are also presented in this section. Finally, the consumer preference for sustainable rice is revealed in the final part.

5.1 Household economic information

Household economic information was analyzed based on the household survey. A household questionnaire was developed to collect data from conventional rice and sustainable rice farmers in Central and Northeast regions of Thailand. Table 5.1 presents outlines of questions that were used to asked farmers in the study areas.

Table 5.1 Household Questionnaire – Key to issues investigated.

Question issues	Relationship to the indicators of stocks, flows, and outcomes
Happiness (Subjective well-being)	Subjective well-being/ happiness in social capital in general and specific time period. The main dimensions of subjective well-being are measured toward such as occupation, family life, financial status, health, and things that matters to you, etc. Well-being relates to health issues, including the medical expenses if incurred.

Question issues	Relationship to the indicators of stocks, flows, and outcomes
Agricultural land information	A general characteristic of agricultural land is observed on: Landownership / size of agricultural land, cost of rice production and preferred rice variety, particular agricultural activities
Rice cultivation practices	All cultivation practices related to rice cultivation, both rice production and post-harvest crops during dry season to capture flow of all inputs and outputs. This includes volume and type of labor, pesticides, fertilizers, seeds, machine rental.
Post harvesting information	Practices during post-harvest to assess outputs associated to flow of residuals.
Observed biodiversity	The living small animals found in the paddy field throughout the cultivation process can be indicated as income and household consumption.
Choice of management system	Whether or not sustainable rice platform practice is undertaken. Driving factors that motivate farmers to uptake the sustainable rice platform can relate to the regression framework of adoption decision. What causes farmer to give up the practice of sustainable rice platform production?
Environmental problems	Farmer perceptions and attitudes to environmental problems in general, including pollution and natural disasters.
Income and spending	Main sources of off-farm income such as salary, wage, and remittance. Analysis of off-farm income will be included in the social capital assessment. Dividends from cooperatives identifies the returns on investment. Gender equity in cooperative membership and shareholdings can also be explored. Items to identify monthly spending behavior of household.
Household saving and debt information	Data to be used as proxy for financial status of household

Question issues	Relationship to the indicators of stocks, flows, and outcomes
Social capital	Trust and social networks capture the stock and outcomes of social capital in community. Trust and social relations

Since the sustainable rice platform is relatively new practice in Thailand, there are few farmers fully adopt such practice. Therefore, besides collecting data from farmers who perform sustainable rice practice, we also collect data from rice farmers who practice GAP, which share some practices with sustainable rice platform (SRP). We therefore identify the GAP practice as sustainable rice practice in this study. Since, there are three groups of farmers in this study, GAP, SRP and conventional rice farmers, the approximate sample size of the study was calculated using a stratified random sampling scheme. A total of 728 farmers were interviewed in total, 352 for conventional 352 for GAP and 24 SRP farmers. The farmer household surveys were carried out across both the central region, including Supanburi, Chainat, and Ayutthaya provinces, and the Northeast region, including Khon Kaen, Udon thani, Nakornratsima, Sakonnakorn, Surin and Ubonratchathani provinces, of Thailand. A simple random sample in each stratum was drawn from the government directory of registered rice farmers generated by DoAE. The survey was conducted from September 2022 until November 2022.

Table 5.2 presents the gender and age characteristics of our sample categorized by practices. Four hundred and forty-four are female, which is around 61 percent of our sample. The female in each rice practice are about 59-62 percent. Five hundred and ninety-six respondents in our sample, which covers about 82 percent of sample, were between 41-70 years old. The proportion of age between conventional and GAP rice farmers are very similar for our sample, 51 – 60 years old mostly. Meanwhile, the proportion of age in SRP is mostly in 61 – 70 years old. This is representative of the situation of Thailand's rice farming and indeed the agricultural sector as a whole as the average age of the head of a farming household in Thailand is about 58 years old (Attavanich et al, 2019).

Table 5.2 Gender and age characteristics of conventional, GAP, and SRP rice farmers from survey

Variables	Practices		
	Conventional	GAP	SRP

	(n=352)		(n=352)		(n=24)	
	Numbers of participants	Percent (%)	Numbers of participants	Percent (%)	Numbers of participants	Percent (%)
Gender						
Female	221	62.78	208	59.09	15	62.50
Male	131	37.22	144	40.91	9	37.50
Age						
Less 41 years	16	4.54	14	3.98	1	4.17
41-50 years	61	17.33	47	13.35	2	8.33
51-60 years	124	35.23	141	40.06	6	25.00
61-70 years	104	29.55	98	27.84	13	54.17
71-80 years	40	11.36	43	12.21	2	8.33
More 80 years	7	1.99	9	2.56	0	0

The information provided in the tables of this part is the comparison between conventional rice farmers to GAP farmer and SRP farmers. Therefore, the numbers of each variable presented in the column of GAP and SRP show the deviation of GAP and SRP from conventional rice practice. The first statistic presented is the average yield per *rai* (1 *rai* is equal to 0.16 Hectare) in wet season rice production from table 5.3. It can be seen that the average yield of conventional rice is about 360 and 845 kilograms per *rai* in the Northeast and Central, respectively. The yields of GAP and SRP are not statistically significantly different from the conventional practice for both regions at the p-value > 0.10. In the Northeast, this represents about 2.25 tons per hectare per year, which is very similar with the average rice yield of this region reported by OAE²². The rice yield in Central region, which is about 5.26 ton per hectare, is quite higher than the average yield reported by OAE, which is about 3.78 ton per hectare. However, if focusing only the average rice yield from sampling provinces reported by OAE, which are in flood plain area, the average rice yield is about 4.13 ton per hectare. Since, the sampling provinces are located in the flood plain area of Central region, higher rice yield is expected.

The next statistic presented is the average total cost of production per *rai* of both regions and rice practices. The cost of conventional rice production in the Central area is on average about 3,185 Baht per *rai* (19,906.25 Baht/ha (\$603.22)), which is quite higher than that if the Northeast area. The cost of rice cultivation in the Northeast region is on average about 2,324 Bath per *rai* (14,525 Baht/ha (\$440.15)). The cost of capital is the main cost for rice cultivation in both regions and all practices. Generally, this cost item is quite similar between regions and across practices.

²² <https://www.oae.go.th/assets/portals/1/fileups/prcaidata/files/type%20rice%205%2064.pdf>

The second highest cost of rice cultivation is chemical fertilizer cost. The rice cultivation in the Central region carries more chemical fertilizer cost than that in the Northeast region. This cost is on average double in the rice cultivation in the Central region when compared to the Northeast region. Interestingly, it seems to be clear that the fertilizer costs of GAP and SRP rice practices are statistically significantly lower than that of conventional rice practice. Particularly, in the Northeast area, the fertilizer costs of GAP and SRP are lower than the fertilizer cost of conventional rice about 114 and 318 Baht per rai (or 712.5 Baht/ha (\$21.60) and 1987.5 Baht/ha (\$60.23)), respectively.

The income generated from rice in each practice are not statistically significantly different from each other, but rice income from Central region is quite higher than that from the Northeast region. The Northeast farmers keep rice production for household consumption more than that of the Central farmers. From income from rice and rice for household consumption, it would be implied that rice farmers in the Central area mainly grow rice for commercial reason more than rice farmers in the Northeast region.

Moreover, when consider to wet season rice production from table 5.3, the average yield, cost of cultivation, and income in Central region are still higher than those from the Northeast area. Even though, the average income from selling rice from conventional and SRP practices are similar, the average cost of production of sustainable rice practices (GAP and SRP) are statistically lower than that of conventional rice practice for both regions. The lower cost of GAP and SRP practices compared to conventional rice practice is mainly generated from the lower cost of chemical fertilizer. In addition, the sustainable rice practice in the Northeast region contains lower cost of labor than conventional rice practice. This information suggests that sustainable rice practices such as GAP and SRP would generate more profit per hectare to farmers than conventional rice practice due to lower cost of production. From our data, the average profit per rai of GAP and SRP practices are higher than that from conventional practice. The profit of selling rice per rai of SRP practice in the Northeast region, for example, is on average about 624 Baht per rai (or 3,905 Baht per hectare (\$119 per hectare)), while the Northeast farmers who practice conventional rice are actually loss by about 175 Baht per rai (or 1,100 Baht per hectare (\$33 per hectare)). The situation is similar for the Central farmers where the SRP farmers earn more profit from selling rice than Conventional counterpart. The main driver of higher profit of SRP farmers is the lower cost of production.

The next group of variables is the structure of household income. On average, when comparing between Central region and Northeast region, farmers from Central region have higher income, asset, and debt than those from the Northeast region. Even though, the Central region farmers own very similar size of land to those in the Northeast region, they rent more land for rice cultivation. This information confirms Central rice farmers center on growing rice for commercial purpose more than those in the Northeast region.

When considering within region, starting with the Northeast region, the structure of household income among conventional, GAP, and SRP rice farmers are quite similar. Specifically, we do not find any statistically significant difference of income from any sources among these farmers except for remittance income of SRP farmers, which is statistically higher than that of conventional and GAP farmers. We also find the similar pattern from farmers in Central region where the income and income structure from conventional, GAP, and SRP farmers are statistically the same.

In respect to household economic information, the conventional, GAP, and SRP rice households have similar monthly household expenditure, which is around 10,000 Baht (\$312.5) for Northeast rice farming household and 11,000 Baht (\$343.75) for Central rice farming household.

Table 5.3 Cost and income of wet season rice production from rice farmer household survey

Variables	<i>Wet season rice</i>					
	Northeast			Central		
	Conventional	GAP	SRP	Conventional	GAP	SRP
Average yield of rice per rai (Kilograms)	359.81	1.276 (0.925)	34.338 (0.432)	842.73	-20.136 (0.511)	5.517 (0.917)
Average total cost per rai (Baht)	2,324.24	-118.306** (0.047)	-385.433** (0.047)	3,185.34	-345.940** (0.008)	-198.884 (0.494)
Average labor cost per rai (Baht)	322.283	-4.298 (0.830)	100.036 (0.134)	452.918	-99.169** (0.019)	- 192.069** (0.038)
Average capital cost per rai (Baht)	1,056.457	16.822 (0.584)	-93.967 (0.288)	855.039	-84.083* (0.054)	-21.164 (0.817)
Average chemical fertilizer cost per rai (Baht)	552.63	-114.195*** (0.0001)	-318.762*** (0.0003)	1,176.89	-177.108* (0.096)	-47.353 (0.851)
Average manure cost per rai (Baht)	40.81	10.793 (0.370)	-28.449 (0.346)	80.56	-56.603** (0.042)	-80.559 (0.262)
Average income from rice (Baht per rai)	2,148.43	17.421 (0.915)	296.465 (0.574)	6,489.22	-198.318 (0.521)	522.765 (0.373)
Average yield of rice per household for consumption (Kilograms)	1,391.72	30.005 (0.751)	15.812 (0.958)	229.80	30.512 (0.743)	-120.423 (0.494)
Observations (Plots)	483	393	22	99	129	16

Note: Numbers in parentheses are p-value. ***, **, and * indicate the significance level at 1%, 5%, and 10%, respectively.

Table 5.4 Key statistics from household survey of conventional, GAP, and SRP rice farmers

Variables	<i>Household income and economic information</i>					
	Northeast			Central		
	Conventional	GAP	SRP	Conventional	GAP	SRP
Average agriculture income (Baht per year)	57,706.19	3,792.85 (0.488)	-3,143.69 (0.845)	307,002.19	21,811.40 (0.596)	26,372.80 (0.769)
Average non-agriculture income (Baht per year)	17,370.139	1,428.35 (0.726)	-11,557.6 (0.306)	26,812.50	-3,869.32 (0.686)	687.50 (0.975)
Average remittance income (Baht per year)	16,069.792	278.683 (0.938)	17,680.2* (0.077)	10,365.00	-6,842.27 (0.104)	-8,815.00 (0.493)
Average household asset (Baht) ^a	730,419.79	74202.40 (0.374)	-188,239.0 (0.498)	896,875.00	172,214.00 (0.286)	26,061.30 (0.925)
Other income	10,415.972	-4,987.18 (0.171)	-9,965.97 (0.451)	4,593.75	10,581.30* (0.051)	-4,593.75 (0.525)
Average expenditure per month (Baht)	10,022.535	-648.709 (0.295)	2,918.090 (0.150)	11,634.375	1,184.15 (0.629)	-4,009.38 (0.549)
Average household debt in the agricultural sector (Baht)	170,651.74	-5,045.320 (0.663)	-65,300.30 (0.773)	202,578.13	18,956 (0.275)	-64,453.10 (0.416)
Average household debt in the non-agricultural sector (Baht)	114,112.85	109,065.53 (0.844)	48,812.50 (0.437)	70,703.13	89,659.09 (0.661)	6,250.00 (0.495)
Average size of agricultural land owned by farmer (Rai)	16.809	0.432 (0.970)	-0.684 (0.844)	14.063	0.210 (0.935)	0.688 (0.907)
Average size of agricultural land rented by farmer (Rai)	3.503	0.448 (0.565)	-3.503 (0.157)	12.652	-1.340 (0.655)	-0.309 (0.967)
Average household savings (Baht)	40,753.503	-450.473 (0.981)	-40,753.5 (0.451)	37,500	117,386 (0.314)	-37,500 (0.569)
Observations	288	264	16	64	88	8

Note: Numbers in parentheses are p-value. ***, **, and * indicate the significance level at 1%, 5%, and 10%, respectively. ^a Household asset was calculated by summing the values of durable assets owned by the household, but the land and housing were not counted.

5.2 Rice yield estimations under different field management practices and different climate scenarios

In this section, the we present the analysis of rice yield prediction from 2021 to 2050 based on different conditions of rice field managements. The rice field managements employed to predict rice yield here are the same as those employed for greenhouse gases estimations and predictions in the previous chapter. There are seven field management conditions consisted of two conventional rice practice conditions and five sustainable rice practice conditions. Table 5.5 presents the details of each condition. Note that table 5.5 is the same as table 4.4 in the previous chapter.

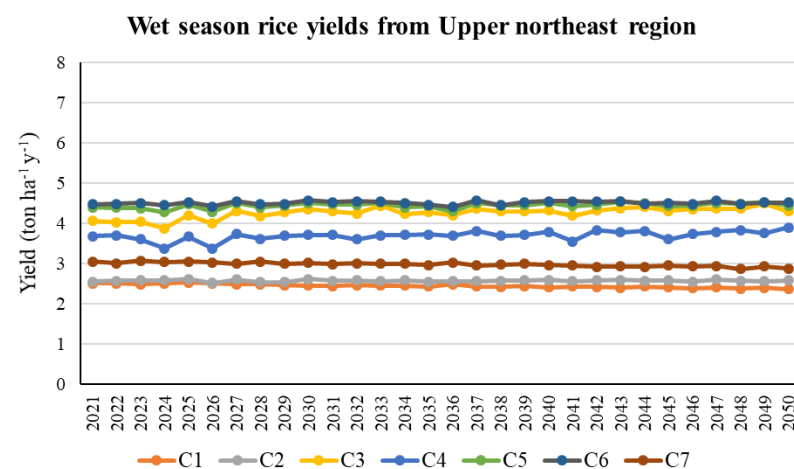
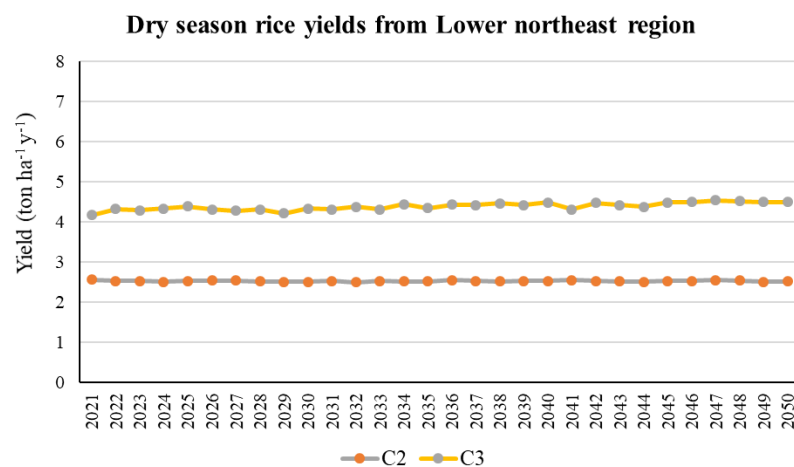
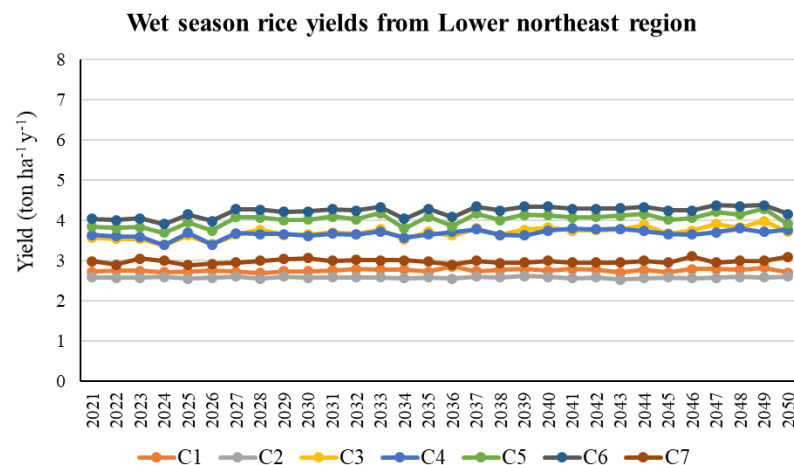
Table 5.5 Conditions of rice field management practices for the simulation

No.	Condition	Field management practices									
		Practice	Cropping system			Crop Residue		Fertilizer application		Irrigation method	
			Singl e rice	Doubl e rice	Rice- Crop rotation	Burn	No- bur n	Chemic al	Recom - mende d	CF	AW D
1	SR-B-C-CF	CON	✓			✓		✓		✓	
2	DR-B-C-CF	CON		✓		✓		✓		✓	
3	DR-NB-RF-AWD	SRP		✓			✓		✓		✓
4	RO _{maize} -NB-RF-AWD	SRP	✓		Maize		✓		✓		✓
5	RO _{bean} -NB-RF-AWD	SRP	✓		Mung bean		✓		✓		✓

No.	Condition	Field management practices									
		Practice	Cropping system			Crop Residue		Fertilizer application		Irrigation method	
			Singl e rice	Doubl e rice	Rice- Crop rotation	Burn	No- bur n	Chemic al	Recom - mende d	CF	AW D
6	RO _{bean} - NB-RF- CF	SRP	✓		Mung bean		✓		✓	✓	
7	SR-NB- RF-CF	SRP	✓				✓		✓	✓	

Environment and management conditions can influence the crop production (Studnicki *et al.*, 2016); therefore, the optimal conditions for growing crops are required to improve the yield. Additionally, when the same crop is planted under the same environment, the management will become the key factor for improving the production. In this study, the yield from rice field including the yield from crop rotation under different practices over 2021-2050 are estimated using the Denitrification-Decomposition (DNDC) model. Figure 5.1 shows the annual yield from different conditions of rice practices over 2021-2050.

When focusing on rice yield, conventional practices in the Central region have shown the highest yield, while those in the northeast region have presented the lowest. This may be attributed to differences in soil management and nutrient availability. Soil organic matter plays a crucial role in improving the soil's capacity to store plant nutrients by reducing runoff loss through enhancing infiltration rate and reducing surface runoff velocity (Oduor *et al.*, 2022). By keeping crop residues in the soil, the SRP management helps to maintain a source of soil organic matter, resulting in reduced nutrient loss and runoff, particularly in the northeast region, which has sand-rich soil. Furthermore, the yield of the central region under SRP management has increased despite a reduction in the amount of fertilizer used. However, it is important to carefully consider the fertilizer rate in order to improve crop yield and ensure that the nutrient requirements of the crop are adequately met without being exceeded.



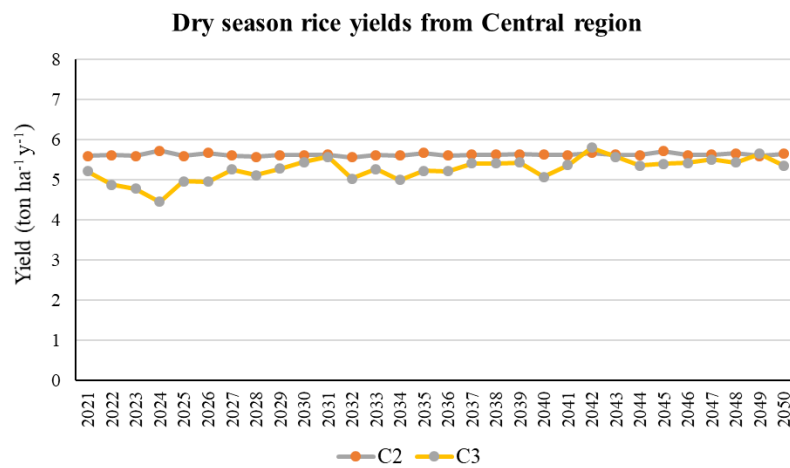
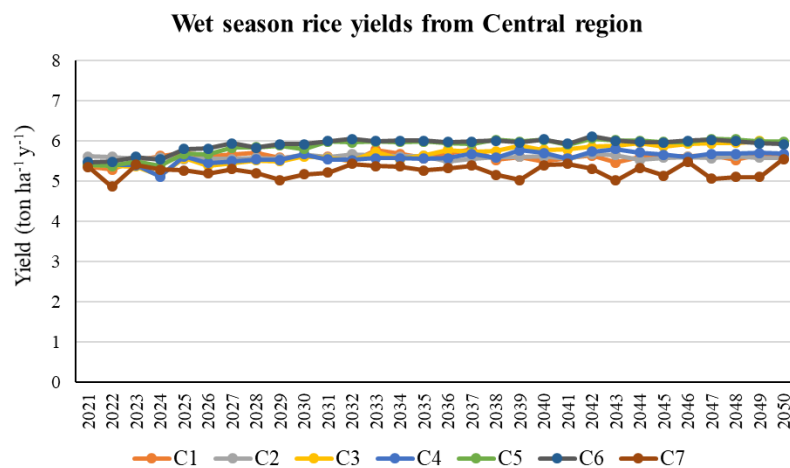
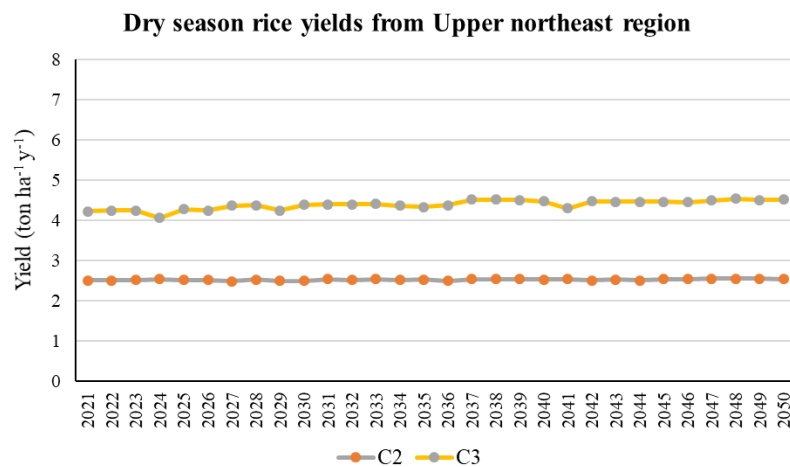


Figure 5.1 Rice yields from seven practices over 2021-2050 in lower northeast, upper northeast, and central regions

Based on the data presented in Table 5.6, the yield in the Northeast and Central regions varies depending on the specific year's climate conditions and management practices. The results show that Scenario 4, which involved implementing conditions C1, C2, C3, and C6, produced the highest yield for both regions. Specifically, the highest annual yields were approximately 27 and 17 Mt per region, respectively. These impressive yields could be attributed to the combination of C3, which involved double rice cultivation, and C6, which involved rotating rice and mung bean crops.

Increasing the SRP areas had a positive impact on rice yield in the Northeast region, whereas in the Central region, rice yield tended to decrease slightly as SRP areas were increased. However, in Scenario 4, where conditions C1, C2, C3, and C6 were implemented, the trend was reversed. In this scenario, rice yield in the Central region began to increase after 2040, suggesting that these conditions have a positive effect on rice production in the region. Therefore, given the varying impacts of increased SRP areas on rice yield across different regions, it is essential to take into account both the region and the potential effects of increased SRP area when designing management strategies aimed at improving rice yield.

Table 5.6 The annual rice production in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050

a) Situation involving C1, C2, C3, and C6 under RCP 4.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	18.79	18.91	19.25	19.75
2030	18.81	19.16	20.08	21.55
2035	18.81	19.39	21.02	23.60
2040	19.03	19.85	22.19	25.99
2045	18.87	19.94	22.88	27.26
2050	18.88	20.14	23.63	26.92

Year	Rice yield (Mt yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	16.64	16.63	16.60	16.55
2030	16.73	16.73	16.72	16.70
2035	16.69	16.68	16.63	16.57
2040	16.58	16.57	16.54	16.64
2045	16.75	16.79	16.87	17.02
2050	16.70	16.75	16.90	17.01

b) Situation involving C1, C2, C3, and C7 under RCP 4.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	18.59	18.61	18.68	18.80
2030	18.55	18.65	18.94	19.43
2035	18.46	18.60	19.06	19.87
2040	18.58	18.79	19.47	20.68
2045	18.39	18.69	19.59	21.01
2050	18.41	18.88	20.22	21.43

Year	Rice yield (Mt yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	16.62	16.60	16.55	16.47
2030	16.69	16.66	16.59	16.47
2035	16.65	16.59	16.44	16.19
2040	16.53	16.48	16.32	16.12
2045	16.69	16.64	16.50	16.28
2050	16.66	16.68	16.69	16.67

c) Situation involving C1, C2, C4, and C6 under RCP 4.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	18.73	18.84	19.13	19.54
2030	18.74	19.04	19.79	20.94
2035	18.73	19.23	20.52	22.50
2040	18.93	19.61	21.47	24.41
2045	18.76	19.64	21.91	25.31
2050	18.76	19.76	22.43	25.02

Year	Rice yield (Mt yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	16.46	16.36	16.05	15.55
2030	16.47	16.14	15.27	13.85
2035	16.35	15.82	14.36	12.32
2040	16.18	15.46	13.55	11.64
2045	16.23	15.27	12.84	11.20
2050	16.09	14.93	12.09	11.20

d) Situation involving C1, C2, C4, and C7 under RCP 4.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	18.53	18.54	18.56	18.58
2030	18.48	18.53	18.65	18.82
2035	18.38	18.44	18.57	18.78
2040	18.48	18.55	18.75	19.11
2045	18.28	18.39	18.62	19.06
2050	18.29	18.51	19.02	19.53

Year	Rice yield (Mt yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	16.44	16.33	16.01	15.47
2030	16.43	16.08	15.14	13.62
2035	16.31	15.74	14.17	11.94
2040	16.14	15.37	13.33	11.12
2045	16.17	15.12	12.47	10.46
2050	16.06	14.85	11.88	10.86

e) Situation involving C1, C2, C5, and C6 under RCP 4.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	18.73	18.85	19.14	19.55
2030	18.74	19.05	19.82	21.00
2035	18.74	19.24	20.58	22.62
2040	18.94	19.63	21.53	24.57
2045	18.78	19.66	22.00	25.51
2050	18.77	19.78	22.49	25.13

Year	Rice yield (Mt yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	16.47	16.36	16.06	15.56
2030	16.48	16.16	15.30	13.92
2035	16.38	15.89	14.55	12.66
2040	16.20	15.53	13.74	11.95
2045	16.26	15.35	13.06	11.53
2050	16.13	15.03	12.34	11.50

f) Situation involving C1, C2, C5, and C7 under RCP 4.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	18.54	18.55	18.57	18.60
2030	18.48	18.54	18.68	18.88
2035	18.39	18.45	18.62	18.90
2040	18.49	18.57	18.81	19.27
2045	18.29	18.41	18.71	19.27
2050	18.30	18.52	19.08	19.64

Year	Rice yield (Mt yr ⁻¹) of Central region			
	BAU	Scenario 2	Scenario 3	Scenario 4
2025	16.45	16.34	16.01	15.49
2030	16.44	16.09	15.17	13.69
2035	16.34	15.81	14.36	12.28
2040	16.16	15.44	13.52	11.44
2045	16.20	15.21	12.69	10.79
2050	16.09	14.95	12.13	11.17

5.3 Factors that influence decision to adopt/ not adopt GAP or SRP rice farming

Our household economic survey also elicited information related to perceptions on GAP or SRP rice farming. In this set of questions, both types of farmers were asked to rank the three most important factors that influenced the GAP or SRP rice practice. The 352 farmers from GAP and 24 farmers from SRP were asked to identify three main reasons for switching from conventional to GAP or SRP rice practices. Note that results presented by table 5.7 were calculated from the top ranked responses by farmers. The good health is the highest ranking of reason to switching in both GAP or SRP for the farmers from both regions, more than 30 percent of total scores from all factors. The market driver from higher price expectation is the second rank, which

is close to the good health score. Meanwhile, the score from reason of high productivity and environmental issues are quite low comparing to health and market issue.

Table 5.7 Survey responses to what do farmers switch from conventional to GAP or SRP rice

Variables	Practices (percent)			
	Northeast		Central	
	GAP	SRP	GAP	SRP
For good health	30.57	30.95	32.46	33.33
For higher price	27.92	30.95	27.46	30.56
For lower cost	15.71	15.48	14.62	19.44
Increasing biodiversity	10.90	9.52	10.85	11.11
Reducing the air pollution	7.47	4.76	7.95	2.78
For higher yield	7.43	8.33	6.66	2.78
Total	100	100	100	100

A second set of questions was asked to the 352 conventional farmers for their perception on GAP or SRP practice, and the results are shown in table 5.8. The first question asked what are the three most important factors that prevent conventional farmers from switching to sustainable farming. We used information provided by farmer to calculate the proportion of how much each reason was chosen as number one reason. The number one barrier preventing conventional farmers to adopt other two practices was lack of knowledge, about 30 percent of conventional rice farmers in both regions.

The second, the third, and the fourth most important factor were close with the 18.6 to 21.9 percent from two regions. The reasons are as follows; the SRP is too complicate, the chemical inputs are necessary, and their areas are unsuitable. Meanwhile, some farmers think that sustainable rice practice could provide lower yield.

Table 5.8 Survey responses to the main factor preventing conventional rice farmers switching to sustainable rice practices

Variables	Region (Percent)	
	Northeast	Central

Lack of knowledge	31.55	30.31
The practice is too complicated	21.61	21.92
Difficult cultivation without chemical fertilizer and pesticide	20.19	20.14
Unsuitable area due to chemical contamination in the water	18.65	19.15
Sustainable rice practice has lower yields.	8.00	8.49
Total	100	100

A second question put to conventional farmers was to ask them to identify what factors would incentivize them to adopt sustainable rice practice. Responses to this question are presented in table 5.9. In the Northeast area, the incentive considered most important by conventional farmers to drive them to adopt sustainable farming is a subsidy from the government. The second and third driving factors are motivation from community leader and clear market availability of sustainable rice. Meanwhile, relatives, neighbors, and government suggestion are lower contributed for sustainable rice adoption. The results from farmers in the Central region are the same pattern with the Northeast. However, the result showed that two of the most important factors for SRP practice adoption are from government suggestions and special privileges from groups. This may be due to the fact that some conventional farmers in Central region are in the mega farm project receiving knowledges and some agricultural equipment from the government.

Table 5.9 Survey responses on the key incentives to encourage conventional rice farmers switching to sustainable rice practices

Variables	Practices (percent)	
	Northeast	Central
	SRP	SRP
Subsidy from the government	19.75	16.67
Following village leaders	18.91	16.67
Availability of market	19.33	13.89
Following government suggestion	14.71	22.22
Receive special privileges from groups	8.40	19.44
Following neighbors	13.66	11.11

Variables	Practices (percent)	
	Northeast	Central
	SRP	SRP
Following relatives	3.99	0.00
Others	1.26	0.00
Total	100	100

The third question in this set was what factors disincentivized conventional farmers continue in sustainable rice practice. In the northeast, the most two important factors reported by this group of farmers, 23 to 25 percent, were that the certificate complication and chemical input restriction in sustainable rice practices. Meanwhile, the issues of knowledge and yield are less concerned. In the central region, the two main issue of farmers are related with certificate, both complication and cost. The less concerned issues are still the same as in the northeast region. The results implied that to make farmers maintain in sustainable rice practices the certificate issue could be more considered.

Table 5.10. Factors disincentivized Sustainable rice farmers to continue sustainable rice practice

Variables	Region (Percent)	
	Northeast	Central
Getting certification is too complicate	25.53	26.56
Difficult to maintain due to restrictions on the chemical inputs	23.42	15.10
Cost of certification is too high	10.51	22.40
Market uncertainty	15.32	13.54
The market price of SRP rice is not different from others	11.11	9.38
Yield is too low	7.51	5.73
Lack of knowledge	6.61	7.29
Total	100	100

5.4 Consumer preference

Introduction

Like other environmentally friendly products, the sustainable rice product needs a consumer pull instead of only a supply push. There are studies showing that consumers are willing to pay a premium price for quality rice. The Viet GAP rice has a price premium of 9 percent to 33 percent than conventional rice when levels of certification and traceability are available (My, Nguyen HD, et al., 2018). In the same study, it was assessed that organic rice could have a price premium of 82 percent, as well as the integrated pest management rice could have 45 percent of price premium compared to conventional rice in Vietnam (My, Nguyen HD, et al., 2018). In Nigeria, the consumers also concern of sustainable rice practices related to food safety and health safety issue (Okpiaifo, Glory, et al., 2020).

The goal of this study is to investigate the importance of sustainable rice practice to consumers as a way to the contribution to the formulation of consumer-based sustainable policies. This is because one of important factors that could lead to the success of demand-driven standards is to understand consumers' preference and willingness to pay for what attributes related to sustainable practices such as environment, society, and health.

As the sustainable rice platform for sustainable rice cultivation is the world's first voluntary standard for rice and just has been introduced, there is relatively limited evidences regarding to consumers' preference of rice sustainability compared to others practices such as organic and GAP especially in Thailand. This study attempts to fill this void by assessing the Thai consumers' preferences for sustainable rice practice.

The objective of this study is therefore to identify what attributes related to benefits of sustainable rice practice consumers interest and value. This set of information is vital to ensure demand of sustainable rice. Sustainable rice production will be sustainable if the producers follow good stewardship practices, and will only be economically sustainable if producers understand what attributes of sustainability consumers are willing-to-pay for. In addition, the evidence from this study will provide consumer-based marketing and labeling strategies that would be able to increase value of the sustainable rice throughout the rice supply chain. The evidence would also guide to improve marketing by matching the sustainable issues advanced by farmers with those preferred by consumers. All of these would help in guiding more effective investments in sustainable rice practice policies that also consider consumers' preferences.

Methodology

To answer to the objective of this part, this study employed choice experiment question to elicit consumers' preferences on various attributes generated by sustainable rice practice. The attributes cover health, environment, and social dimensions. The health attribute consists of health issue by air pollution due to rice straw burning as this health issue directly affects not only farmers but also consumers. For the environment attribute, this study includes attributes related to biodiversity and greenhouse gasses emission from different rice cultivations. The social attribute focuses on fairness of benefit sharing based on farmer group and social capital generated by different rice practices. The summary of attributes and attribute levels purposed is presented in table 5.11

Table 5.11 Attributes and levels

Attribute	Attribute level
Number of days in which PM2.5 exceeded standard levels (Unit: day)	70 80 90
A share of the money that farmers will receive from the sale of rice	40% 60% 80%
Price of organic jasmine rice (or white rice) per kilogram (Unit: Baht)	30 40 50 60
Level of biodiversity conservation	Low No change High
Decreasing the amount of CH ₄ emissions from changing sustainable rice cultivation to conventional rice cultivation	No change Reduced by 50%
Sustainable rice certification	Yes No

The details of each attribute and its levels are described as follows;

1. The PM2.5 level attribute represents the difference in post-harvest activity between sustainable rice cultivation and conventional rice cultivation. One of the main causes of PM2.5

contamination in the air is from burning rice straw after harvesting. However, for sustainable rice cultivation, burning after harvesting is prohibited. This would correspond to a reduction in the PM2.5 level. According to the World Air Quality Index project (2020), the peak concentration levels of PM2.5 from rice straw burning usually occur from January to May. During that period, the PM2.5 level exceeded the standard level for about 90 days. We use this number as the reference and then design two fictive reductions of the number of days in which the PM2.5 level exceeded the standard level.

2. The second attribute is the money shared by farmers. Nowadays conventional farmers would receive a few shares of the money from the market approximately 40% due to selling to the middleman as paddy rice. On the other hand, sustainable farmers are able to sell directly rice production to consumers, therefore, they can receive benefits more than conventional farmers around 20%. We want to test whether this factor would be able to convince consumers' decision to consume sustainable rice production.
3. The next attribute is the price of rice. This attribute is designed to capture what would be the price at which consumers would accept to buy milled rice (Jasmine rice and white rice). The attribute level covers the domestic average price in 2022-2023.
4. This attribute provides information to consumers that sustainable rice cultivation has a significant impact on the ecosystem because the processes of sustainable rice create a diverse range of habitats that support a variety of species, including fish, plants, amphibians, reptiles, mollusks, crustaceans, and insects. These species serve as sources of food and medicine and play important roles in biological control and nutrient recycling, helping to sustain agricultural production. Our study of biodiversity conservation levels is separated into 3 attribute levels, which are low, no change, and high level. We want to test whether this factor would be able to convince consumers' decision to buy sustainable rice production.
5. For the attribute of the amount of CH₄ emissions reduction by 50%, this attribute presents a process of sustainable rice practice. There is a significant SRP method that can reduce CH₄ emissions by using alternate wet and dry (AWD).
6. The final attribute is the certification of sustainable rice practices. This attribute presents how SRP verified the effect on consumers' decisions. The attribute level contains two situations, which are rice is certified with SRP verify and one with no certification.

The six attributes with their levels create $3^3 \times 2^2 \times 4^1 = 432$ possible combinations. We reduced these possible combinations to 72²³. Next, we randomly paired them to form a choice set with each choice set containing two different combinations and the third choice containing the information of each attribute under a conventional rice product. Note that the first two choices are framed as SRP rice products. The third choice is fixed in every choice set and framed as the conventional rice product. This resulted in 10 different choice sets in total. Note that since, we interest consumers' preferences for two types of rice, which are jasmine rice and white rice, there are two main sets of questionnaires that were differed only by the type of rice. This means one set of questionnaires was framed as jasmine rice product, while another one was framed as white rice product. Beside the difference in framing types of rice, both sets of questionnaires are identical.

Table 5.12 Example of choice set

²³ This is called fractional factorial designs. The design is able to estimate the main effects, but not the interaction effects. The design has properties of orthogonality and balance, whereby each attribute's level occurs in the same or similar frequency as other levels (Zwerina, 1997). We used the macro module developed for choice experiment, experimental design, and conjoint choice analysis in SAS software to arrange this design (Kuhfeld, 2005).

Attributes	Sustainable rice A	Sustainable rice B	Conventional rice
Number of days in which PM2.5 exceeded standard levels (Unit: day)	80 days	70 days	90 days
A share of the money that farmers will receive from the sale of rice	 60 %	 60 %	 40 %
Price of organic jasmine rice (or white rice) per kilogram (Unit: Baht)	60 Bath	50 Bath	30 Bath
Level of biodiversity conservation			
Decreasing the amount of CH4 emissions from changing sustainable rice cultivation to conventional rice cultivation	Reduce 50 %	No change	No change
Sustainable rice certification	No		No
I prefer to choose.....	☐	☐	☐

Survey implementation

The data for this research were gathered through face-to-face interviews conducted in six provinces across the North, Central, and Northeast regions of Thailand. For the North region, the

survey was conducted in Chiang Mai and Nakhon Sawan provinces. The survey was conducted in Nakhon Ratchasima and Udon Thani provinces for the Northeast region. Bangkok and Chonburi provinces were the representative of the consumers for the Central region.

The study focused on consumers who regularly purchase rice products in these provinces. The survey locations were selected based on high population density and included markets, parks, shopping malls, and villages. As a token of appreciation for their time, participants received a local rice product upon completing the entire survey.

Randomly chosen respondents at each location signed a consent form before engaging in one-on-one interviews. To ensure unbiased responses, participants were randomly assigned to answer either jasmine rice product questionnaire or white rice product questionnaire. In addition, the order of attribute presentation was randomized to mitigate the potential bias arising from participants favoring the first issue they read. Subsequently, enumerators verbally reiterated the details of each attribute after participants read the information sheets.

Once consumers confirmed their understanding of the situation, they were asked to respond to ten sets of choice questions. After completing the choice experiment section, respondents proceeded to finish the remaining sections of the questionnaire. In total, 816 consumers took part in the survey, with 419 participating in the jasmine rice survey and 397 in the white rice survey.

Econometric Model and Monetary Valuation

In the preference approach, it is presumed that an individual seeks to optimize utility while considering their income. In this context, the consumer's utility can be defined by the following equation, which represents the utility function (1).

$$U(X_0, y) = U(X_1, y + WTA)$$

where, X denotes the vector encompassing factors associated with consumption conditions, and X_1 is greater than or equal to X_0 . Enhancements in X contribute to an increase in consumer utility (i.e., $\partial U / \partial X > 0$). An individual's expressed preference, in terms of willingness to accept (WTA), refers to the minimum additional income amount that consumers would demand to transition from their current conditions to the new conditions.

We applied the conditional logit model to analyze the choice between alternative situations. Our model is rooted in a random utility model (RUM) where consumers opt for the condition offering the maximum utility. However, the actual utility remains unknown to us; instead, we can only observe the indirect utility function denoted as V . The unobservable component or stochastic element of the utility, denoted as ε , is also unknown. Consequently, the utility can be expressed as follows:

$$U_{ij} = V_{ij} + \varepsilon_i$$

where U represents the utility function. The indirect utility function, observed through choice experiment questions, involves attributes as parameters. Therefore, V can be articulated as a function of the attributes associated with each alternative.

$$V_{ij} = \alpha_i + \beta \mathbf{X}_i, \quad \forall_i \in C$$

where, X represents the vector of k attributes, β is the coefficient vector, α is the alternative-specific constant (ASC), and i denotes an alternative in the choice sets C . The likelihood that a consumer j will choose alternative i is determined by the probability that the utility derived from selecting choice i surpasses that of any other choices. Assuming that the stochastic component follows an independently and identically distributed (IID) Gumbel random variable, the probability of selecting choice i from the available alternatives $(1, 2, \dots, k) \in C$ can be explicitly formulated.

$$P_{ij} = \frac{\exp(\mu(\alpha_i + \beta \mathbf{X}_i))}{\sum_{k \in C} \exp(\mu(\alpha_k + \beta \mathbf{X}_k))}$$

where μ represents a scale parameter that is inversely correlated with the variance of the error term. The likelihood functions of the conditional logit model with a single dataset can be expressed as follows:

$$L_r = \sum_{i=1}^N \sum_{P_i \in C} y_{in} \ln P_{in}(\mathbf{X}_{in} | \boldsymbol{\alpha}, \boldsymbol{\beta})$$

where $y_{in} = 1$ is equal to 1 if a respondent selects choice i , $= 0$ otherwise, n represents the index of respondents from the choice experiment data, and $P_{in}(\mathbf{X}_{in} | \boldsymbol{\alpha}, \boldsymbol{\beta})$ denotes the probability of a respondent choosing choice i .

In case of valuation estimation, following Hanemann (1999), welfare measures obtained from the conditional logit model can be calculated as a marginal rate of substitute (MRS) between interested attribute and marginal utility of income presented as follows

$$MP_k = -\frac{\beta_k}{\beta_p}$$

where MP_k is the value of attribute k . The value of β_p is the marginal utility of income, represented by the coefficient of price, and β_k is coefficient of the attribute that we want to identify monetary value.

Results

Data was obtained from 816 individuals who participated in the choice experiment survey during September to October 2023. The proportion between Jasmine rice and white rice consumption of consumers who participated during this survey is approximately 50:50 percent. Table 5.13 presents the results of the estimation.

Both the jasmine rice and white rice consumption of consumers provide very similar results from conditional logit model in terms of significance level and sign of coefficients. All attributes in both models were significant, suggesting that these attributes would alter consumers' decision on whether or not to accept to buy the sustainable rice products. Starting with number of days in which PM2.5 exceeded standard levels attribute, the coefficient of this attribute in both models is statistically significant with negative sign indicating that consumers emphasize the environmental issues about PM2.5 in rice field. This result is in line with our expectations because consumers

concern air pollution caused by burning rice straws after harvest and it affects to consumers' decisions to consume sustainable rice productions with prohibition of post-harvest burning.

In case of a share of the money that farmers will receive from the sale of rice, the coefficient of this attribute is significant with positive sign suggesting that the consumers are concerned about a share of money to farmers. Particularly, in case of consumers who consume jasmine rice due to the bigger of this variable's coefficient than that of white rice product.

The coefficient of the price jasmine rice is negatively significant in both types of rice. This result indicates that the price of rice effects on consumers' decisions to buy rice. Interestingly, this result demonstrates the coefficient of white rice price that are larger than jasmine rice. Consequently, consumers who purchase white rice are more sensitively with price change than those consume jasmine rice.

The next variable that is also statistically significant is the level of biodiversity conservation. The coefficient is positive effects on consumers' decisions to accept sustainable rice production in both of consumer types. This variable represents the level of biodiversity conservation in rice field that demonstrates a rich array of diverse species, encompassing fish, plants, amphibians, reptiles, mollusks, crustaceans, and insects in the rice field. These varied species not only serve as valuable sources of food and medicine but also play crucial roles in biological control and nutrient recycling. These ecological functions contribute significantly to sustaining agricultural production.

For greenhouse gas emissions caused by CH₄ issue, this variable is the least impact on consumers' decisions to accept sustainable rice production. The size of coefficient is smaller than all variables. However, it is a statistically significant negative effect that means consumers also are concerned about the GHG emissions.

The last variable that is significant is the sustainable rice certification. As expected, this variable is statistically significant with positive sign suggesting that the consumers are more willingness to pay if rice product are guarantee by SRP verify.

Based on the findings from the choice experiment survey, it appears that factors directly affecting consumers, such as the portion of money farmers receive from rice sales, along with environmental considerations such as biodiversity, CH₄ emissions, and PM_{2.5} levels, are crucial elements that could motivate consumers to purchase for sustainable rice production.

Table 5.13 Results of the estimation of the consumers' choice experiment

Variable	Jasmine rice	White rice
Number of days in which PM2.5 exceeded standard levels (Unit: day)	-0.009*** (0.003)	-0.006** (0.003)
A share of the money that farmers will receive from the sale of rice	0.155*** (0.002)	0.010*** (0.002)
Price of organic jasmine rice (or white rice) per kilogram (Unit: Baht)	-0.010*** (0.002)	-0.017*** (0.003)
Level of biodiversity conservation	0.542*** (0.039)	0.545*** (0.040)
Decreasing the amount of CH4 emissions from changing sustainable rice cultivation to conventional rice cultivation	-0.002*** (0.001)	-0.006*** (0.001)
Sustainable rice certification	1.001*** (0.060)	1.04*** (0.062)
Alternative A	0.325*** (0.119)	0.667*** (0.121)
Alternative B	0.430*** (0.123)	0.753*** (0.125)
Log-likelihood	-6,134.134	-5,728.204
Observations	12,570	11,910
Number of samples	419	397

Note: Standard errors are in parentheses.

***, **, and * represent significance levels at 1%, 5%, and 10%, respectively.

To identify what attributes would receive more attention from consumers, we use the results of the estimation presented in Table 3 to calculate the monetary value of each attribute. The monetary values are presented by Table 5.14

Table 5.14 Monetary value of each attribute elicited from consumer's choice experiment

Variable	Value (Baht per Kilogram)	
	Jasmine Rice	White Rice
Number of days in which PM2.5 exceeded standard levels (Unit: day)	-0.84** (0.40)	-0.37* (0.22)
A share of the money that farmers will receive from the sale of rice	1.50*** (0.28)	0.62*** (0.11)
Level of biodiversity conservation	52.28*** (11.42)	32.68*** (4.71)
Decreasing the amount of CH4 emissions from changing sustainable rice cultivation to conventional rice cultivation	-0.23** (0.10)	-0.33*** (0.08)
Sustainable rice certification	97.15*** (20.72)	62.56*** (8.49)

Note: Standard errors are in parentheses. ***, **, and * represent significance levels at 1%, 5%, and 10%, respectively.

The monetary values are estimated using Krinsky Robb (parametric bootstrap) method (Hole, 2007). Table 5.14 reveals the results. The second and third columns present the marginal monetary values calculated based on results from conditional logit models of jasmine rice choice experiment question and white rice choice experiment question.

For both types of rice, SRP certification seems to be the most important factor for consumers to decide to buy the SRP rice because the value placed by consumers on this attribute is the highest. This signals the concern of moral hazard as the certification would help them to identify exactly whether they purchase real SRP rice. The second important factor that would convince consumers to buy SRP rice is biodiversity. The higher the biodiversity level in rice fields is the higher chance for consumers to buy the SRP rice. This pattern is the same for both types of rice.

For the third important factor, the factor is different between jasmine rice and white rice. Jasmine rice consumers seem to care more about how much share farmers received from price of rice sold in the markets. On the other hand, white rice consumers significantly placed less value on this factor than jasmine rice consumers. The difference is about 141 percent (1.50 Baht per kilogram of jasmine rice versus 0.62 Baht per kilogram of white rice).

The attributes related to environment, which are GHG emissions and level of PM2.5, seem to receive relatively less attention from consumers when buying both types of rice. This can be presented by the amount of willingness to pay of these attributes are the lowest among attributes.

Conclusion

This part presents the consumers' preference when buying rice. We develop various conditions of sustainable rice and conventional rice through variables that would be different between sustainable rice practice and conventional rice practice. These variables cover level of GHG emissions, biodiversity, air pollution, fairness, SRP certification, and price of rice. In addition, jasmine rice and white rice, which are the common rice consumed by Thai consumers, are added to our analysis with choice experiment questions.

The results show that generally consumers seem to prefer sustainable rice practice to conventional rice because all benefit generated from sustainable rice practice is significantly accepted and contains higher monetary value than those of conventional counterpart. When considering the details of each variable from sustainable rice practice, SRP certification is the most important factor determined consumers to buy the sustainable rice. The next factor that consumers pay attention on when decided to buy rice is biodiversity level. These first and second important factors are the same for both jasmine rice buyers and white rice buyers. However, jasmine rice buyers would consider more about the fairness than white rice buyers. If they know that farmers receive higher share from price of rice, it is the higher chance they will buy jasmine rice with this condition. For the environment factors, level of GHG emissions and level of PM2.5, consumers also see these factors as important factors when decide to buy rice. These two factors receive relatively less attention compared to other factors.

The results from this study would help to provide the information of what consumers care when they purchase rice. This information would help to develop information package and label to promote sustainable rice practice that generates many benefits and fit with interest of consumers.

5.5 Summary

This part highlights the effects of sustainable rice practice on household economy compared to conventional rice practice. The data from household survey presents that the rice yields of sustainable rice and conventional rice practice are similar. The main difference between these two rice practices is the cost of cultivation. Our data point out that the cultivation cost of sustainable rice practice is lower than that of conventional rice practice for both regions. The main variable that significantly reduces the cultivation cost of sustainable rice practice is chemical fertilizer cost. With similar rice yield compared to the conventional rice and lower cost of cultivation, sustainable rice farmers in both Central and Northeast regions earn more profit from selling rice compared to conventional rice farmers.

While the use of pesticides in rice cultivation increases productivity, it also leads to higher health risks for people as pesticide concentrations in the environment increase. Especially for farmers who are directly exposed to pesticides. Not only farm workers who spray pesticides, but also those who mix and load the pesticides, sow pesticide seeds, weed and harvest sprayed crops, and clean and dispose of the containers (Tago et al., 2014). The pesticides most commonly used by the farmers could cause symptoms such as nausea, vomiting, chest tightness, malaise, decreased urination, kidney failure, lung swelling, itchy rash, skin irritation, toxicity, and pulmonary fibrosis. Prolonged exposure to this substance has also been associated with Parkinson's disease. Some substances can cause severe nerve irritation and easily lead to death (Sangchom, 2013). Measured by the average expenditure on pesticides per hectare, the number of pesticides used in SRC was less than half of the amount used in CP. The difference ranged from 5% to 78% of the average expenditure. In our survey, a statistical test showed a significant difference between the two proportions at a 5% significance level. The 10 common symptoms associated with cultivation included headache, eye irritation, skin irritation/burns, fever, diarrhea, allergies, sore throat, joint pain, nausea, and muscle twitching/pain. Both household groups had the same proportion of each symptom. Joint pain was the most commonly reported symptom among sampled households, followed by headache and fever. Nevertheless, none of these symptoms were fetal or chronic health effects.

In addition, when we predict rice yields under sustainable rice and conventional rice practices over the next 38 year, 2022-2050, the predictions reveal that sustainable rice practice would provide significant more rice yield than conventional practice especially in the Northeast

region where the rice yield under sustainable rice practice would be higher by almost two-fold than the conventional rice practice during such period. This implies that with the lower cost of production and increasing in yield, sustainable rice practice would be able to generate more profit to the Northeast farmers than conventional rice practice. For the Central region, the story is a bit different. Specifically, rice yield slightly decreases as SRP areas increase for the Central region. However, rice yield in the Central region would begin to increase after year 2040 as SRP areas increase. Again, with lower cost of cultivation and somewhat increase in rice yield, Central rice farmers would gain more profit from selling rice if they adopt sustainable rice practice even the profit gain would not be as high as that of the Northeast farmers.

6.1 Introduction

In Thailand, the landscape predominantly comprises a mosaic of agricultural land use. Rice fields occupy the largest proportion of this land use and are known to support high levels of biodiversity. This is due to the diverse management regimes used in the farming process, which can quickly alter the conditions of the rice fields based on factors such as water regime, drainage, temperature, soil type, topography, and location. Each crop rotation in the rice fields encompasses a diversity of habitats that are subject to rapid change, providing a variety of niches for diverse rice forms. These habitats are ephemeral in nature, meaning that they are short-lived, which contributes to the high levels of biodiversity in rice fields. The rice agriculture practices have been well documented to support high levels of biodiversity (Ediridinghe and Bambaradeniya 2006; Bambaradeniya et al. 2004). The management of monoculture rice crops, from seedling to harvesting, has a significant impact on the ecosystem of the rice field. By changing the conditions of the rice field, the farming process creates a diverse range of habitats that support a variety of species. This demonstrates the close relationship between agriculture practices and biodiversity in Thailand, with rice agriculture playing a crucial role in maintaining the country's diverse ecosystems.

Rice fields are home to diverse species, including fish, plants, amphibians, reptiles, mollusks, crustaceans, and insects. These species serve as sources of food and medicine and play important roles in biological control and nutrient recycling, helping to sustain agricultural production. Rice fields also serve as semi-natural nurseries for aquatic biodiversity, such as insects, amphibians, and fish (Kim, Lee, and Jang, 2011). A high level of biodiversity in rice fields promotes trophic linkages, reduces pest damage, and enriches soil fertility (Ediridinghe and Bambaradeniya, 2006). Conservation of invertebrate and microbial biodiversity is crucial for the sustainable production of rice. However, agronomic practices such as fertilization and pesticide use can negatively impact biodiversity, leading to loss of nutrients, blooms of unicellular algae, a proliferation of freshwater snails and mosquito larvae, and other fertility-related problems (Roger, Heong, and Teng, 1998). Conventional rice farming practices, relying heavily on chemical fertilizers and pesticides, pose a threat to the biodiversity and functioning of ecosystem services in rice fields. Additionally, burning rice straws after harvesting season due to labor shortage and

convenience also contributes to this issue. To address environmental and health concerns, some farmers and consumers are switching to organic farming practices, utilizing ecosystem services for pest management and enhancing functional biodiversity (Wachter and Reganold, 2014).

The biodiversity of organisms at the landscape level is strongly linked to landscape structure, composition, and arrangement. These landscape variables are crucial for the ecological processes and services of the landscape. To fully understand the biodiversity of organisms in rice fields, it is necessary to consider the spatial and temporal scales of the surrounding landscape as well as its vertical composition. Adjacent mosaic ecosystems can provide a source of biodiversity for rice fields by offering heterogeneity and serving as refugia for flora and fauna during regime shifts (Dermiyati and Niswati, 2014). The interactions between organisms and environmental factors, including agronomic practices, shape the structure of rice field ecosystems, which are made up of diverse populations in a trophic cascade (Simpson et al., 1994). Therefore, a comprehensive evaluation of the relationship between biodiversity and landscape characteristics is essential for conserving biodiversity in the rice field ecosystem. The main objectives of this part are 1) to assess the biodiversity of insects in the rice field and compare them between the conventional and SRP farming practices, 2) to assess the diversity of vegetation, especially trees, that existed on the rice fields and compare them between the conventional and SRP.

For the first objective, the study encompasses three frameworks to achieve the objective: 1) landscape analysis for sampling scheme, 2) fieldwork for insect diversity sampling, and 3) modeling of insect biodiversity at the landscape scale. The landscape analysis framework examines the agricultural landscape's characteristics, configuration, and ecological context in Northeast and central Thailand. The results of the landscape analysis then inform the design of the fieldwork sampling scheme. The fieldwork for insect sampling focuses on collecting insects from the rice fields, which serve as the baseline for the local biodiversity data. The data from the first two frameworks are then combined and used as input for the biodiversity in the landscape modeling framework, which provides the relationships between biodiversity and the landscape.

For the second objective, which aims to observe the diversity of trees that remain on the rice field, the data were obtained from the household questionnaire survey, field survey of trees on farms, and secondary data retrieved from relevant authorities.

6.2. Landscape Analysis for sampling schemes

The study area of this project encompassed the Northeast and central regions of Thailand, which were selected as they represent a diverse range of geographical, climatic, and agricultural features. To ensure the representativeness of the sample sites, stratified clustered sampling methods were used, which considered land use matrix, distance to forest, and land use diversity indicator.

The stratified clustered sampling method is a well-established technique in statistical sampling, which involves dividing the study area into different strata and selecting sample sites from each stratum to ensure that the sample is representative of the population being studied. The number of clusters was determined using the elbow's method, which is a technique that identifies the optimal number of clusters being stratified. After the landscape was stratified into different clusters, each rice farming land use unit was then assigned to the stratified land use clusters.

For northeast Thailand, the optimal number of strata identified was eight, as illustrated in Figure 6.1. In this region, the rice paddies can be categorized as follows:

1. Rice paddy in an urban-dominant landscape
2. Rice paddy in a rangeland-dominant landscape
3. Rice paddy in a wetland-dominant landscape
4. Rice paddy in a field crop-dominant landscape
5. Rice paddy in a plantation-dominant landscape
6. Rice paddy in a forest-dominant landscape
7. Rice paddy in an isolated forest landscape
8. Large patch of rice paddy

While central Thailand had a smaller number of optimal strata, with five strata identified (Figure 6.2). In the central region, the rice paddies can be categorized as follows:

1. Rice paddy in the tree and forest-dominant landscape
2. Large patch of rice paddy
3. Rice paddy in a mixed land use/urban-dominant landscape
4. Rice paddy in a forest-dominant landscape
5. Rice paddy in a field crop-dominant landscape

This variation in the number of strata selected for each region reflects the differences in the geographical and environmental features between the two regions, highlighting the need for a tailored approach to sample selection based on the specific characteristics of the study area.

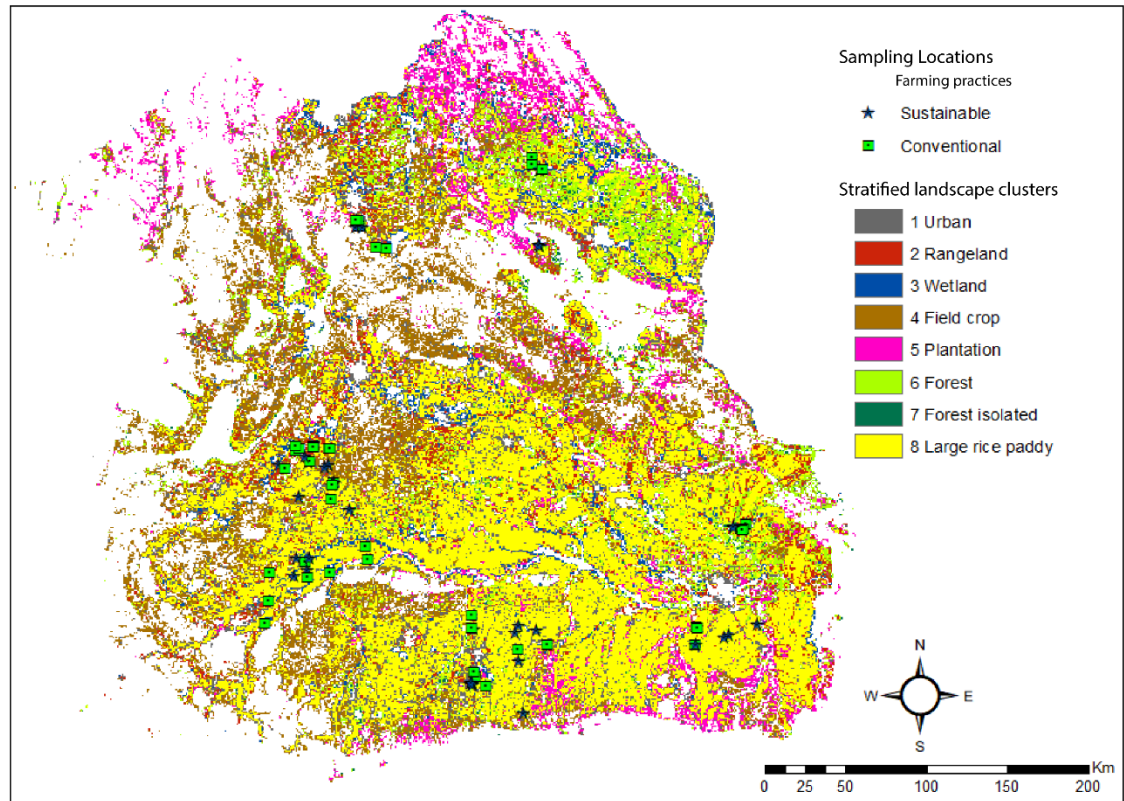


Figure 6.1 The landscape characteristic of rice paddies in northeast Thailand was clustered into eight strata used as a guild line for the field surveyed. The strata were used as the ecotype to represent biodiversity assessment.

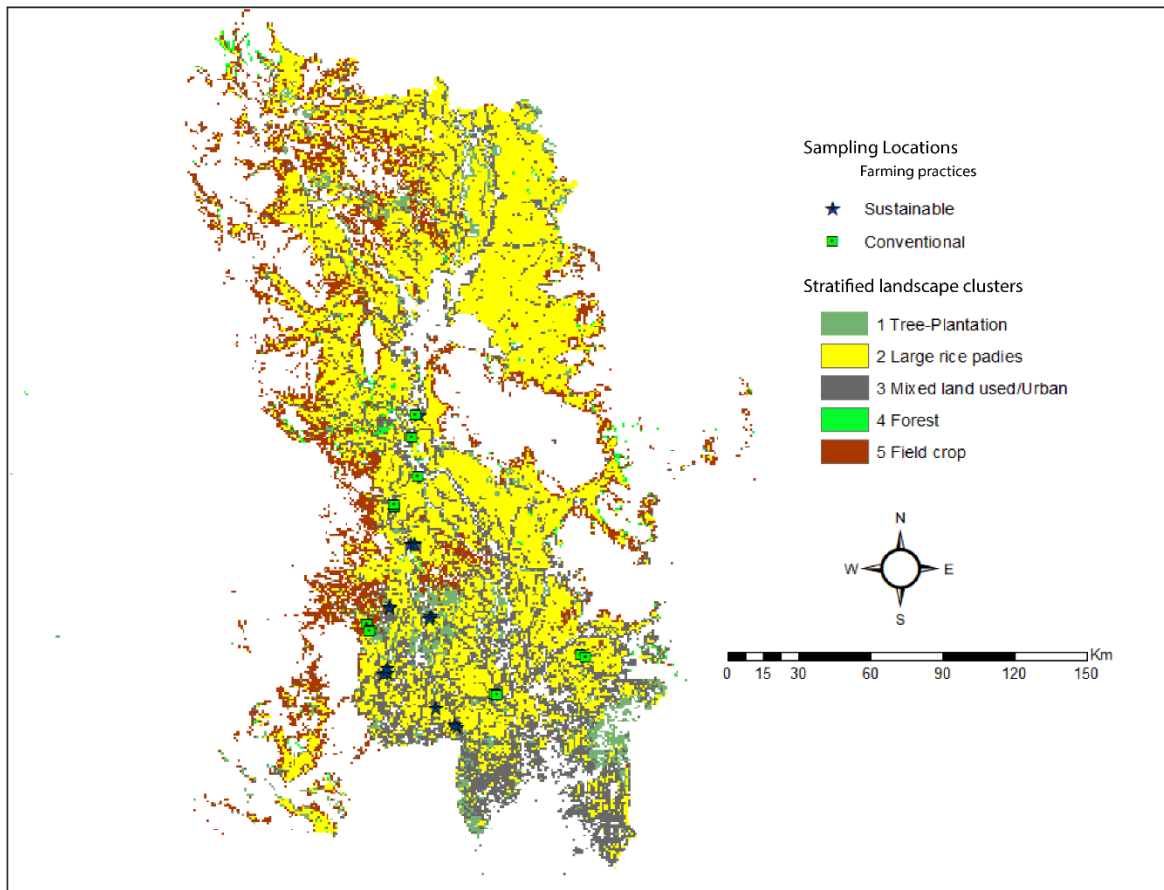


Figure 6.2 The landscape characteristic of rice paddies in central Thailand was clustered into five strata used as a guild line for the field surveyed. The strata were used as the ecotype to represent biodiversity assessment.

6.3. Insects sampling

In total, there were 84 and 26 sampling sites in Thailand's Northeast and central regions, respectively. In the northeastern, sampling sites consist of 45 sites practicing conventional rice farming and 39 sites practicing Sustainable rice farming (SRP), while the sites in the central region comprise 13 conventional rice farming and 13 sites of SRP practice, as illustrated in Figure 6.1 and Figure 6.2. The researchers employed a vacuum sampler at each sampling site to collect aerial insects living in rice fields. The insects were then examined and identified, with the number of individuals of each species being recorded. This process provided the researchers with valuable data on the diversity and abundance of insect populations in the study area, which could then be

analyzed to understand better the region's ecology and the impact of different farming practices on insect populations, diversity, and community.

The identification of insect species and feeding guilds/functional groups was carried out by the Department of Entomology, Faculty of Agriculture, Khon Kaen University. This process involved a detailed examination of each insect's morphological characteristics and an analysis of their feeding habits and ecological roles. By identifying the different species of insects present in the study area, the researchers could better understand the impact of farming practices on the diversity of insect populations and their ecological roles in the region's ecosystem.

6.4. Quantifying biodiversity for the insects

The diversity of insects at each site was evaluated using species richness, the Shannon-Wiener Diversity index, and the Simson Diversity index. The evaluation followed a sampling approach from landscape characteristics, farming practices, biodiversity, and ecological function.

(

). The biodiversity of local sites was recorded during field studies and analyzed based on different farming practices.

Table 6.1 Biodiversity and functional diversity sampling schemes.

Landscape characteristics	Farming practices	Biodiversity	Biodiversity function
Distance to a forest	Conventional	Insects and others arthropod lives in rice paddy	- Herbivores (pest)
Dominance land used			- Predators
Land use diversity			- Decomposers
Climate	SRP		- Parasite
			- Pollinator

Firstly, species richness, the total number of species present in each site, and each rice practice were counted and compared. However, the number of species (species richness) alone is not the best approach for biodiversity study. Species evenness is a term used to describe how evenly distributed the individuals are among the different species in a community or ecosystem. It measures whether there is a similar number of individuals for each species or whether one or a few species dominate the community. Evenness is related to, but distinct from, the concept of diversity.

A diverse community can have low evenness if one or a few species are very abundant, while a less diverse community can have high evenness if the species are evenly distributed. The Shannon-Wiener Diversity Index takes into account both diversity and evenness, so it provides a more comprehensive view of the biodiversity of a community or ecosystem. Therefore we employed the Shannon-Wiener biodiversity index to quantify and model biodiversity at the regional scale, linking it with ecosystem services in the study area. The Shannon-Wiener biodiversity is a way to measure the diversity of a group of species in an ecosystem. It considers the number of different things and how evenly they are distributed. A higher diversity index indicates a greater variety of things and a more even distribution, while a lower diversity index indicates fewer things or an uneven distribution. It's a useful tool for ecologists and other scientists studying biodiversity.

Furthermore, another biodiversity index used in this study is Simpson's index. The Simpson Diversity Index is a widely used quantitative measure of diversity in an ecological community. It calculates the probability that two randomly selected individuals from a given community will belong to the same species. The index is expressed as a value between 0 and 1, where 0 indicates no diversity (i.e., all individuals belong to the same species) and 1 indicates maximum diversity (i.e., all species are represented in equal numbers). The index can be used to compare the diversity of different communities or to track changes in diversity over time. Higher values of the Simpson Diversity Index indicate greater diversity within a community, whereas lower values suggest that a few species dominate the community. The Simpson Diversity Index is widely used in ecology, conservation biology, and environmental management to assess human activities' impact on biodiversity, prioritize conservation efforts, and monitor ecosystem changes over time.

The Shannon and Simpson index measures diversity in an ecological community but differs in how they account for species richness and evenness. The Shannon Diversity Index considers both the number of species present in a community (species richness) and the relative abundance of each species (species evenness). The Shannon Diversity Index ranges from 0 to infinity, with higher values indicating greater diversity. This index is sensitive to species richness and evenness changes, making it a valuable tool for comparing the diversity of different communities. The Simpson Diversity Index, on the other hand, is primarily a measure of dominance or concentration within a community. It is based on the probability that two randomly selected individuals from a community belong to the same species. The Simpson Diversity Index ranges from 0 to 1, with higher values indicating greater dominance or concentration within the community. The index is

more sensitive to changes in the dominant species than the number of species or their evenness. The Shannon Diversity Index is more sensitive to species richness and evenness changes. At the same time, the Simpson Diversity Index is more sensitive to changes in dominance or concentration within a community. Both indices help assess biodiversity and can provide valuable information for conservation and management purposes.

To be able to quantify species richness and diversity indices from the field observation data and compare them among the study sites, the rarefaction curves method was used. Rarefaction curves were used to alleviate the effect of unequal sampling sites on the species richness and biodiversity. It is a graphical representation of the relationship between the number of individuals or samples and the number of species observed. It is a way to estimate the number of species in a community if a smaller number of individuals were sampled.

A rarefaction curve is created by randomly sampling the number of individuals in a community without replacement, and the number of species in each subsample is recorded. The process is repeated, with the number of individuals in the subsample increasing each time until all individuals in the community have been sampled. The curve is then plotted with the number of individuals sampled on the x-axis and the number of species observed on the y-axis. Rarefaction curves are commonly used to compare the diversity of different communities and to estimate the completeness of sampling.

6.5. Spatial Modeling for Biodiversity of the insects

One another task of this study is to enhance the understanding of insect diversity at the landscape level. We employ a machine learning approach, specifically the randomForest method, to achieve this aim. We utilize land use, rice farming practices, and climate data to predict spatially explicit biodiversity indices in Thailand's central and northeastern regions. The modeling process integrated a comprehensive set of covariates, including diverse landscape metrics such as land use density, distance to the nearest patch of specific land use, and climatic variables derived from Worldclim (Fick and Hijmans, 2017). These covariates were employed to develop separate models for Thailand's central and northeastern regions, employing the randomForest method as the modeling technique.

The resulting models were then used to spatially predict the study area's biodiversity indices at the landscape level. Predictions were made using current and future land use scenarios

to test the robustness of the models. The future scenarios were based on four different land use change models, including predictions for 2025, 2030, 2035, 2040, and 2045. Overall, this modeling approach provides a powerful tool for predicting insect diversity at the landscape level and can be used to inform conservation and management strategies in the study area. The use of machine learning methods like randomForest can help identify critical areas for conservation and target specific management practices to enhance biodiversity in agricultural landscapes.

6.6. Summary of Insects' diversity surveys

In this study, for northeast Thailand, a total of 20,101 individuals of organisms were found from the survey of 84 sampling sites. These insects were classified into 127 families, 210 genera, and 343 species. The summary of sample data separated by strata and rice farming practices is shown in Table 6.2.

For the central regions, a total of 49,323 individuals of organisms were found from the survey of 79 sampling sites. These insects were classified into 79 families, 63 genera, and 157 species. The summary of sample data separated by strata and rice farming practices is shown in Table 6.3. Only 3 out of 5 landscape strata of this region were sampled due to the limitation of farmer's contract and permission.

Table 6.2 Total number of families, genera, and species of insects across sampling sites from rice paddies in each stratum and rice farming practices in the northeastern region of Thailand. NA indicates no sampling effort was made.

Strata	Practices	number of Families	number of Genera	number of Species
1 Urban	Conventional	34	40	47
	SRP	36	38	41
2 Rangeland	Conventional	74	93	128
	SRP	56	67	71
3 Wetland	Conventional	48	54	67
	SRP	24	19	22
4 Field crop	Conventional	NA	NA	NA
	SRP	39	44	53
5 Plantation	Conventional	37	36	42
	SRP	26	29	34
6 Forest	Conventional	60	77	94

	SRP	60	79	98
7 Forest Isolates	Conventional	22	22	27
	SRP	NA	NA	NA
8 Large rice paddies	Conventional	87	123	156
	SRP	88	123	176

Table 6.3 Total number of families, genera, and species of insects across sampling sites from rice paddies in each stratum and rice farming practices in the central region of Thailand.

Strata	Practices	number of Families	number of Genera	number of Species
1 Plantation	Conventional	23	30	34
	SRP	21	31	34
2 Large rice paddies	Conventional	38	70	86
	SRP	45	71	98
3 Mixed land used-Urban	Conventional	37	54	69
	SRP	34	59	74

6.7. Observed Species Richness and diversity indices of the insects

In the northeastern region, the species richness and diversity indices were quantified and presented in Figure 6.3. The results showed that conventional farming had a mean and standard error (SE) of species richness of 15.29 (SE 0.48), a mean Shannon diversity index of 2.14 (SE 0.03), and a mean Simpson diversity index of 0.81 (SE 0.008). In comparison, SRP had values of 14.88 (SE 0.45), 2.17 (SE 0.04), and 0.82 (SE 0.01) for species richness, Shannon diversity index, and Simpson diversity index, respectively. The results showed no significant difference between conventional and SRP, suggesting that in the northeastern region, both rice farming practices are likely to support biodiversity and ecosystem balance at the same level.

In the central region, the species richness and diversity indices were quantified and presented in Figure 6.4. The results showed that conventional farming had a mean of species richness of 15.36 (SE 0.92), a Shannon diversity index of 1.73 (SE 0.09), and a Simpson diversity index of 0.70 (SE 0.03). While SRP had values of 15.65 (SE 0.97), 1.38 (SE 0.13), and 0.54 (SE 0.049) for species richness, Shannon diversity index, and Simpson diversity index,

respectively. Again, in the central region, species richness, Shannon, and Simpson diversity index did not show a significant difference between the farming practices.

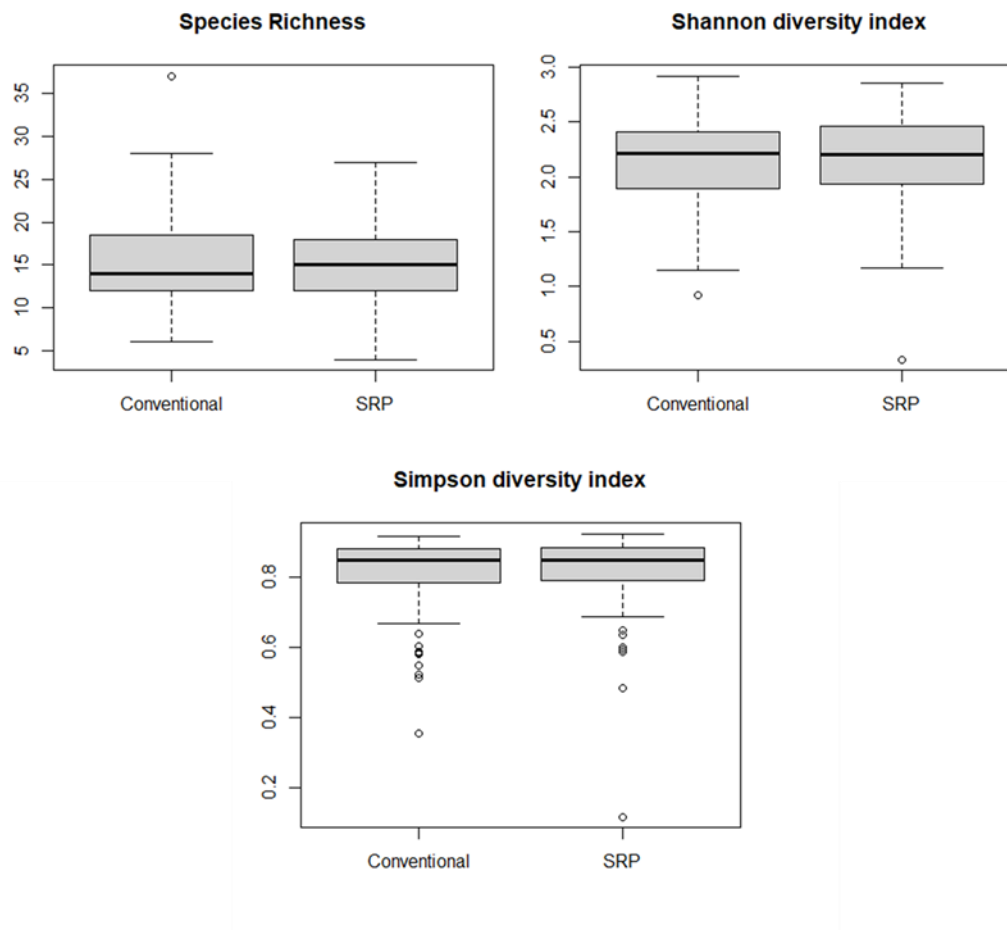


Figure 6.3 Observed species richness and biodiversity indices consisting of Shannon and Simpson diversity indices from sampling sites in the northeastern region of Thailand. The boxplots compare each observed sample index between conventional practice and SRP.

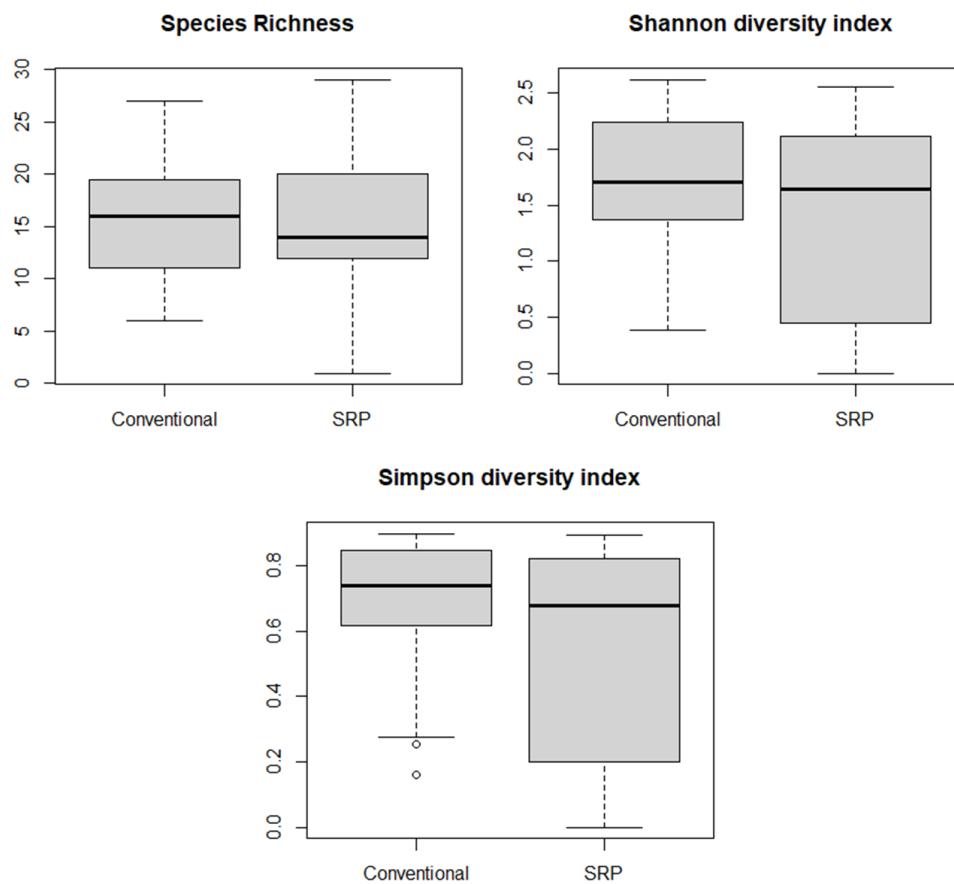


Figure 6.4 Observed species richness and biodiversity indices consisting of Shannon and Simpson diversity indices from sampling sites in the central region of Thailand. The boxplots compare each observed sample index between conventional practice and SRP.

6.8. Estimated pooled biodiversity; rice farming practices and geography has a different impact on biodiversity.

Although, at the sampling site scale, the species richness, Shannon, and Simpson diversity index showed no significant difference between the conventional and SRP farming practices in both the Northeast and Central of Thailand as demonstrated in section 6.6, we further investigated the pool biodiversity of insects in each region. We estimated the pool biodiversity of insects to understand the biodiversity pattern at a larger scale of the northeastern and central regions. We employed rarefaction curves to estimate species richness, beta biodiversity, Shannon diversity index, and Simpson diversity index using pooled samples from both conventional rice farming and sustainable rice farming practices (SRP). These curves were utilized to assess the rate of change in biodiversity as the sample size increased, mitigating any bias caused by unequal sample sizes, aggregated geographic distribution, and environmental gradient variations between farming practices.

In the northeastern region of Thailand, the rarefaction curve in Figure 6.5 illustrates a comparison of various biodiversity metrics between conventional rice farming practices and the SRP. The metrics evaluated include species richness, beta-biodiversity represented by the Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index. Regarding species richness, it is observed that conventional rice farming exhibits a higher level compared to the SRP practice. However, when considering the Shannon and Simpson diversity indices, the SRP demonstrates a higher level. These findings suggest that, in the Northeast, while conventional rice farming supports a greater number of species, the SRP practice promotes a more diverse and balanced ecosystem, as reflected by the higher values of the Shannon and Simpson diversity indices.

In the central region, in contrast to the northeastern, our findings from Figure 6.6 revealed that species richness and beta diversity were higher in SRP practices. While the Shannon and Simpson diversity indexes were higher in conventional farming, suggesting a greater diversity and balance in the ecosystem.

These results highlight regional variations in biodiversity patterns and indicate that the choice between conventional farming and SRP practices can have differing impacts on biodiversity depending on the specific geographic location.

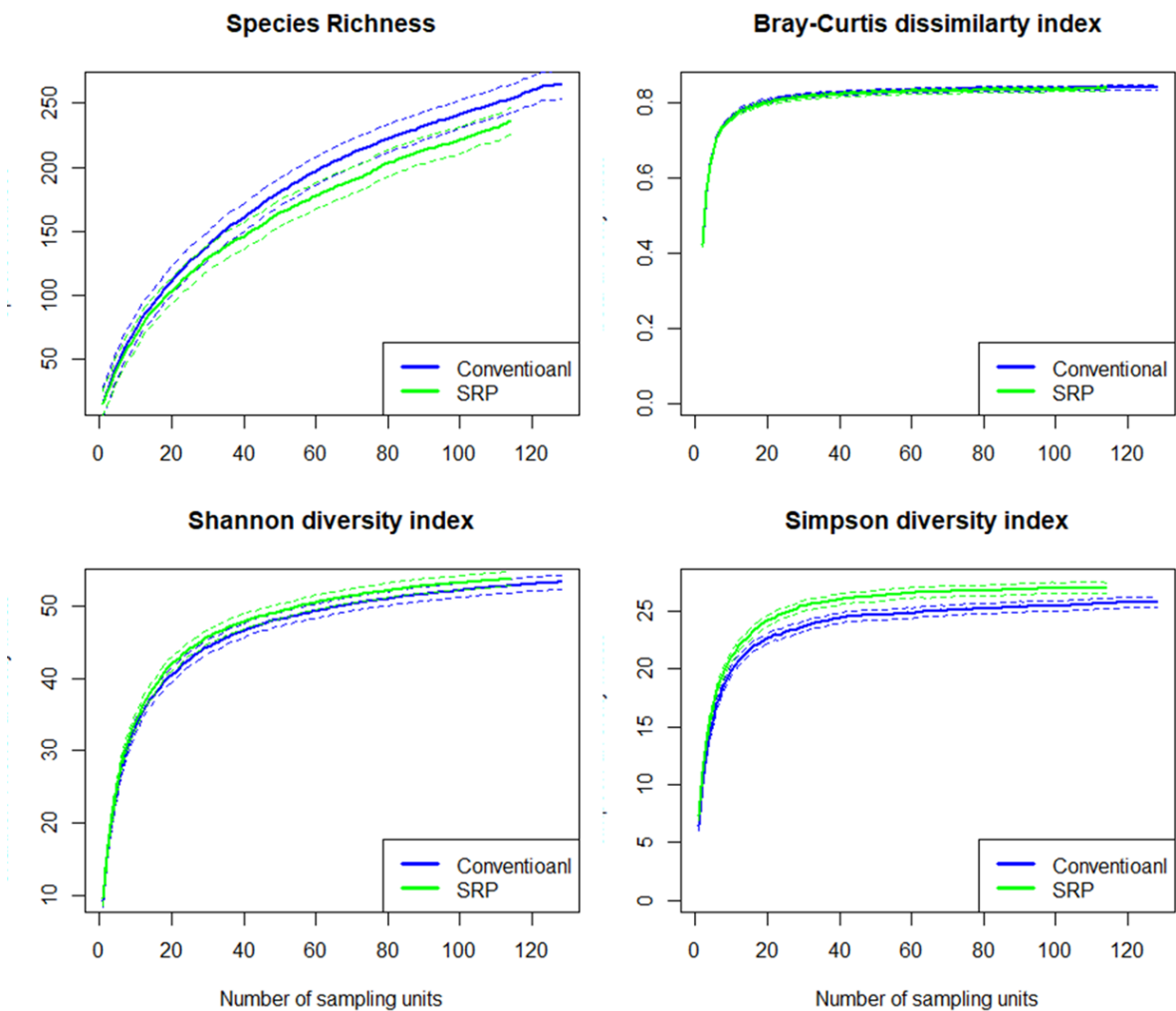


Figure 6.5: Rarefaction Curve comparing Species Richness, Beta-biodiversity (Bray-Curtis Dissimilarity Index), Shannon Diversity Index, and Simpson Diversity Index between Conventional Farming Practice and the SRP in the Northeastern Region of Thailand.

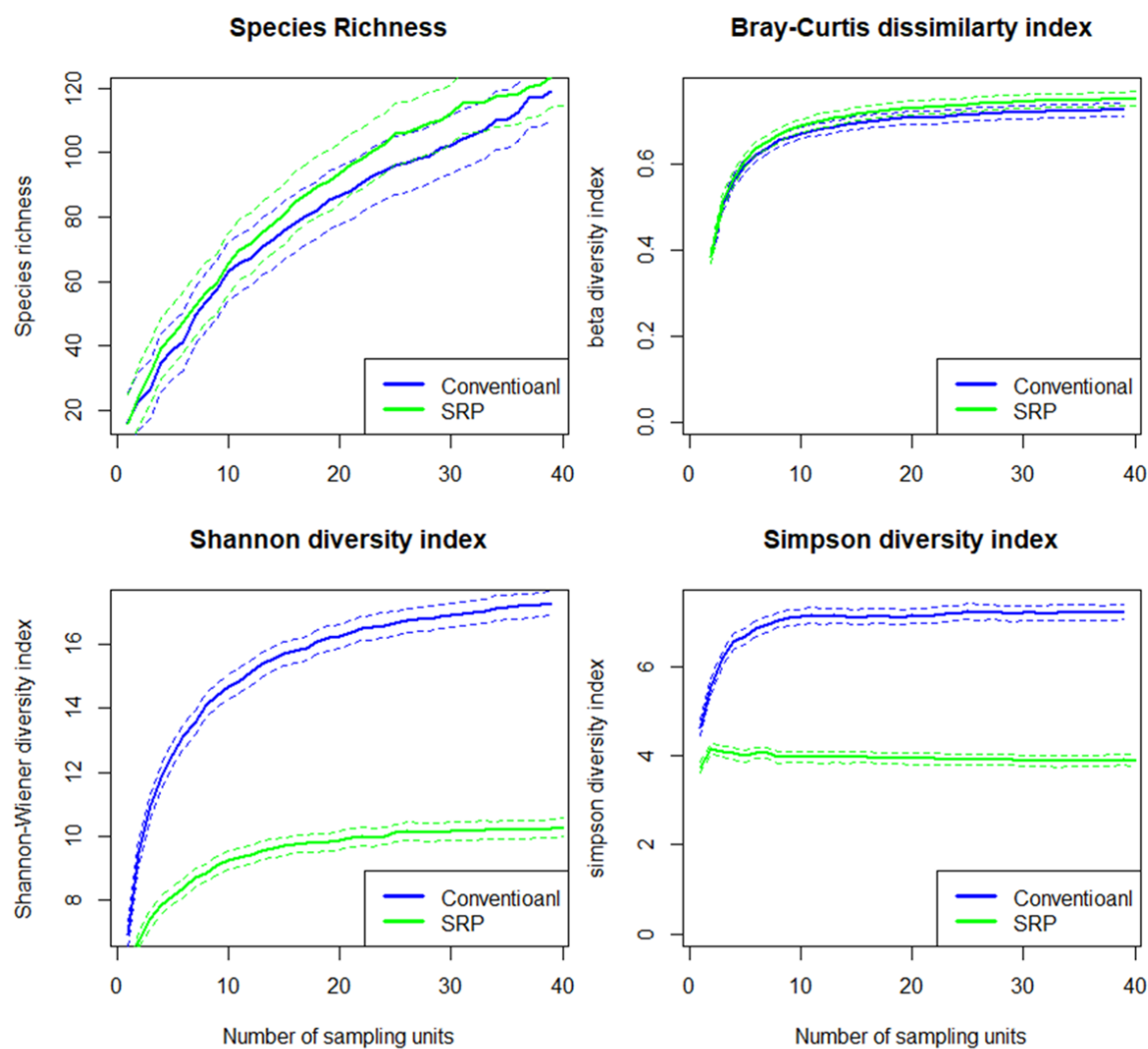


Figure 6.6: Rarefaction Curve comparing Species Richness, Beta-biodiversity (Bray-Curtis Dissimilarity Index), Shannon Diversity Index, and Simpson Diversity Index between Conventional Farming Practice and the SRP in the Central Region of Thailand.

6.9. Species Richness and diversity indices among functional groups of Insects

In addition to analyzing the overall species richness and diversity indices of the insect community, we also focused on specific functional groups of insects. To evaluate the species richness within functional groups, we again employed rarefaction methods to estimate rarified species richness for each functional group. Our analysis encompassed three functional groups, i.e., predators, pests, and decomposers. Although some insects were functionally classified as pollinators and parasites, the number of samples was too low and prohibited the analysis, and we

therefore omitted these two functional groups. For each agricultural practice, we calculated the rarified species richness and diversity indices.

In the northeastern region, in the predator functional group, we found that the conventional farming practice exhibited higher species richness than SRP. However, the other diversity indices did not show a significant difference, as indicated in Figure 6.7. For the pest functional group, we observed that conventional farming had higher species richness compared to SRP. However, the other SRP practices demonstrated higher Shannon and Simpson diversity indices, as depicted in Figure 6.8. Unfortunately, the decomposer group had insufficient samples to calculate rarified biodiversity indices. Nevertheless, we observed that species richness was higher in SRP than conventional farming for this functional group (Figure 6.9).

Moving on to the central region, we made an interesting discovery: the farming practice of SRP resulted in greater species richness, beta diversity, Shannon, and Simpson index in the predator functional group, contrasting with the findings from the Northeast. Figure 6.10 highlighted a significantly higher value of the indices in SRP than the conventional rice practice. For the pest functional group, conventional farming exhibited higher species richness than SRP in the central region. However, the conventional practices showed higher Shannon and Simpson diversity indices for the pest functional groups, as illustrated in Figure 6.11.

These results suggest that the SRP farming practice may promote higher species richness in certain regions and functional groups but may not be as effective in others. These findings have important implications for the management of rice paddies and the conservation of biodiversity in agricultural landscapes. Further research is necessary to explore the underlying mechanisms driving these patterns and to develop effective strategies for promoting biodiversity conservation in rice farming.

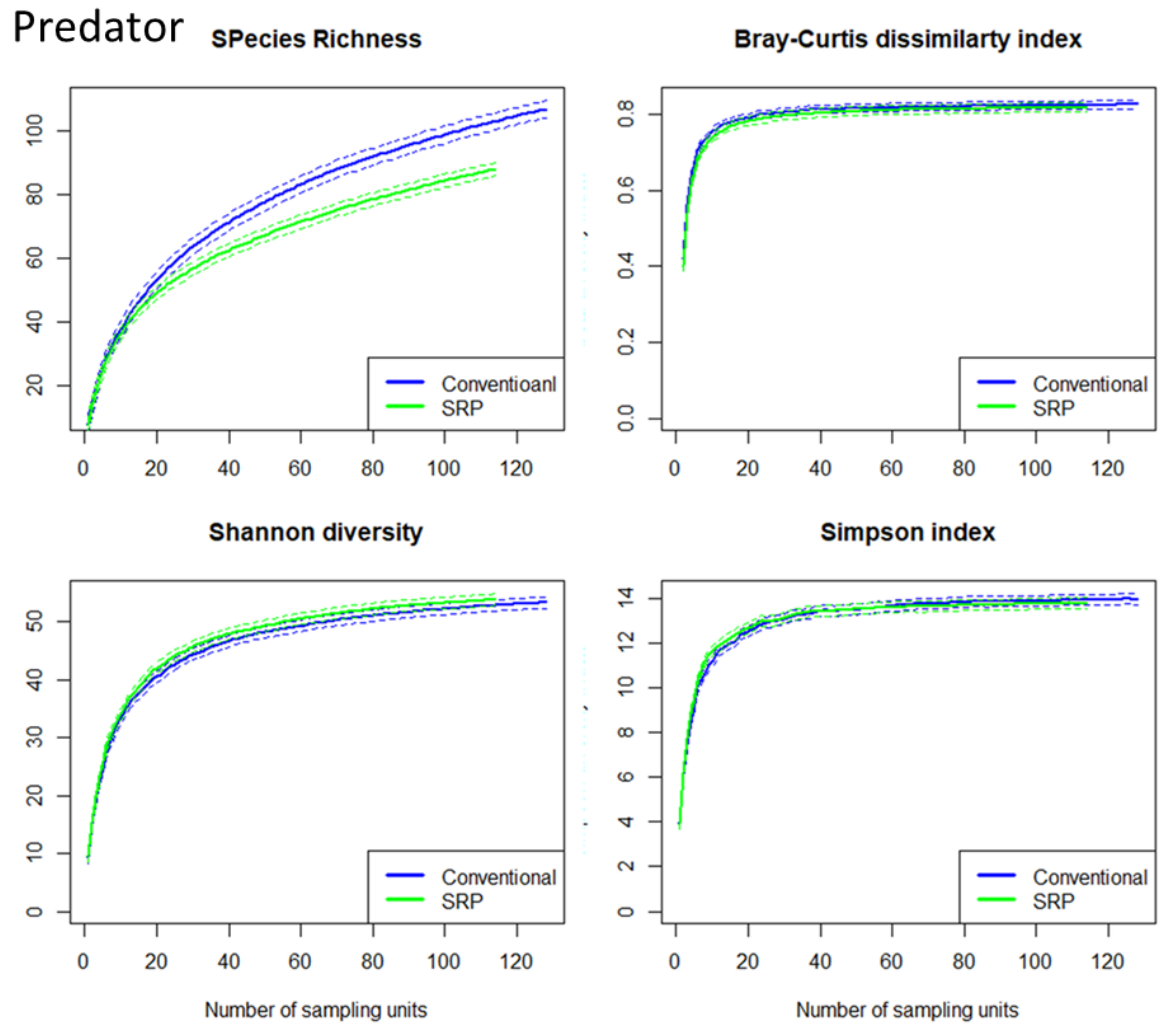


Figure 6.7 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index of predator function groups between conventional farming practice and SRP in the northeastern region of Thailand

Pest

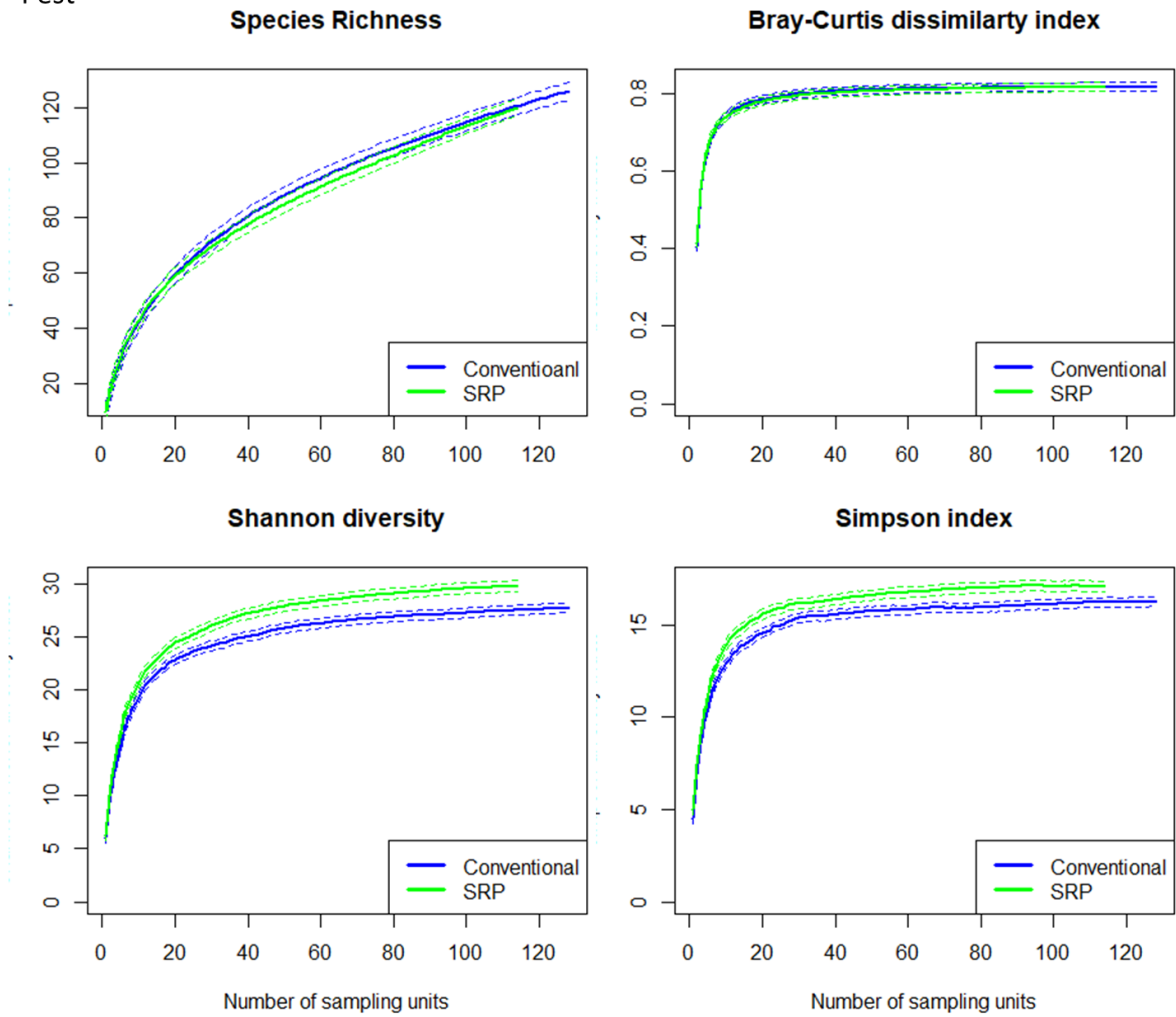


Figure 6.8 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index of pest function groups between conventional farming practice and SRP in the northeastern region of Thailand

Decomposer Species Richness

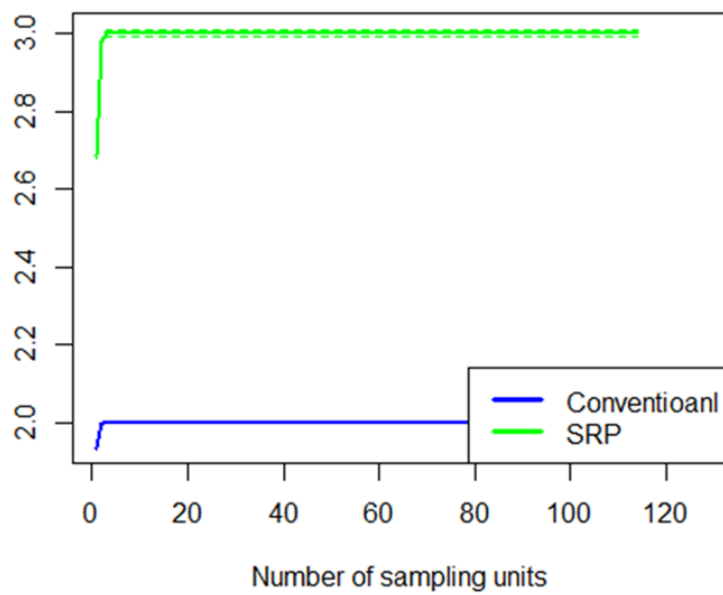


Figure 6.9 Rarefaction curve of species richness of decomposer function groups between conventional farming practice and SRP in the northeastern region of Thailand

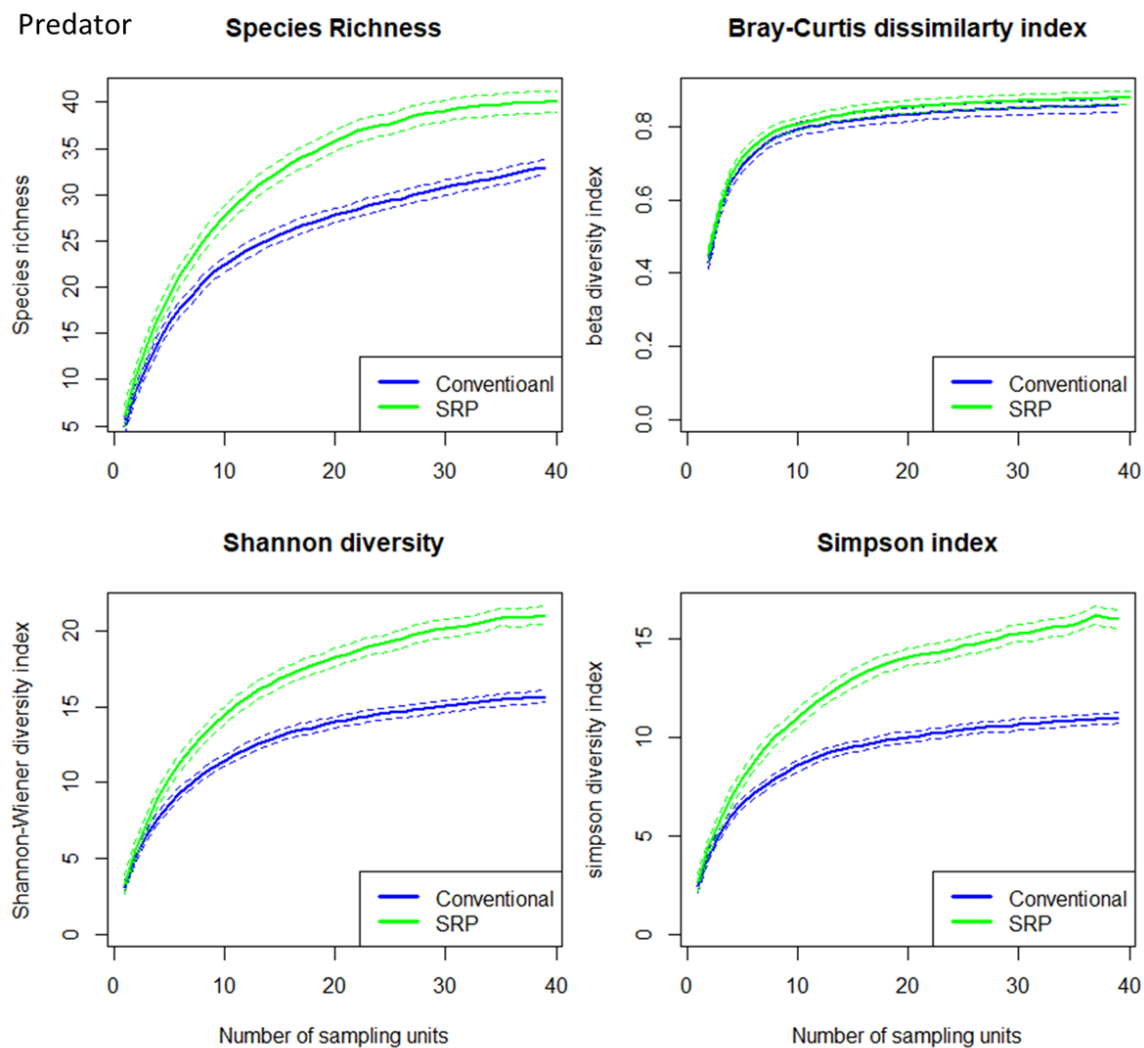


Figure 6.10 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index of predator function groups between conventional farming practice and SRP in the central region of Thailand

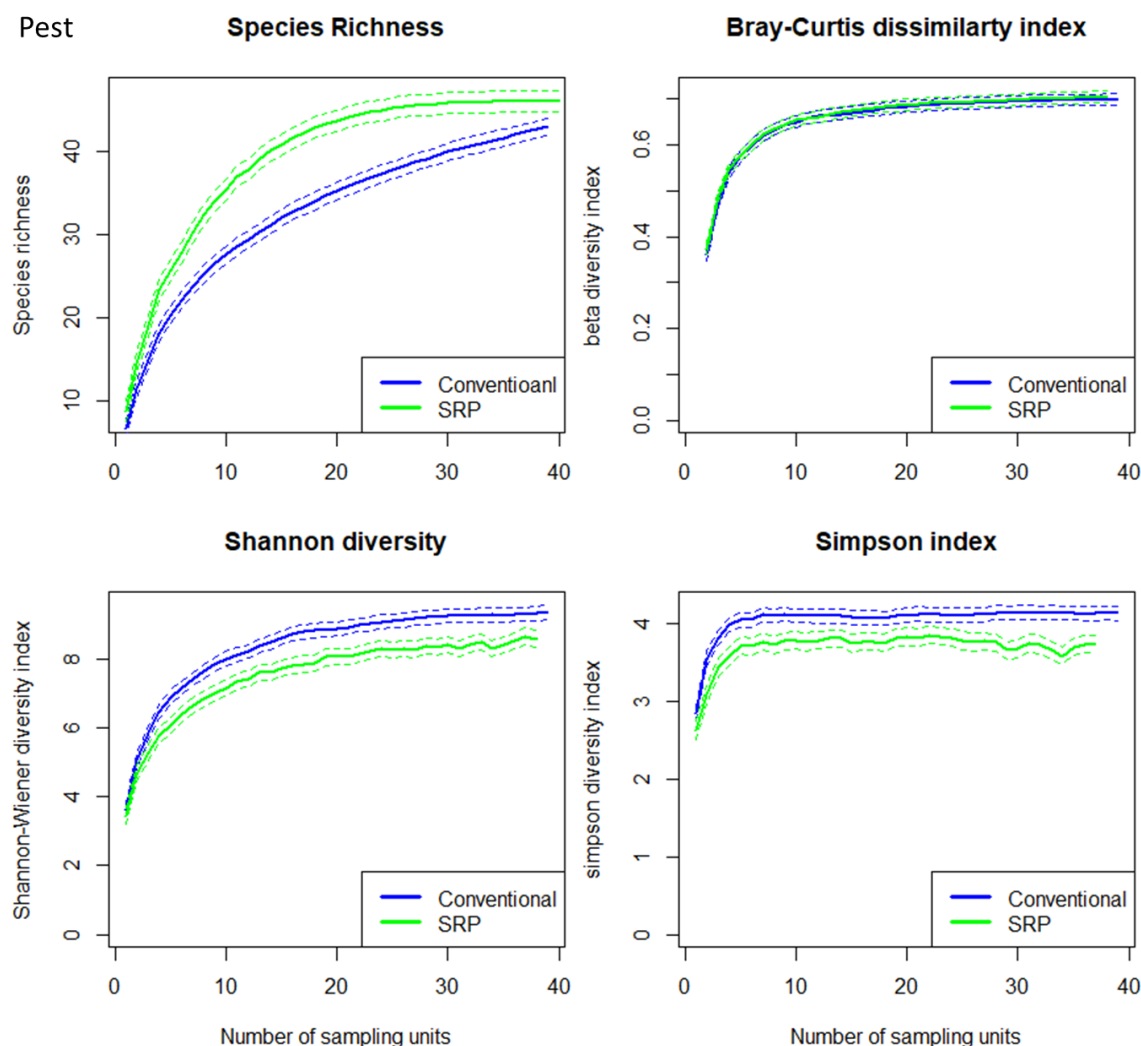


Figure 6.11 Rarefaction curve of species richness, Beta-biodiversity represented by Bray-Curtis dissimilarity index, Shannon diversity index, and Simpson diversity index of pest function groups between conventional farming practice and SRP in the central region of Thailand

6.10. Relative abundance of functional groups

The aim of this analysis was to evaluate the dominance of important functional groups within the predator and pest communities. We utilized data obtained from these insect communities and employed a measure of relative abundance as a population index for both pests and predatory insects. By comparing the ratios between the relative abundances of these two groups, we were able to gain insights into their respective prevalence and interrelationships.

In the northeastern region of Thailand, we discovered no significant differences in the relative abundance of pests and predators between conventional and SRP rice farming practices

(see Figure 6.12). This finding suggests that the population dynamics of these groups remained relatively balanced in both farming systems within this region. However, intriguing results emerged when we extended our study to the central region of Thailand. We observed higher relative abundances of pests and predators in conventional rice farming practices than in SRP rice farming (Figure 6.12). This discrepancy suggests that the conventional rice farming practices in the central region may have created more favorable conditions for the proliferation of both pests and predators.

Remarkably, in the central, despite the increased abundance of pests and predators in conventional rice farming, we found that the ratio between predator and pest relative abundances was higher in SRP rice farming. This finding implies that the SRP rice farming practices in the central region may have facilitated a more balanced predator-prey relationship. The higher ratio suggests a potentially enhanced ability of the predator community to control pest populations in SRP rice farming compared to conventional rice farming.

These findings contribute to our understanding of the ecological dynamics within rice farming systems in different regions of Thailand. The absence of differences in relative abundances of pests and predators in the northeastern region indicates a relatively stable ecological balance between these groups regardless of the farming practices employed. However, the higher abundances of both pests and predators in conventional rice farming in the central region, along with the increased predator-to-pest ratio in SRP rice farming, highlight the potential benefits of adopting sustainable farming practices, such as SRP, to promote natural pest control and achieve more sustainable pest management strategies.

Further research and investigations are warranted to explore the underlying mechanisms driving these observed differences between the regions and farming systems. Understanding the factors that influence the functional dominance of pest and predator communities will help inform the development of effective and environmentally friendly pest management strategies in rice farming, ultimately contributing to the sustainability and productivity of agricultural systems.

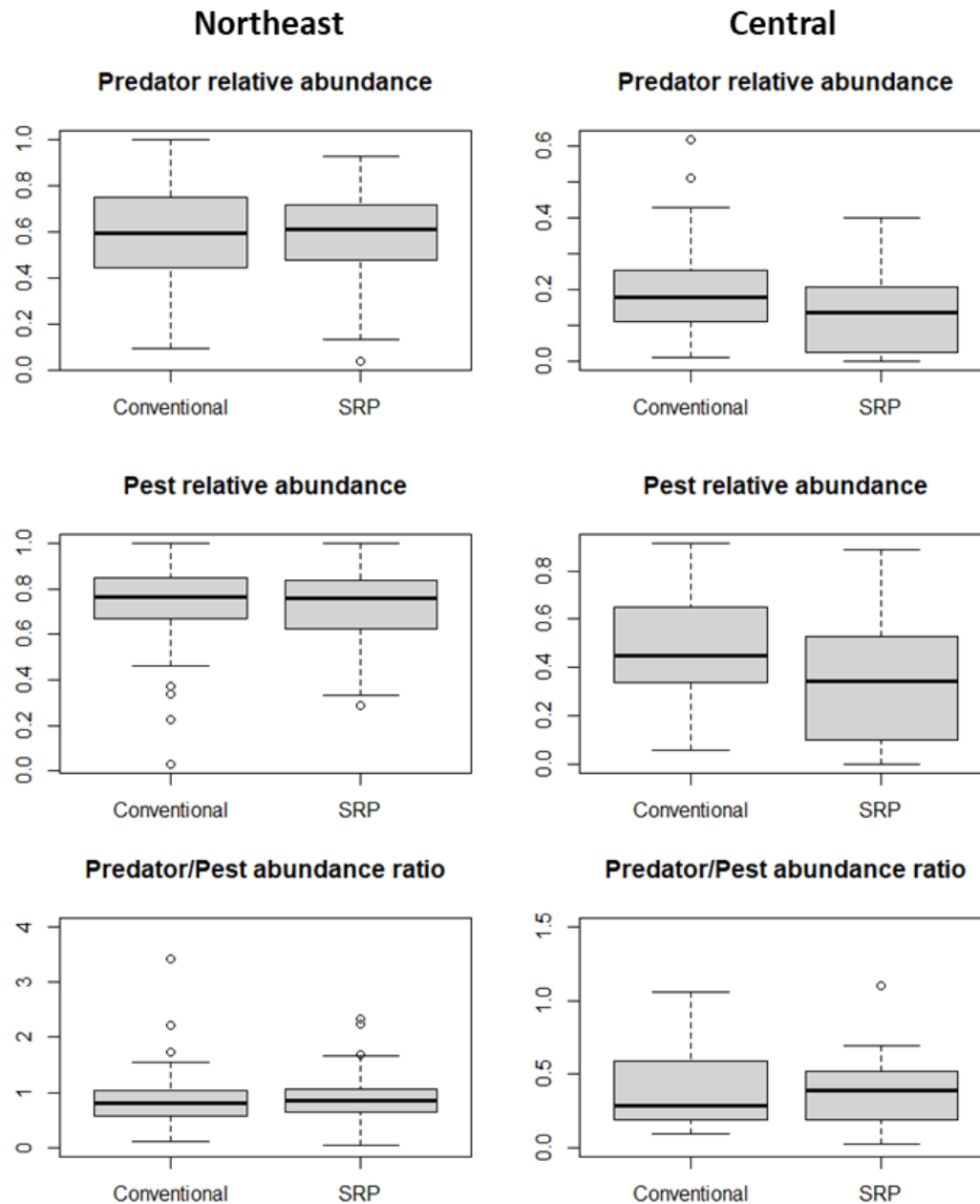


Figure 6.12 Relative abundance of pest and predator functional groups and abundance ratio between predator and pest in central and northeast region.

6.11. Spatial modeling and estimation of biodiversity

To forecast the Shannon and Simpson diversity indices at the landscape scale for the northeastern and central regions, we employed the randomForest model. Our analysis involved

identifying the key predictor variables, i.e., land use covariates (Table 6.4) and bioclimatic variables (Table 6.5) that determined the biodiversity at the landscape level.

The results for the Northeast are presented in Figure 6.13 and Figure 6.14. These figures illustrate the importance of the plot and predicted map for the Shannon diversity index and Simpson index, respectively, specifically for the northeastern region. The analysis found that the most significant predictor variables for this region were bioclimatic factors, indicating their crucial role in determining diversity in an ecosystem. However, certain land-use factors also significantly impacted the diversity models, particularly wetland (lu8) and SRP rice farming (lu2).

When examining the diversity model for the central region, we observed a similar pattern, with bioclimatic variables being the most critical main effects. However, the significant land-use factors influencing the biodiversity index in this region consisted of SRP farming (lu2), crop fields (lu3), and wetlands (lu8) (Figure 6.15 and Figure 6.16).

Our findings from the Northeast and Central regions emphasize the critical role of bioclimatic factors in shaping ecosystem diversity. However, it is important to recognize the significant impact of human activities, such as the utilization of natural land, i.e., including wetlands, and adopting different rice farming practices, on maintaining biodiversity within the rice cultivation landscape. Considering these factors is essential for future conservation and management efforts. Incorporating these findings into decision-making processes can contribute to more effective conservation strategies and sustainable land use planning.

To assess the Shannon diversity index for different spatial units in the northeastern and central regions of Thailand, our study employed various models using the collected data. These models were then utilized to predict the Shannon diversity index for each spatial unit, which was subsequently mapped out for further analysis. In Figures 6.17 through 6.20, we presented the prediction map for the northeastern region of Thailand, illustrating the predicted values for each spatial unit. Furthermore, Figure 6.21 showcased the temporal changes of the Shannon diversity index for each scenario, providing a comprehensive depiction of how the index may fluctuate over time.

Similarly, for the central region of Thailand, we presented the prediction map in Figures 6.22 through 6.25, offering an overview of the predicted values for each spatial unit. To complement this, Figure 6.26 presents the temporal changes of the Shannon diversity index, providing insights into the fluctuations of the index over time. These visual representations enabled

us to analyze the patterns and trends that emerged from the data, facilitating a deeper understanding of the dynamics within each region.

The prediction maps consistently revealed an increasing trend in Shannon diversity index values throughout the study area, indicating positive developments for biodiversity. Although the mean values of future scenarios did not exhibit statistical significance, there was a noticeable pattern of rising minimum values for the Shannon diversity index. This finding holds particular importance as it suggests that areas with initially lower biodiversity may experience the most significant improvements over time.

By utilizing these prediction maps and examining the temporal changes of the Shannon diversity index, we gained valuable insights into the spatial distribution and temporal dynamics of biodiversity in the northeastern and central regions of Thailand. These findings provide a basis for informed decision-making in conservation and land management practices, helping policymakers and stakeholders develop targeted strategies to protect and enhance biodiversity in these regions.

Table 6.4 Land use covariates in randomForest models to predict species richness and diversity indices.

Land use ID	Description
1	Conventional rice
2	SRP rice
3	Field crop
4	Tree plantation/orchard
5	Rangeland/grassland
6	Forest
7	Urban
8	Wetland
9	Water
10	Etc.

Table 6.5 Bioclimatic variables used in random forest models to predict species richness and diversity indices.

BioClim	Description
bio 1	Annual Mean Temperature

bio 2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
bio 3	Isothermality (BIO2/BIO7) (×100)
bio 4	Temperature Seasonality (standard deviation ×100)
bio 5	Max Temperature of Warmest Month
bio 6	Min Temperature of Coldest Month
bio 7	Temperature Annual Range (BIO5-BIO6)
bio 8	Mean Temperature of Wettest Quarter
bio 9	Mean Temperature of Driest Quarter
bio 10	Mean Temperature of Warmest Quarter
bio 11	Mean Temperature of Coldest Quarter
bio 12	Annual Precipitation
bio 13	Precipitation of Wettest Month
bio 14	Precipitation of Driest Month
bio 15	Precipitation Seasonality (Coefficient of Variation)
bio 16	Precipitation of Wettest Quarter
bio 17	Precipitation of Driest Quarter
bio 18	Precipitation of Warmest Quarter
bio 19	Precipitation of Coldest Quarter

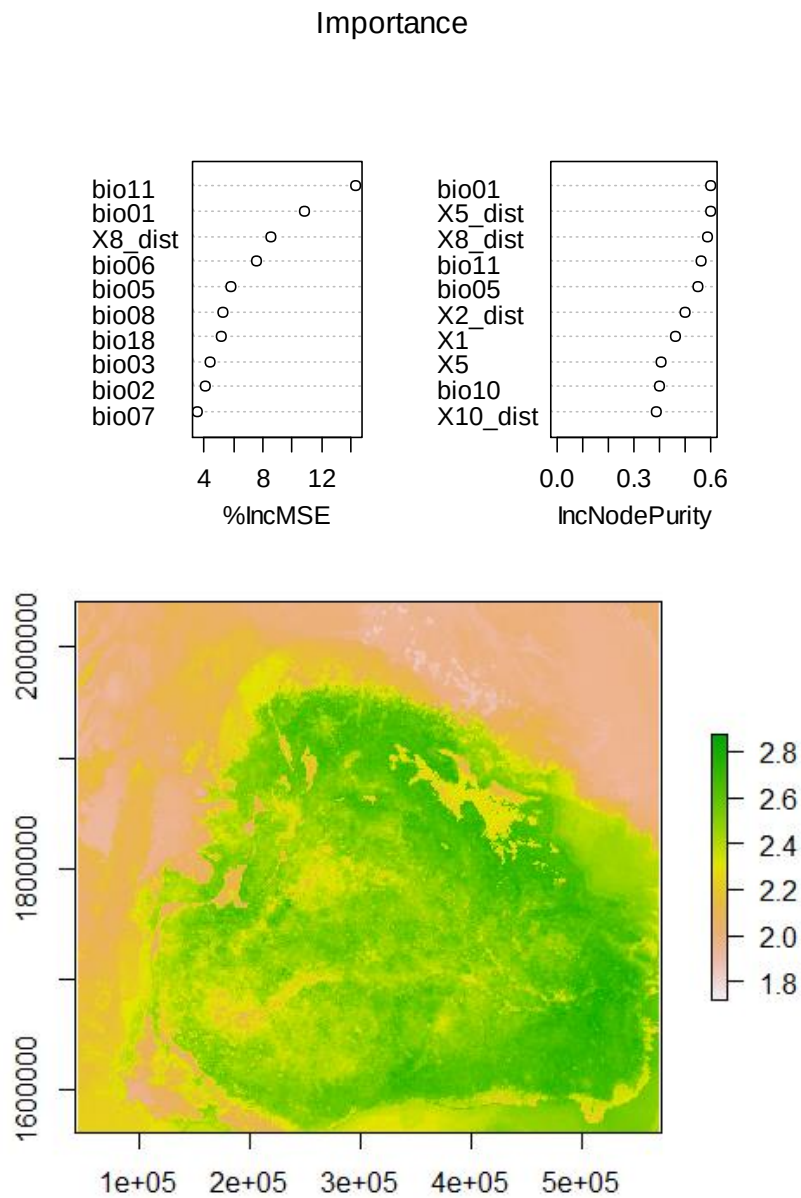


Figure 6.13 Importance index of random forest model to spatially predict Shannon diversity index of insect species. The predicted map of the Shannon diversity index in the northeastern region of Thailand.

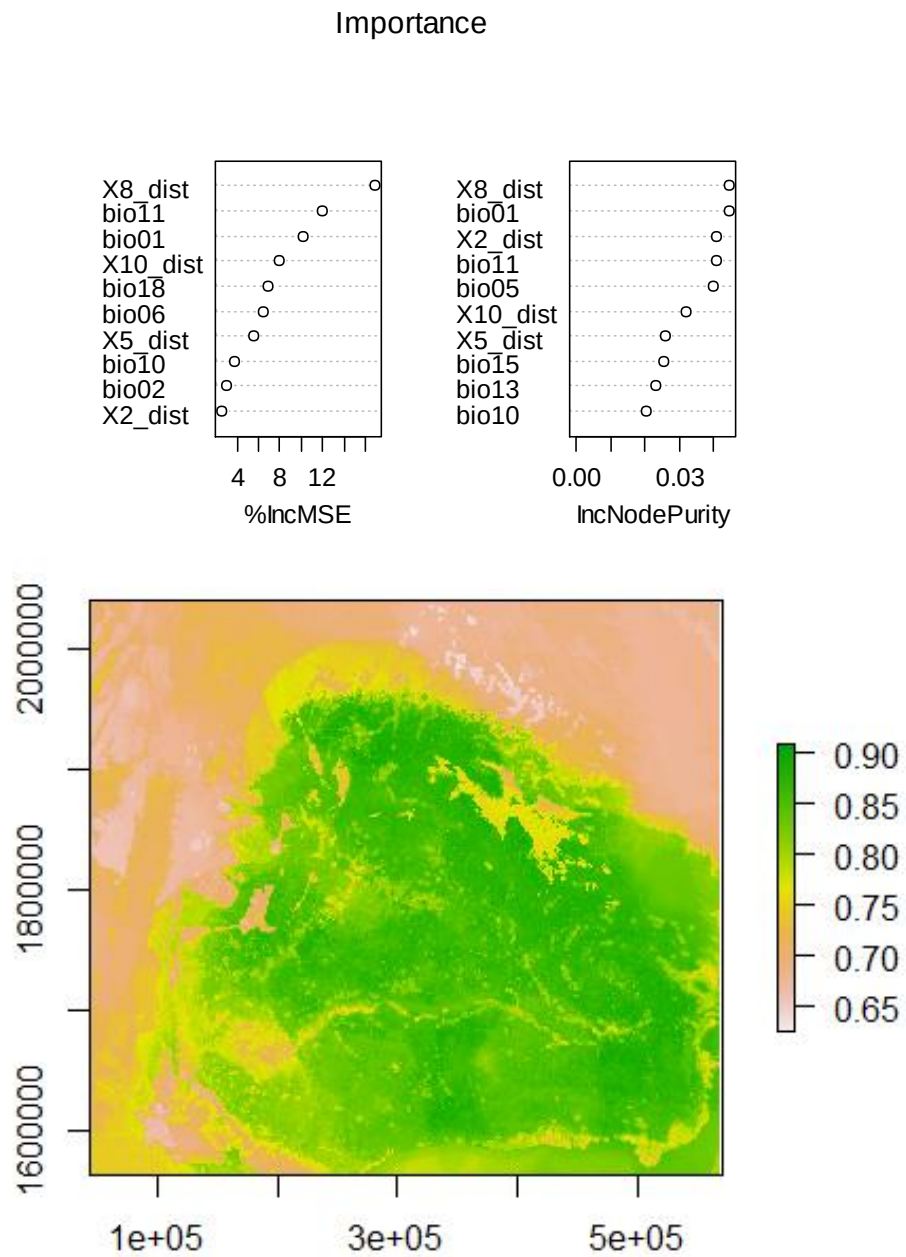


Figure 6.14 Importance index of random forest model to spatially predict Simpson diversity index of insect species. The predicted map of the Simpson diversity index in the northeastern region of Thailand.

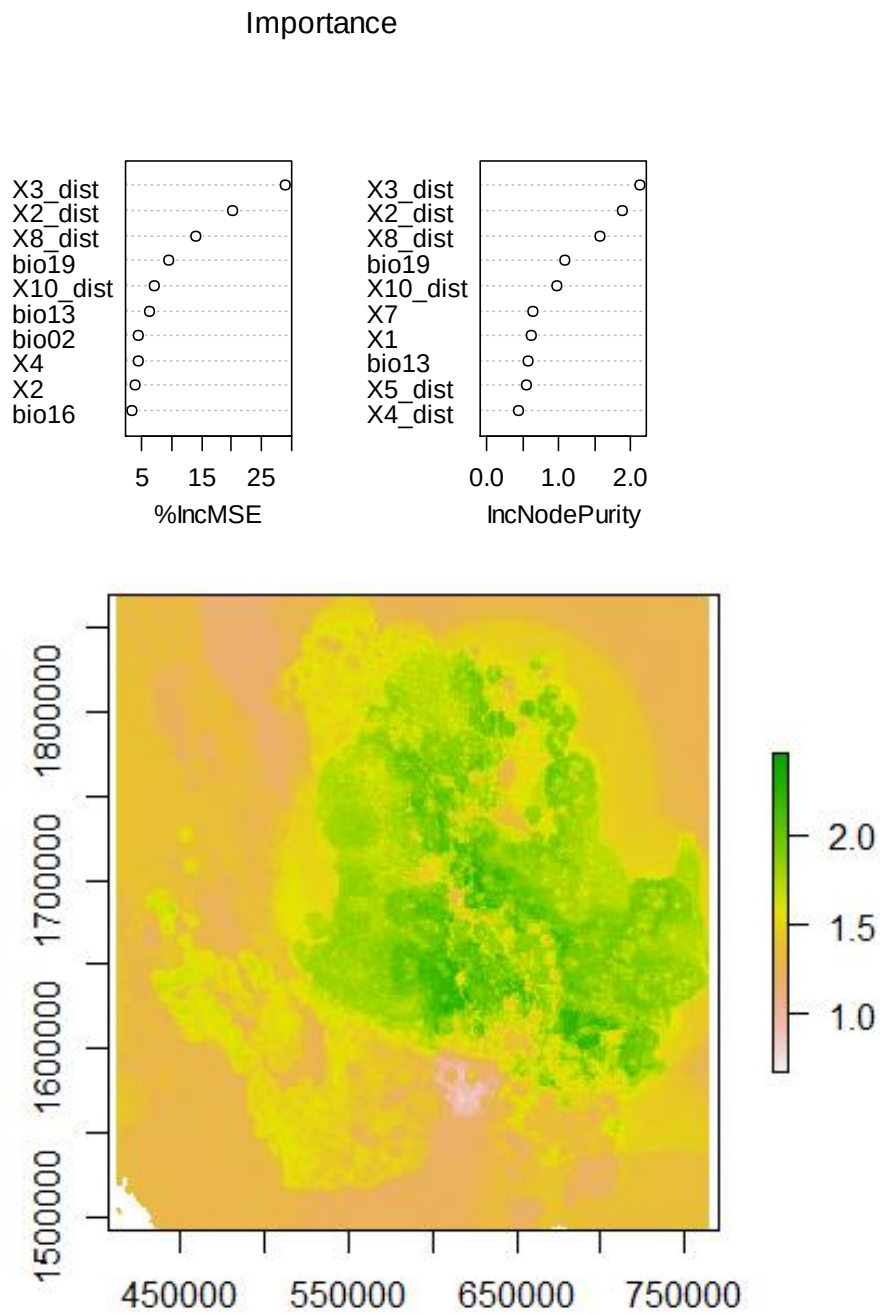


Figure 6.15 Importance index of random forest model to spatially predict Shannon diversity index of insect species. The predicted map of the Shannon diversity index in the central region of Thailand.

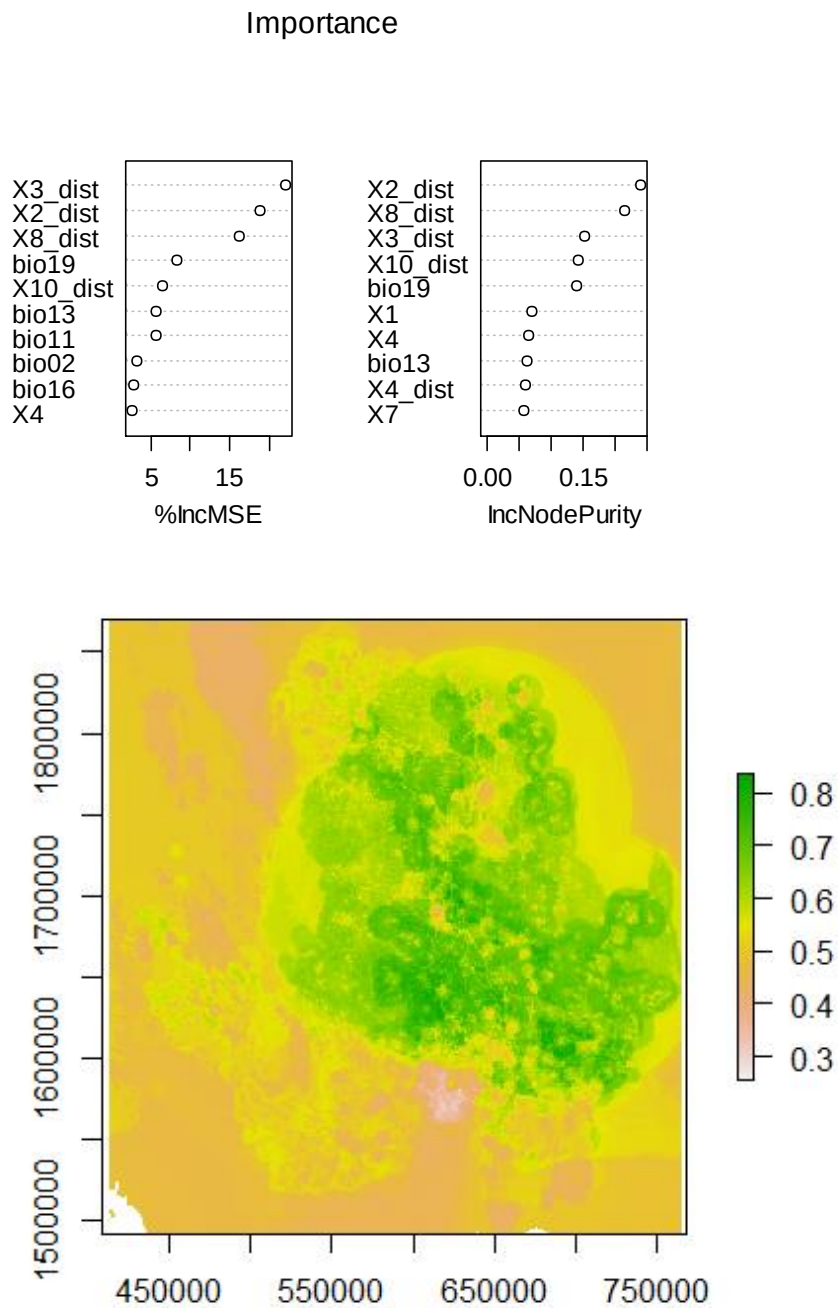


Figure 6.16 Importance index of random forest model to spatially predict Simpson diversity index of insect species. The predicted map of the Simpson diversity index in the central region of Thailand.

3.5. Prediction of future scenarios

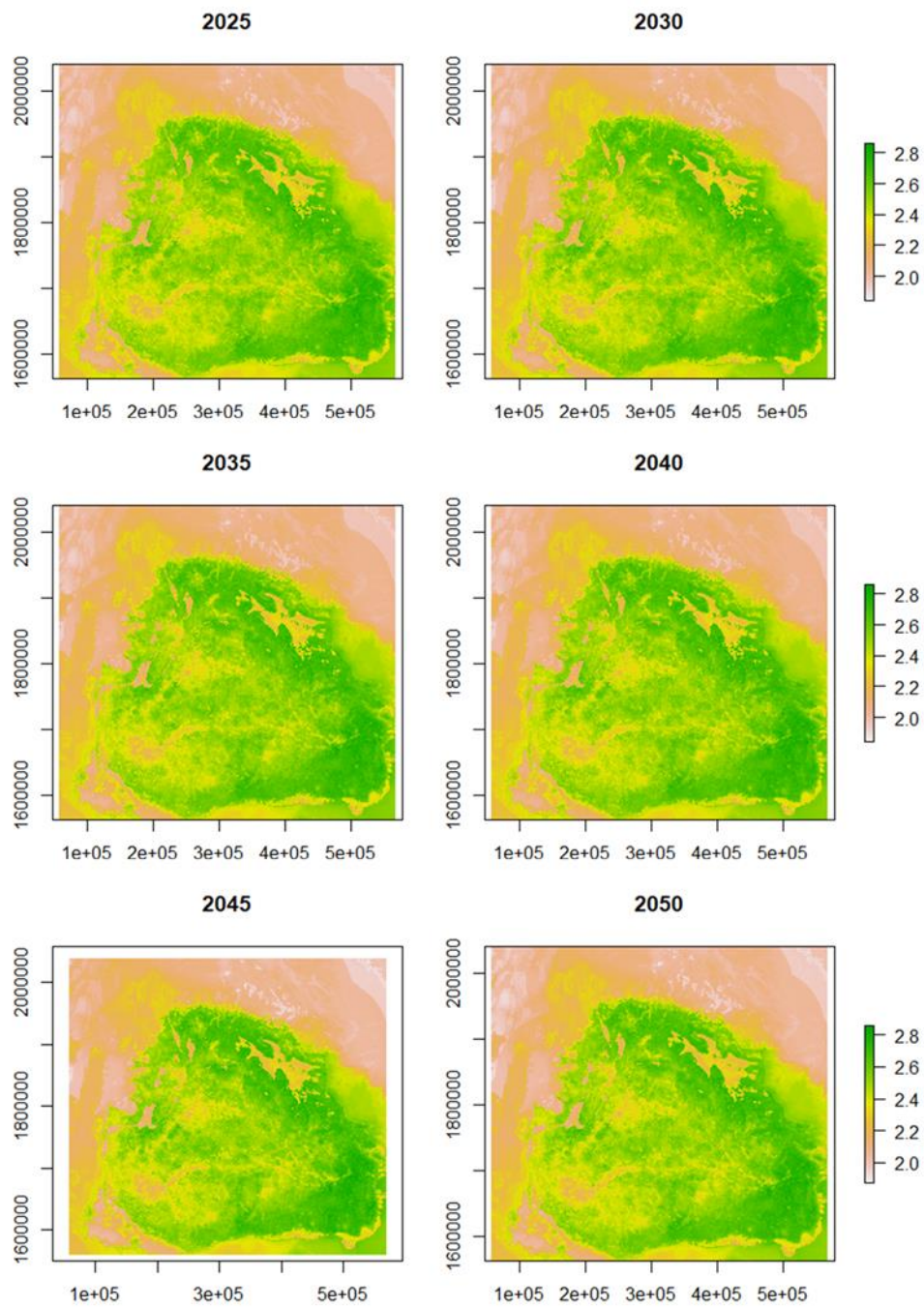


Figure 6.17 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 1.

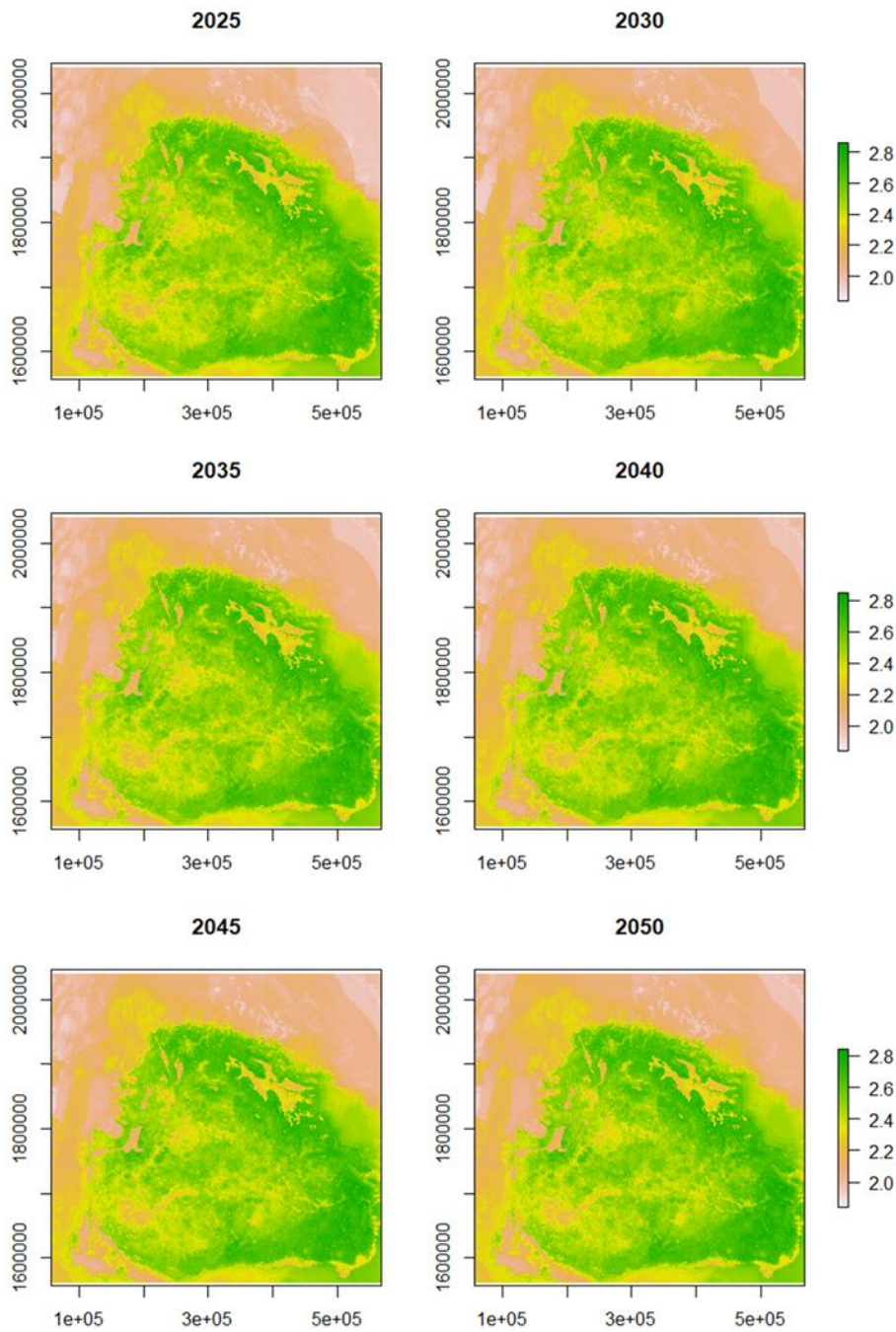


Figure 6.18 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 2.

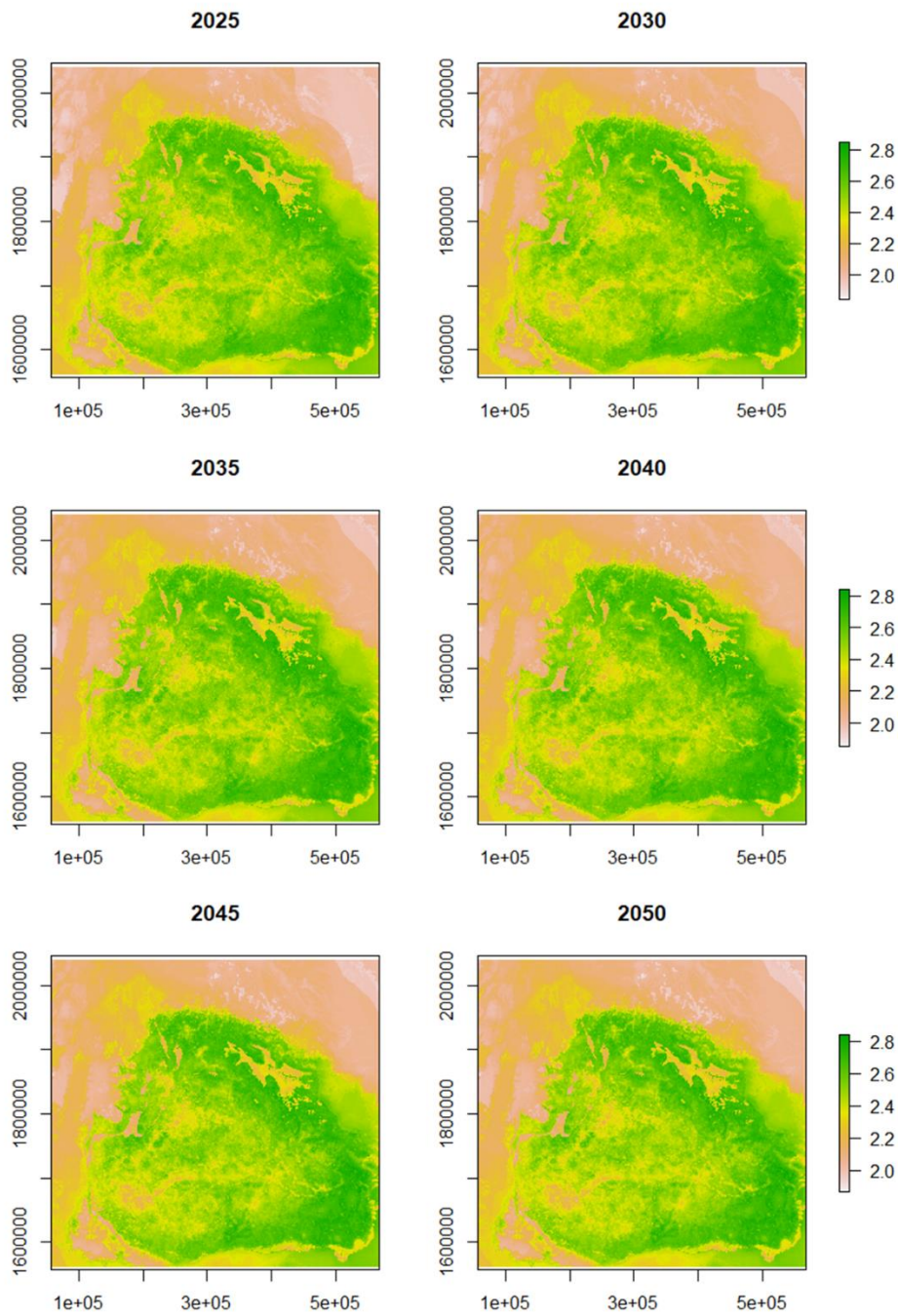


Figure 6.19 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 3.

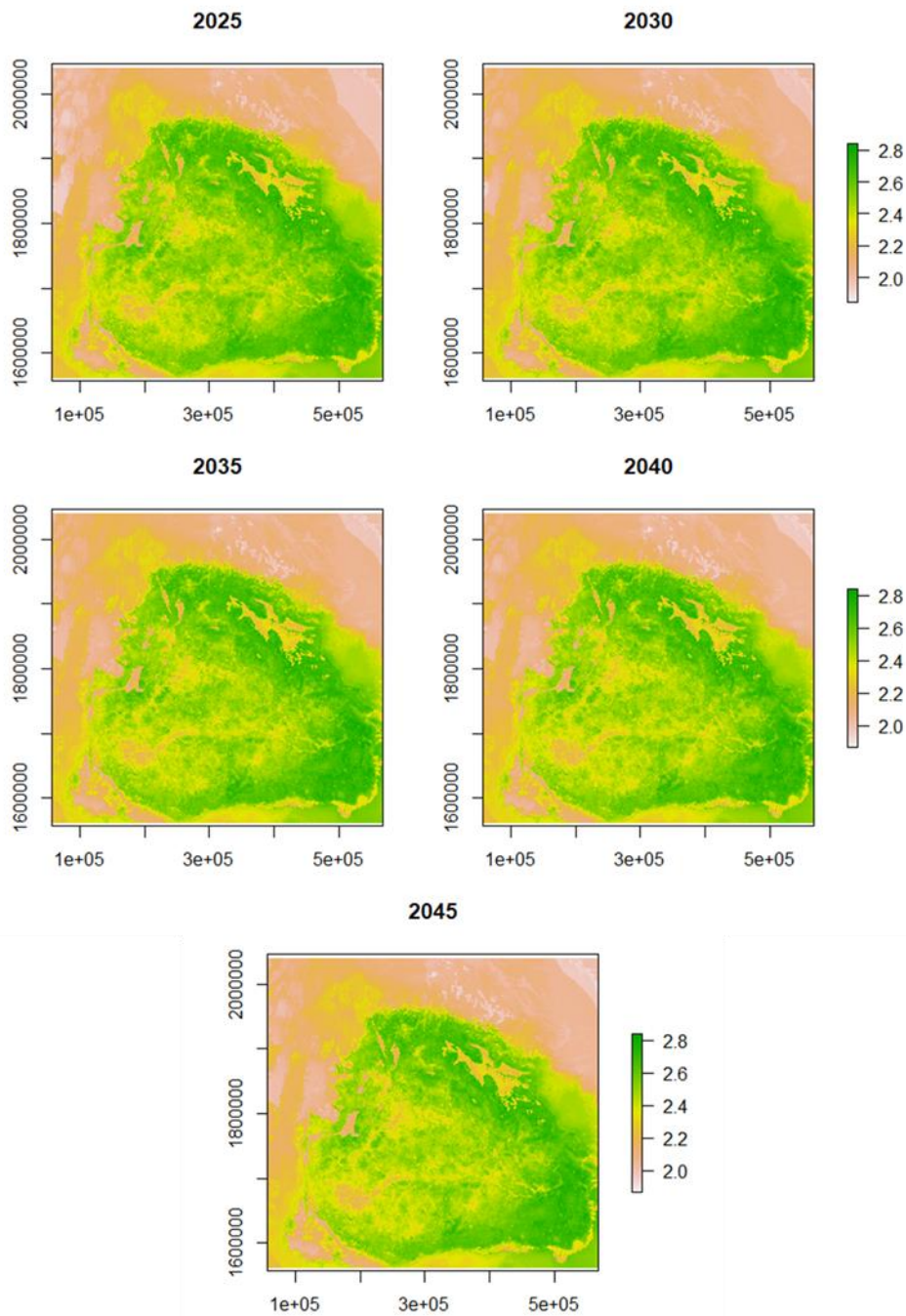


Figure 6.20 The predicted map of the Shannon diversity index in the northeastern region of Thailand based on the future scenarios 4.

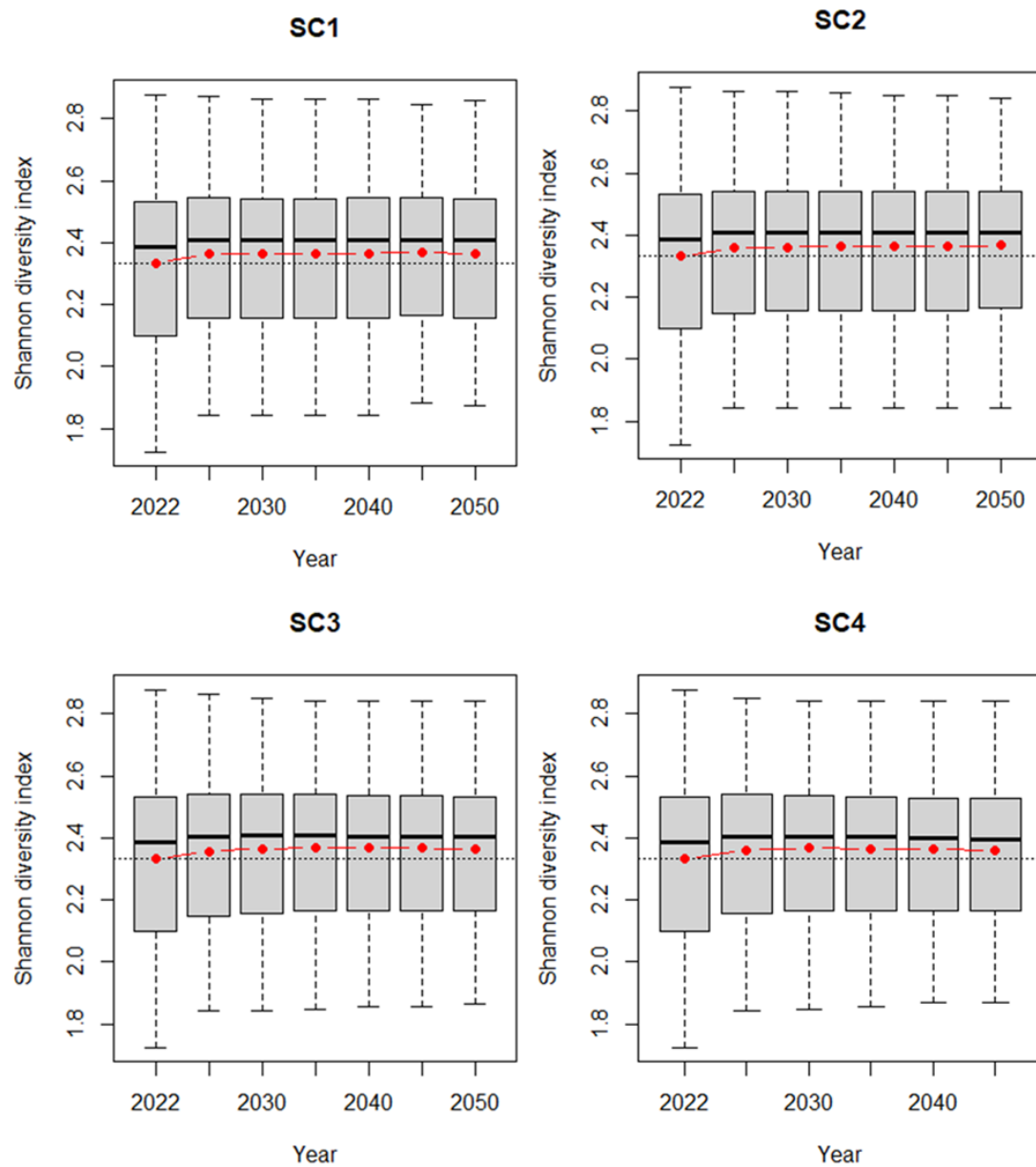


Figure 6.21 Shannon diversity index of each spatial unit pixel (300 meters resolution) of predicted future scenarios of the northeastern region of Thailand.

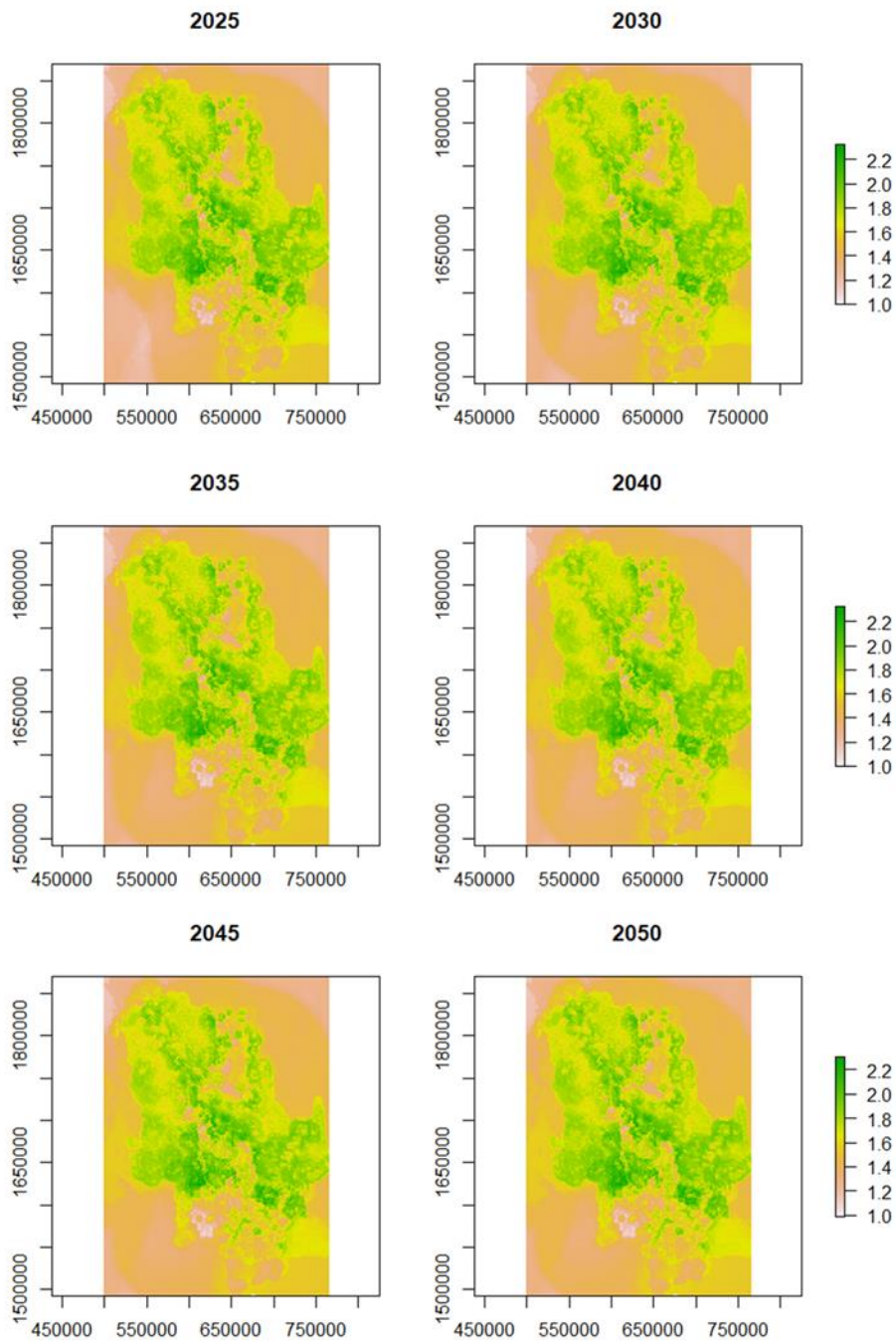


Figure 6.22 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 1.

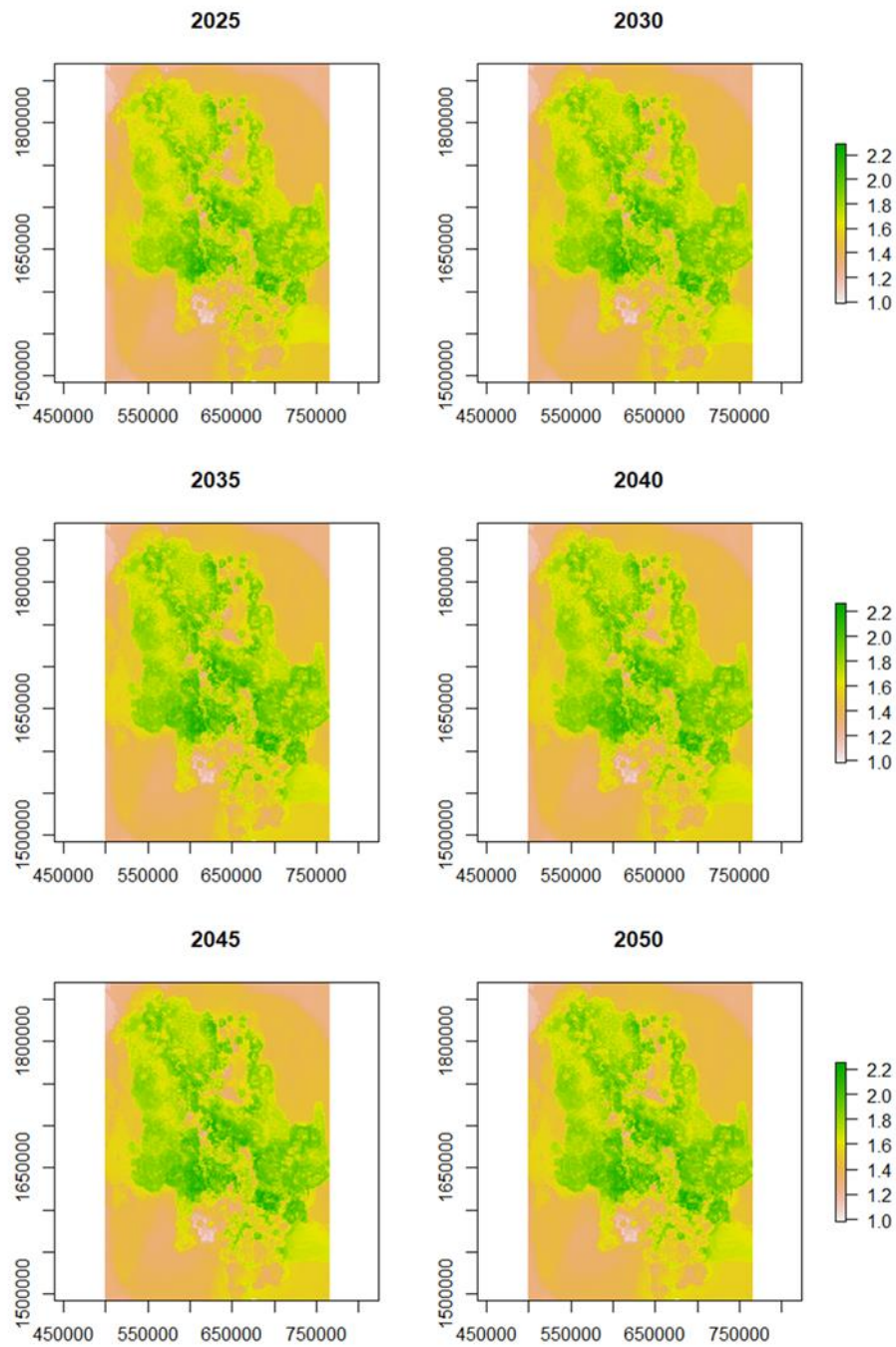


Figure 6.23 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 2.

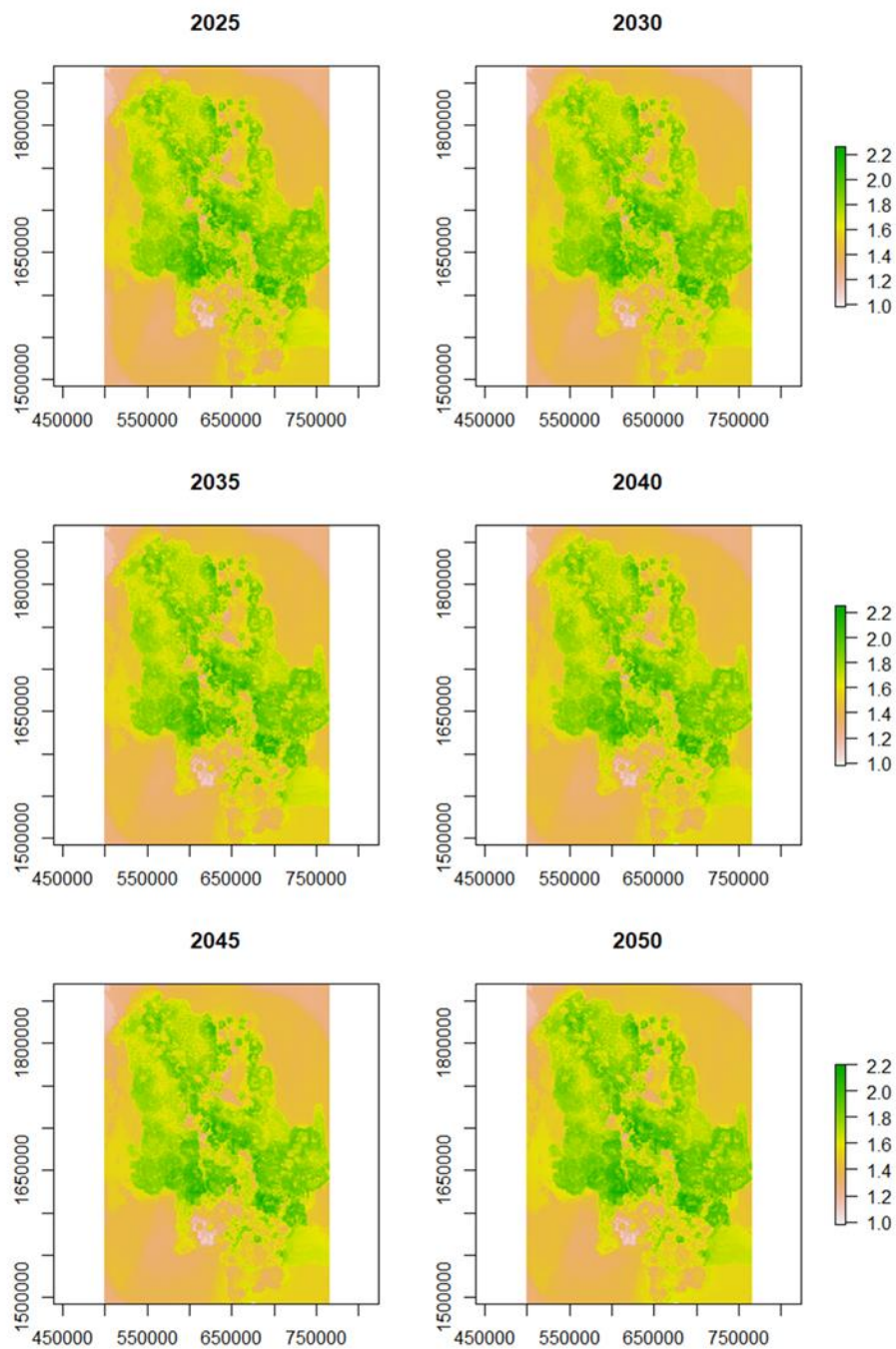


Figure 6.24 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 3.

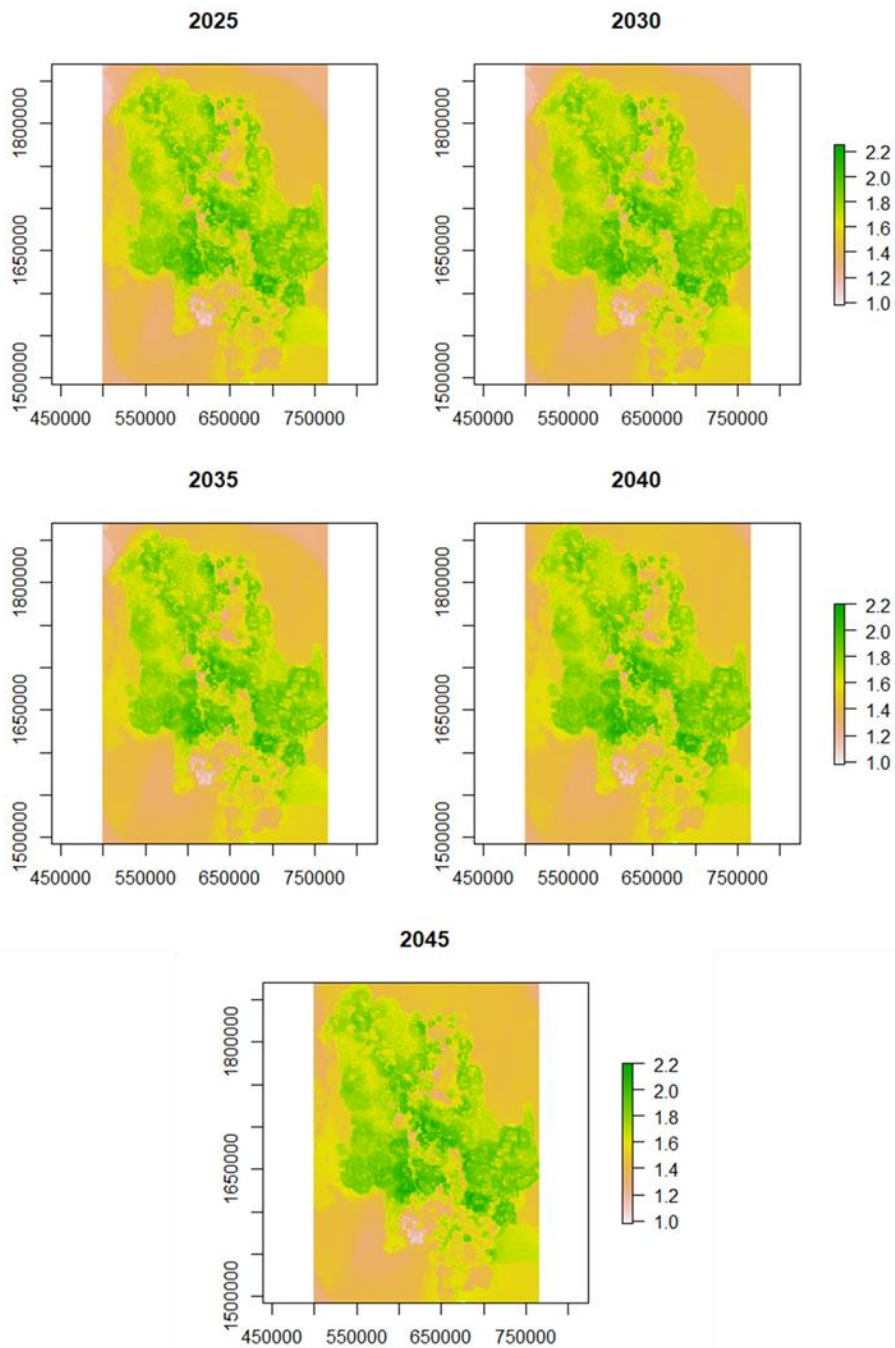


Figure 6.25 The predicted map of the Shannon diversity index in the central region of Thailand based on the future scenarios 4.

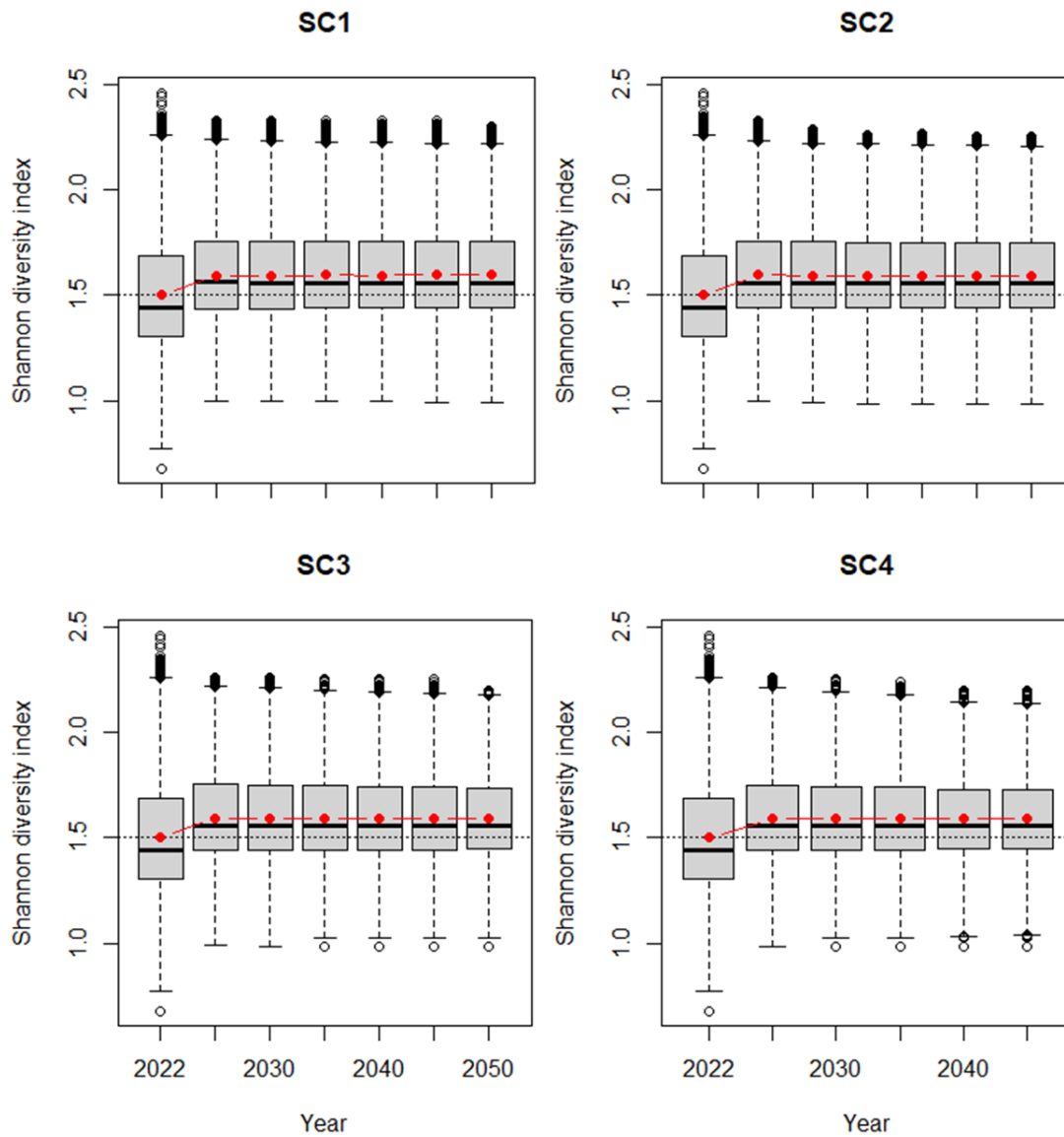


Figure 6.26 Shannon diversity index of each spatial unit pixel (300 meters resolution) of predicted future scenarios of the central region of Thailand.

6.12. Summary for biodiversity of insects in rice cultivation landscape

At the site scale, there is no significant difference in insect diversity between conventional and SRP practices, both in the Northeast and Central regions. In the northeastern region, the comparison of species richness and diversity indices between conventional and SRP farming practices showed no significant difference. Both practices had similar values for species richness, Shannon diversity index, and Simpson diversity index, indicating that they support biodiversity and ecosystem balance at the same level. Similarly, in the central region, there was no significant difference in species richness and diversity indices between conventional and SRP farming practices. Both practices exhibited similar values for species richness, Shannon diversity index, and Simpson diversity index. These findings suggest that both conventional and SRP farming practices have comparable effects on biodiversity and ecosystem balance in both the northeastern and central regions.

However, when considering biodiversity at a larger scale, regional variations became apparent. In the northeastern region, conventional rice farming supported higher species richness compared to SRP. However, SRP practices promoted a more diverse and balanced ecosystem, as indicated by higher values of the Shannon and Simpson diversity indices. Conversely, SRP practices exhibited higher species richness and beta diversity in the central region. Conventional farming had higher Shannon and Simpson diversity indices, suggesting greater diversity and balance in the ecosystem. These findings emphasize the importance of considering regional variations in biodiversity patterns and indicate that the choice between conventional farming and SRP practices can have different impacts on biodiversity depending on the specific geographic location.

Focusing on the functional groups of the insects, in the northeastern region, conventional farming had higher species richness in the predator and pest functional groups compared to SRP. However, SRP showed higher Shannon and Simpson diversity indices for the pest functional group. In the central region, SRP farming resulted in higher species richness, beta diversity, Shannon, and Simpson indices in the predator functional group compared to conventional farming. Conventional farming had higher species richness in the pest functional group, but SRP had higher Shannon and Simpson diversity indices. These findings suggest that the effectiveness of SRP farming in promoting species richness varies across regions and functional groups. This has important implications for biodiversity management in rice paddies and agricultural landscapes.

The analysis that aimed to assess the dominance of functional groups in predator and pest communities in rice farming revealed that no significant differences were found in the relative abundance of pests and predators between conventional and SRP farming in the northeastern region. However, in the central region, conventional farming had a higher abundance of pests and predators compared to SRP farming. Despite this, the predator-to-pest ratio was higher in SRP farming in the central region, indicating a more balanced predator-prey relationship. These findings suggest that SRP practices promote natural pest control and sustainable pest management. Further research is needed to understand the underlying mechanisms and develop effective pest management strategies in rice farming.

The analysis of landscape factors that influence biodiversity in the northeastern and central regions of Thailand showed that bioclimatic factors were found to be the most significant predictors of diversity, but land-use factors, including wetlands and sustainable rice farming, also played a role. Maps and temporal analyses of the Shannon diversity index showed increasing trends in biodiversity values, particularly in areas with initially lower biodiversity. These findings have implications for conservation and land management, aiding decision-making and the development of targeted strategies to protect and enhance biodiversity in these regions.

In summary, the analysis revealed that there were no significant differences in species richness and diversity indices between conventional and SRP farming practices at the sampling site scale in both the northeastern and central regions of Thailand. However, when considering pool biodiversity at a larger scale, regional variations emerged. In the northeastern region, conventional farming had higher species richness, but lower Shannon and Simpson diversity indices compared to SRP. In contrast, the central region showed higher species richness, beta diversity, and Shannon and Simpson diversity indices in SRP farming. The study also highlighted the importance of bioclimatic factors in shaping ecosystem diversity, along with the influence of land-use factors such as wetlands and rice farming practices. The findings emphasized the potential benefits of adopting sustainable farming practices like SRP for promoting biodiversity and natural pest control. The prediction maps and temporal analyses provided insights into the spatial distribution and dynamics of biodiversity, aiding decision-making in conservation and land management. Further research is needed to understand the underlying mechanisms and develop effective strategies for biodiversity conservation in rice farming.

These results hold far-reaching implications for conservation initiatives and the efficient management of natural resources in Thailand. By accurately predicting changes in the Shannon diversity index, policymakers and researchers better understand how to safeguard and preserve the region's biodiversity. Armed with this knowledge, they can make well-informed decisions regarding land use, resource allocation, and conservation strategies to promote sustainable development for future generations.

Ultimately, this research contributes to the collective knowledge base on biodiversity conservation, serving as a foundation for informed actions to mitigate the threats facing Thailand's natural ecosystems. By emphasizing preserving and enhancing biodiversity, policymakers and stakeholders can collaborate to safeguard the country's ecological heritage and ensure a sustainable future for both wildlife and human communities.

6.13. Trees on the Farms

This section aims to observe “trees on farm” or “agroforestry” in rice cultivation if there are any patterns between regions and cultivation practices: CON vs. SRP that may relate to rice yields and water usage, specifically water from rainfall and irrigation. Data were obtained from the household questionnaire survey, field survey of trees on farms, and secondary data retrieved from relevant authorities, e.g., the Royal Forest Department. This helps identify farming practices and the number of tree/plant species on paddy fields on sustainable and conventional rice paddies in the Northeast and Central regions. At each sampling rice field, tree species were identified and recorded as well as the total number of each species. The tree species data and tree density observed on different rice farming practices (SRP and CON) were compared. This study also examined farming practices that may affect water use, including the maintenance of trees on farms (agroforestry).

Tree species with the number of individuals for both native and cultivated plants, recorded from conventional (CON) and SRP rice farming practices, are summarized in Table 6.6. Significantly, the total tree density and density of native trees on paddy fields in the Northeast are higher than in the Central Plain. Tree diversities (species richness), both native and cultivated species in the Northeast, are also significantly higher than in the Central Plain. Overall, rice paddies identified as the SRP show greater abundance and vegetation diversity, including the total tree density, the native tree density, the total tree species, and the diversity of native species.

Table 6.6 also provide the list of plant species recorded, their status, and their density. Even if significant connections between the number of “trees on farm” and amounts of yields and water use may not be recognized when comparing the CON against the SRP practice, “agroforestry” can add on intangible values to the rice paddies or agroecosystems, including local biodiversity sanctuary, household food provisioning, source of additional income, and local climate regulation. Specifically, keeping native trees or planting new trees on farms, including trees for food and income, can be observed throughout the Northeast (Figure 6.27 a-d). This practice helps protect trees, maximize the use of land, and maintain local livelihoods.

Table 6.7 displays key factors suggesting that the SRP is environmentally friendlier than the CON practice. A mixed performance between the CON and SRP was observed in the Central Plain. This is perhaps due to the nature of rice production in the region, which is more likely commercial-based than in the Northeast. Meanwhile, the SRP practice in the Northeast clearly

illustrates that all the considered issues, i.e., yield, amounts of water footprints, vegetative abundance, and diversity, outperformed the CON practice.

Table 6.6. Number of trees and species observed on farms by rice farming practices.

Vegetative structure	Conventional practice			Sustainable rice practice			Grand total
	C. Plain	NE	Total	C. Plain	NE	Total	
Sampled areas (ha)	80.16	56.16	136.32	27.68	24.16	51.84	188.16
No. of trees recorded	915	1,407	2,322	271	1,694	1,965	4,287
Total tree density (trees/ha)*	23.77	33.59	28.95	16.35	105.19	67.11	39.64
No. of native trees	70	266	336	48	292	340	676
No. of cultivated trees	845	1,141	1,986	223	1,402	1,625	3,611
Native tree density (trees/ha)*	1.67	6.44	4.19	4.87	17.10	11.86	6.34
Cultivated tree density (trees/ha)	22.09	27.14	24.76	11.49	88.08	55.26	33.30
No. of all tree species of farm	4.94	9.58	7.39	7.67	15.63	12.21	8.74
No. of tree species per ha*	2.68	4.66	3.72	2.65	7.19	5.25	4.15
No. of native species per ha*	0.71	1.81	1.29	0.70	3.04	3.04	1.50
No. of cultivated spp. per ha	1.96	2.85	2.43	1.96	4.15	3.21	2.65

Note: * depicts significant differences of the means from t-tests: CON vs. SRP, for the tested variables at 0.01.

Table 6.7. A summary of key indicators suggests that the SRP is more environmental-friendly than the CON practice.

Item	Central Plain		Northeast	
	CON	SRP	CON	SRP
Rice yields (tons/ha)	-	+	-	+
WF-green (m ³ /ton)	+	-	+	-
WF-blue (m ³ /ton)	+	-	+	-
WF-grey (m ³ /ton)	-	+	+	-
Total WF (m ³ /ton)	-	+	+	-
Total tree density (trees/ha)	+	-	-	+
Native tree density (trees/ha)	-	+	-	+

Tree species richness per ha	~	~	-	+
Native tree species richness per ha	~	~	-	+

Note: + = bigger/higher amounts, - = smaller amounts, ~ = relatively same amounts, green = more environmental-friendly practice, peach color = less environmental-friendly

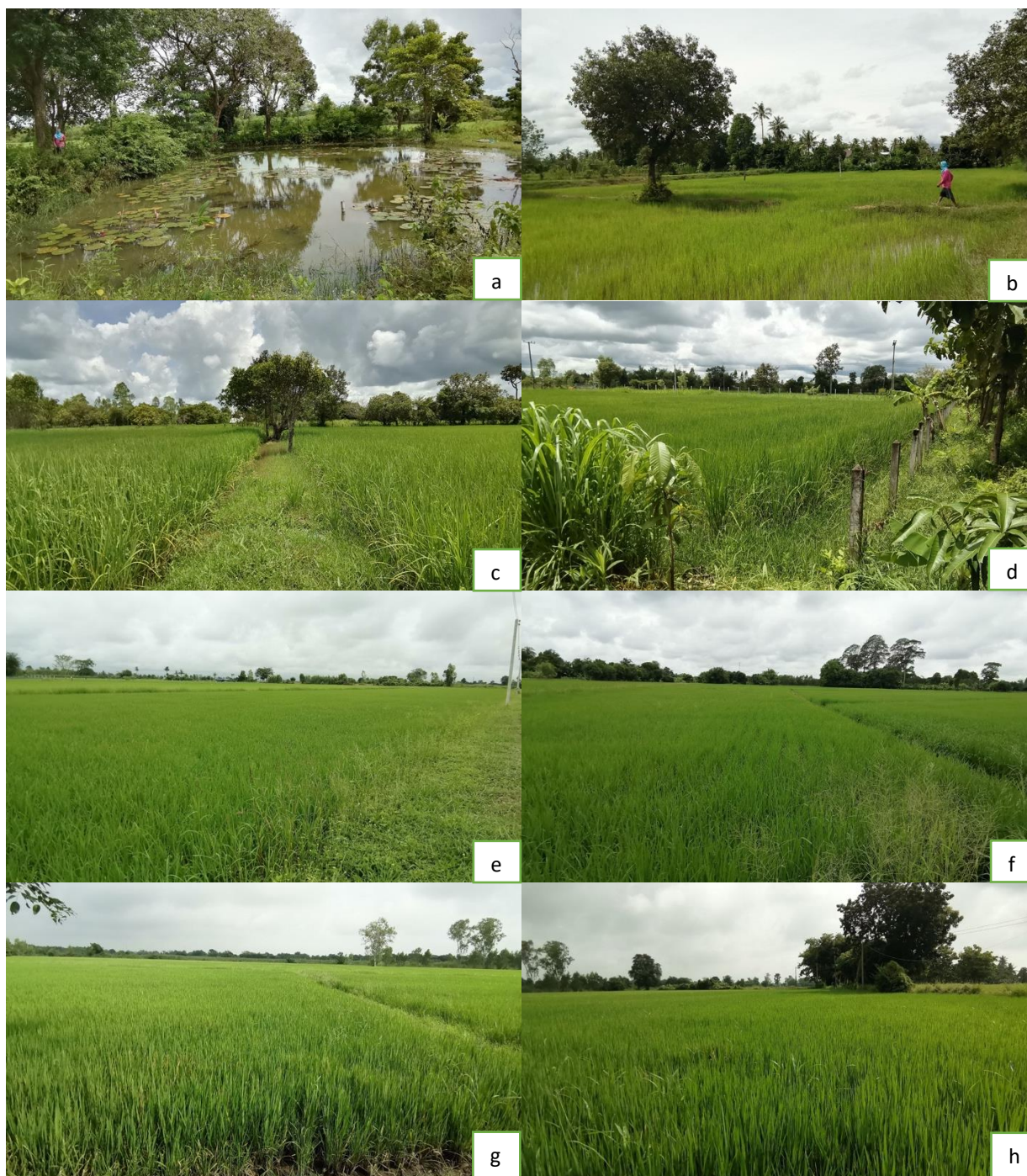


Figure 6.27. Rice paddies and trees on farm in some of the SRP surveyed sites: a-b. Surin, c-d. Ubonratchathani, e-f. Chai Nat and g-h. Suphanburi.

6.14. Farmer's climate change adaption

This section covers farmer's perceptions toward water management and some adaptation practices to climate change. The majority of respondents (64.01%) reported having farmlands outside irrigation areas, meaning that they rely on rainwater for rice farming. For farmers where rice paddies are located inside irrigation zones, only about one-fourth (22.57%) said their paddy fields are located adjacent to irrigational canals (Table 6.8). This implies more or less difficult access to irrigation water, so rice farming still depends mainly on rainwater. Climate change will inevitably impact rice farming, especially shifting rainfall distribution patterns, flooding, and drought.

Meanwhile, farmers use irrigation water nearly free of charge, except spending on water pumps, fuel, hoses, and other miscellaneous items. Even though the RID tried to enforce water usage payment, it has not been successful in doing so yet. Subsequently, this impacts irrigation efficiency, including poor facility maintenance and limited water distribution.

Table 6.18 summarizes background information on the sampled farmlands and farmer's perceptions of water management, including irrigation efficiency, water use conflicts, and their capacity to handle climate change. Overall, farmers expressed "moderately agreed" with statements on water management and climate change adaptation. Statements asked about farmer's knowledge of the impacts of climate change and their impression towards governmental assistance systems got high scores rated as "strongly agreed", implying that farmers are quite knowledgeable and/or aware of climate change and its impacts. And they are more or less satisfied with the current assistance provided by governmental authorities. Farmers expressed their moderate satisfaction with irrigation management, including effective water distribution, availability, and fair access to irrigation water. Lastly, they reflected no critical water conflicts in their community.

Table 6.8. Farmer's water management practices and

Item	Data
1. Rice paddies located in irrigation areas	Yes = 35.99 %, No = 64.01 %
2. If yes, parts of the rice paddies located adjacent to irrigation canals	Yes = 22.57 %, No = 77.43 % Major canal = 35 %, Minor canal = 65 %
3. Farmers paid for irrigation water use fees	Yes = 5.37 %, No = 94.63 % Avg. payment < US\$ 5 per year
4. Farmer's perception	Mean score (standard deviation)
4.1. Water canals are in good conditions throughout the year.	1.63 (1.27)
4.2. Irrigation water is available for use all year.	1.48 (1.21)

4.3. Fair access to irrigation water.	1.52 (1.27)
4.4. Current system to collect water use fee is effective.	1.33 (1.33) ^a
4.5. Current water use fee is reasonable.	1.26 (1.34) ^a
4.6. Irrigation management is effective.	1.49 (1.27) ^a
4.7. There are water-use conflicts in your community.	1.03 (1.18)
4.8. You satisfied with current irrigation management.	1.59 (1.27)
4.9. Drought, flooding and drastic climate fluctuation are parts of climate change.	2.62 (0.76)
4.10. You are capable of handling climate change without any assistances from outside agencies/authorities.	1.70 (1.10)
4.11. Relevant governmental authorities set up effective and sufficient systems/technologies to help you handle with climate change.	2.10 (1.04)
Overall score	1.61 (1.04)

Note: n = 728 households from nine provinces.

Agreement level: 0.00-1.00 = slightly agreed, 1.01-2.00 = moderately agreed and 2.01-3.00 = strongly agreed

Farmer's adaptation practices are presented in Table 6.9 and Table 6.10. These are common among farmers either with the CON or SRP farming practices. Digging small ponds on farmland is the most common activity, especially in the Northeast. Small ponds store rainwater during the rainy season and supply water for use throughout the year. Farmers also raise fish in the ponds and/or plant vegetables and trees on/around pond borders, so they serve as a household's food source and financial cushion during economic hardship. Changing rice planting methods, specifically from transplanting to direct sowing, is the second most common practice, followed by changing rice varieties to those more tolerant to drought or floods. Meanwhile, agroforestry (e.g., trees on farms and alley cropping) and groundwater extraction have become more common as a self-relied system so that farmers depend less on external factors. On the other hand, reducing the number of flooding days, amounts of rice planting areas due to available water, and use of digital technologies and gadgets, e.g., drones, weather forecasts, and spatial data applications, are the three least practices. Even though a growing number of farmers introduced digital or so-called "smart farming technologies" in rice farming, the number remains small due to high technical requirements, limited accessibility, and affordability.

Lastly, although farmers do their best to adjust their farming practices due to climate change or socioeconomic dynamics, e.g., aging, labor limitation, and urbanization, they expressed needed assistance, especially from governmental authorities. The three most needed help include

an effective and transparent price assurance system for farm products, easy access to agricultural extension and consultant services, and a reliable weather forecast system (Table 6.11). Since Thailand's rice farming mainly relies on rainwater, farmers need a reliable weather forecast system to help them plan and adjust their planting activities accordingly. Especially drastic and fluctuating weather conditions are observed more frequently due to climate change. Finally, price assurance and agricultural extension, and consultant services are most needed, especially during this time period with climate change, urbanization, and disruptive technologies. Farmers need scientific data, e.g., weather, water availability, soil conditions, fertilizer application, and planting techniques, to support their traditional knowledge and practice to adapt to the changing environment. Reasonable prices must be assured so farmers can continue farming.

Table 6.9. Climate change adaptation practices of the interviewed farmers.

Adaptation practice	Yes (%)	No (%)
1. Dug water pond(s) on farmlands to store water for use, esp. in dry seasons ¹	56.04	43.96
2. Changed rice varieties to more drought/flooding tolerant ³	37.50	62.50
3. Purchased insurance covering damages from natural disasters	15.80	84.20
4. Changed a rice planting method from transplanting to direct sowing ²	47.80	52.20
5. Reduced a number of days to flood the paddy fields ⁻¹	5.49	94.51
6. Extracted ground water	20.47	79.53
7. Allocated some parts of the farmland to practice agroforestry	25.14	74.86
8. Increased areas of agroforestry to improve crop productivity	11.95	88.05
9. Reduced amounts of rice planting areas according to water conditions ⁻²	8.93	91.07
10. Used technologies to help decide when and how to apply fertilizers ⁻³	10.16	89.84

Note: 1, 2, 3 indicate the three most common adaptation practices. -1, -2, -3 indicate the three least practices.

Table 6.10. Information on farmer's adaptation practice

Items	N	Mean	Std. Deviation
Average pond size (m ³)	408	2,701.77	2,716.25
A number of ponds on farmland	405	1.40	0.72
Pond digging expense (Baht)	286	14,985.14	19,659.53
Insurance liability (Baht per year)	69	3,670.61	9,389.74
Points of ground water accessed	156	1.23	0.64
Ground water depth (m)	152	33.80	23.69
Ground water system cost (Baht per point)	138	16,581.88	15,042.35
Area size on farm with agroforestry practice (Rai)	96	3.37	4.55
Area size on farm with agroforestry practice (% to the total farmland)	90	17.64	18.23

Table 6.11. Farmer's needs to assist them to adapt to climate change.

Assistances	Needed (%)	Not needed (%)
1. Reliable weather forecast system ³	93.40	6.60
2. Natural disaster insurance	89.70	10.30
3. Low interest farming loan	88.00	12.00
4. Farming technologies for effective farming design and management	93.00	7.00
5. Agricultural extension and consultant services with easy access ²	94.50	5.50
6. Marketing development, easy access and available throughout	92.58	7.42
7. Financial support for digging small ponds and ground water extraction	86.20	13.80
8. Effective and transparent price assurance system for farm products ¹	96.70	3.30

Note: 1, 2, 3 indicate the three most needed assistances expressed by the interviewed farmers.

Part 7 Water use in rice cultivation: Water supply, quality, and footprint

Introduction

Unlike many food crops, rice plants tolerate water logging. In the climate of Southeast Asia, with heavy monsoon rains and seasonal flooding, rice cultivation thrives. This adaptation of nature allows rice to outcompete weeds, such that water provides an ecosystem service of natural weed control. Furthermore, rainwater helps transferring nitrogen from the sky to the soil. Rainwater contains nitrogen in forms that plants can absorb. Farmers notice that rainwater stimulates more plant growth than water from other sources, which is beneficial because they don't need to apply as much artificial fertilizer. The additional fauna and flora which is attracted to rice wetlands, also contribute to various ecosystem services, including pest control, food resources and soil fertility enhancement.

Rice is among many cash-crops, including soybeans, cotton and nuts, that consumes large amounts of water (Table 7.1). When rice is grown out of season or outside floodplains, irrigation supply is required to generate and maintain these ecosystem services when needed. Irrigation supply is limited. Areas such as the Central Plains of Thailand have abundant access to irrigation infrastructure, but even so, water supply for rice production is not guaranteed, particularly in drought years. Rice is only one amongst several competing uses for irrigation supplies.

In this component of the TEEBAgriFood study, we analyzed water supply, water quality and water footprint in sustainable and conventional rice cultivation practices. The purpose of this analysis is to measure and value hydrological ecosystem services, which we would expect would be provided differently in the future under alternative scenarios. The two key ecosystem services to be assessed are: water supply and water quality amelioration.

Table 7.1. Water footprints (WF) of different cash-crop types.

Crop type	Total WF	WF _{green}	WF _{blue}	WF _{grey}	Ref.
Cotton (m ³ /ha)	9,059	3,192	5,867	-	Gebremariam et al., (2021)
Cassava (m ³ /ton)	465.87	194.01	187.33	84.53	Vetayavethin and Limsiri (2019)
Corn root (m ³ /ton)	1.39	0.765	-	0.625	Cheroennet & Suwanmanee (2017)
Soybean (m ³ /ton)	1,972.3	1,547.8	282.8	162.5	Costa et al., (2021)
Cotton (m ³ /ton)	1,825.2	1,160.5	447.9	238.7	
Corn (m ³ /ton)	512.4	495.3	96.8	62.2	
Soybean (L/kg)	805	684	-	121	Tozzini, Pannunzio & Soria (2021)
Maize (L/kg)	533	161	-	371	
Wheat (L/kg)	992	371	-	621	
Rice (m ³ /ton)	624.31	393.32	124.86	106.13	Li, Wu & Deng (2022)
Maize (m ³ /ton)	527.26	174.00	131.82	221.45	
Soybean (m ³ /ton)	1,298.21	480.34	649.11	168.77	
Rice (m ³ /ton)	1,097	691.11	208.43	186.49	Kashyap & Agarwal (2021)
Wheat (m ³ /ton)	871	130.65	452.92	287.43	
Beans (m ³ /kg)	0.821-2.191	0.648-1.646	0.249-0.689	-	Wang, Zhao & Tian (2021)
Sugar crops (m ³ /ton)	197	130	52	15	Mekonnen & Hoekstra (2011)
Nuts (m ³ /ton)	9,063	7,016	1,367	680	
Sugarcane (m ³ /ton)	202	90	87	25	Kongboon & Sampattagul (2012)
Cassava (m ³ /ton)	509	192	232	85	

7.1 Methods

The study consists of firstly a literature review on water supply, water quality and water footprint of rice production in Thailand and other countries under different rice practices. Similarities/differences between the two rice cultivation practices, including land preparation and tillage; methods of planting; farm maintenance, and harvesting, are investigated. Secondly, measurements of water supply, water quality parameters and water footprints according to the methods outlined below are conducted. Thirdly, the study gathered and assessed quantitative and qualitative data on rice farming practices and farmer adaptation to climate change. Figure 7.1 depicts a methodological framework of the water use study in different rice cultivation: sustainable rice (SRP) vs conventional rice practice (CON).

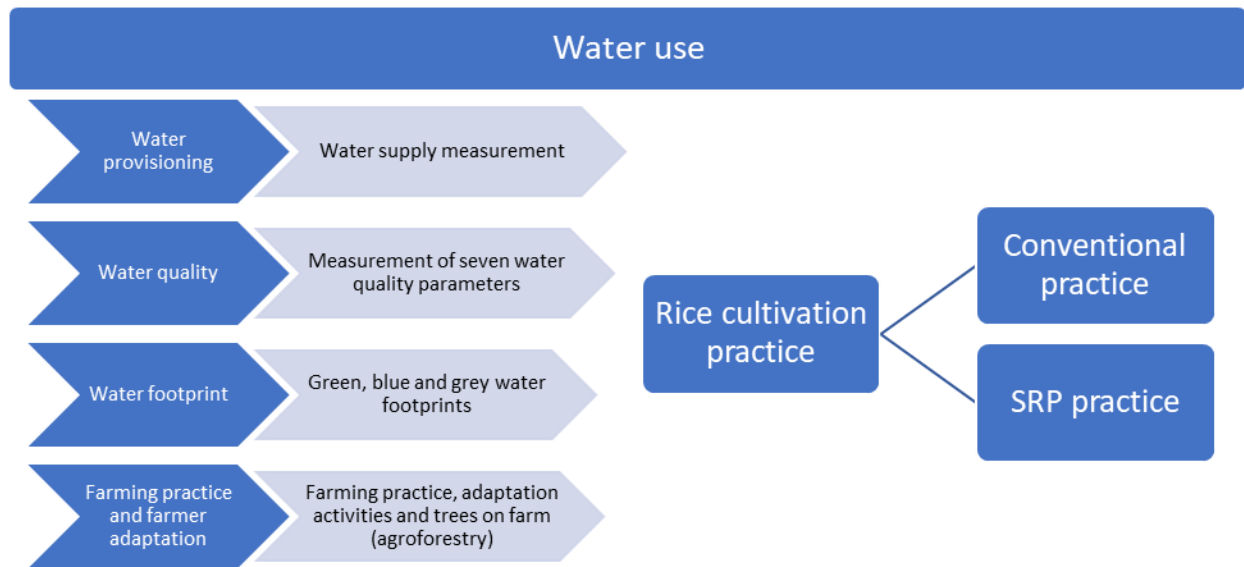


Figure 7.1. Methodological framework for the study on water use in rice cultivation.

7.1.1 Measurement of water supply

To quantify water supply, the approach proposed in this study is based on parameters which are available from meteorological and hydrological datasets. The water supply (WS in mm/year) was estimated following Equation 1 (Mastrorilli et al., 2018):

$$WS = SPTC - ET - EF \quad (\text{Equation 1})$$

where SPTC is the precipitation water (mm/year), ET is evapotranspiration (mm/year) and EF is the water requirement for maintaining the aquatic ecosystems (mm/year). EF data were sourced from the Global Environmental Flow Information System (<http://eflows.iwmi.org/>), developed by the Food and Agriculture Organization (FAO). Moreover, amounts of stored runoff water were obtained from the Royal Irrigation Department's database to estimate available water supply.

7.1.2 Measurement of water quality

Eight parameters (Table 7.2) of physical and chemical characteristics of surface water were measured to examine water quality from different rice cultivation practices. Three of these parameters were compared against Thailand's surface water quality standard, developed by the Pollution Control Department. This helps assess whether surface water satisfies the criteria for Class III quality: Fair condition, with some pollutant contamination, suitable for consumption after

customary water treatment and disinfection processes and for agriculture. The standard requires a pH value of between 5-9, a minimum level of dissolved oxygen level of 4 mg/L, and a maximum level of nitrates (NO₃) of 5 mg/L. In this study, we did not measure pesticide contamination in water since the potential risk of pesticides in rice cultivation mainly occurs in forms of “air pollutants” in which farmers usually get exposed to such pesticide during spraying.

According to previous analyses of nutrient contamination from rice cultivation process, nitrogen recovery (in which nitrogen is finally released back to the atmosphere as N₂ gas) rarely exceeds 30-40% in wetland rice cultivation systems. Rice is primarily grown in clay soils, thus restricting N loss by leaching. Phosphate fertilizer is generally applied as base fertilizer before transplantation of paddy rice. Concentration of phosphate in surface drainage has been reported to gradually decrease throughout the entire growth period, but the phenomenon may be different in case of all year loading with low levels of precipitation (Wu et al., 2022).

Table 7.2. Eight water quality parameters to be measured from different rice fields.

Physical parameters	Chemical parameters
Turbidity	Acidity / alkalinity (pH)
Total dissolved solids	Salinity (% salinity)
	Electrical conductivity
	Dissolved oxygen (DO)
	Nitrate concentration (NO ₃)
	Phosphate concentration (PO ₄)
Thailand’s Water Quality Standard for surface water: Class III Fair condition – with some pollutant contamination, suitable for (1) consumption after customary water treatment and disinfection processes and (2) agriculture (Pollution Control Department, 1994)	

7.1.3 Estimation of water footprint

The volumetric footprint of water represents the amount of freshwater used in rice cultivation, from land preparation to crop harvesting. This includes irrigation water (blue water), rainwater (green water) and water required to dilute polluted water to reference quality (grey water). On average, rice cultivation in Thailand has a water footprint of 1,665 m³/ton. This is the equivalent of one hectare of rice cultivation requiring about 6,340 m³ of water per ha. Different rice varieties have different water demands and cope differently to water shortage. Khao Dawk Mali 105 has the highest water scarcity footprint (598 m³ H₂O e/t paddy rice) as the Northeastern area where it is cultivated, has the highest water stress index (Mungkung et al., 2019). Moreover, AWD water management technique is assumed to help reduce amounts of water use in rice

cultivation with minimal impact on rice yield. Lampayan et al. (2015) reported that demonstration trials and training in eight countries in Asia with large scale adoption in the Philippines, Vietnam and Bangladesh illustrated that AWD has reduced irrigation water input by up to 38% with no yield reductions if implemented correctly.

For rice crops, total water demand is estimated by adding amounts of water required in each of the crop cultivation stages, including land preparation (soil saturation), planting (standing water layer, percolation and crop evaporative demand) and harvesting (land drying). The water footprint of paddy rice ($m^3/unit$) is calculated as the ratio of the total volume of water used ($m^3/year$) to the quantity of the production (ton/year). The total water footprint of the process of growing rice (WF_{total}) is the sum of the green, blue and grey components (Equation 2) (Hoekstra et al., 2011):

$$WF_{total} = WF_{green} + WF_{blue} + WF_{grey} [m^3/ton] \quad (\text{Equation 2})$$

The green component in the water footprint of the process of growing rice (WF_{green} , m^3/ton) is calculated as the green component in crop water use (CWU_{green} , m^3/ha) divided by the crop yield (Y , ton/ha) (Equation 3). The blue component (WF_{blue} , m^3/ton) is calculated in a similar way (Equation 4):

$$WF_{green} = CWU_{green} / Y \quad (\text{Equation 3})$$

$$WF_{blue} = CWU_{blue} / Y \quad (\text{Equation 4})$$

The grey component in the water footprint of growing rice (WF_{grey} , m^3/ton) is calculated as the chemical application rate to the field per hectare (AR , kg/ha) times the leaching-run-off fraction (α) divided by the maximum acceptable concentration (c_{max} , kg/ m^3) minus the natural concentration for the pollutant considered (C_{nat} , kg/ m^3) and then divided by the crop yield (Y , ton/ha) (Equation 5).

$$WF_{grey} = [(\alpha \times AR) / (c_{max} - C_{nat})] / Y \quad (\text{Equation 5})$$

The green and blue components in crop water use (CWU , m^3/ha) are calculated by accumulation of daily evapotranspiration (ET , mm/day) over the complete growing period (Equation 6 and 7).

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \text{ (volume/area)} \quad (\text{Equation 6})$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \text{ (volume/area)} \quad \text{(Equation 7)}$$

where ET_{green} represents green water evapotranspiration and ET_{blue} blue water evapotranspiration. The factor 10 is applied to convert water depths in millimeters into water volumes per land surface in m^3/ha . The summation is done over the period from the day of planting (day 1) to the day of harvest (lgp stands for length of growing period in days).

7.1.4 Investigation of farming practice and farmer adaptation to climate change

This study also examined farming practices that may affect water use, including the maintenance of trees on farm (agroforestry), water rights and accessibility to irrigation, and farmer adaptation to climate change. Data were obtained from the questionnaire survey, a field survey of trees on farm and secondary data retrieved from relevant authorities e.g., the Royal Forest Department. This helps identify farming practices, access to water, farmer adaptation activities to climate change i.e., flood and drought, and the number of tree/plant species on paddy fields on sustainable and conventional rice paddies in the Northeast and Central Plains. The number of tree species and the total number of trees were recorded to create a species list, and assessed total tree density. These data were tested against different rice cultivation practices: the SRP vs. CON.

7.2 Results

7.2.1 Climatic conditions and variability in the past 25 years (1997-2021)

Climatic patterns determine ecosystem composition, structure, function, and ecosystem services in which our livelihoods depend upon. Changing climatic conditions will directly impact ecosystems and ecosystem services, including water provisioning and usage. Thailand is located in a tropical zone where its climatic patterns are influenced by the Southwestern and Northeastern monsoons. The Southwestern monsoon brings moisture to the entire country between May and October. The Northeastern monsoon causes dry weather to mainland Thailand between November and April. The monsoon provides the South with extra rainfall as moisture accumulates in the Gulf of Thailand. According to the Koppen-Geiger climate classification, Thailand's major climatic pattern is a tropical savanna – dry winter climate (Aw). Some coastal areas in the South are classified as Equatorial climate (Af) where all 12 months have an average precipitation of at least 60 mm. The South essentially has a monsoon climate (Am).

According to the Royal Irrigation Department (RID), the average annual rainfall depth (1995-2018) in the country's major river basins is 1,322.72 mm/year, where the South alone

receives 2,188.08 mm/year and 1,051.13 and 1,246.04 mm/year for the Central Plain and Northeast, respectively. In addition, the average annual rainfall during 1997-2021 obtained from Thailand's Meteorological Department (TMD) is 1,322.64 mm and 1,534.45 mm for the Central Plain and Northeast, respectively (Table 7.3). Temporal distribution of the rain in the Central Plain and Northeast are similar in which rainfall over 100 mm occurs in May and continues on until October. This pattern determines the beginning of rain-fed rice growing season. Moreover, the Central Plain's daily minimum temperature is higher than the Northeast's, same as the daily maximum temperature, except that the Northeast surpassed the Central Plain around 2012 onward. Nevertheless, the two regions show increasing temperature with decreased amounts of rainfall during this 25-year period.

Table 7.3. Climatic conditions during 1997-2021 by provinces.

Province	Min. Temp (Celsius)	Max. Temp (Celsius)	Relative Humidity (%)	Wind speed (km/day)	Sun hours (hrs/day)	Amounts of rainfall (mm/month)	Amounts of rainfall (mm/year)
Central Plain	20.68	35.76	75.28	101.32	6.60	110.76	1,322.64
Ayutthaya*	20.52	36.65	75.26	131.08	6.22	90.04	1,080.47
Bangkok	22.66	36.08	71.64	145.37	6.14	131.31	1,444.44
Chainat*	21.23	36.37	74.29	61.99	7.24	87.30	1,047.63
Kampaengpetch	20.66	36.54	75.78	33.49	No data	107.65	1,291.76
Lopburi	20.65	36.79	72.81	83.06	No data	94.24	1,130.87
Nakornnayok	14.99	26.70	87.98	110.66	No data	287.23	3,446.71
Nakornpathom	20.39	36.31	78.13	74.10	6.68	87.56	1,050.70
Nakornsawan	20.80	36.82	72.84	64.85	6.84	102.28	1,227.35
Pichit	20.62	36.11	76.95	77.35	6.82	101.54	1,218.49
Petchabun	19.68	36.85	72.86	35.44	6.06	96.83	1,161.96
Pitsanulok	20.34	36.09	73.37	80.29	7.23	110.93	1,331.21
Pathumthani	22.05	36.88	74.31	135.37	5.91	111.90	1,342.86
Sukhothai	20.40	36.53	77.01	58.78	6.06	100.98	1,211.79
Samutprakan	22.69	34.15	72.89	274.91	7.05	104.93	1,259.20
Samutsongkhram	21.87	34.82	76.28	204.83	No data	91.31	1,095.68
Supanburi*	20.87	36.75	74.46	52.49	6.42	82.59	991.13
Uthaithani	21.20	37.48	72.92	98.46	7.10	96.05	1,152.65
Northeast	18.98	36.16	74.23	95.03	6.48	129.49	1,534.45
Bueng Kan	18.83	35.53	77.69	111.74	No data	287.18	3,159.00
Buriram	19.08	36.37	75.15	99.51	No data	109.75	1,316.94
Chaiyaphum	19.99	36.42	69.46	83.91	No data	96.04	1,152.50
Khon Kaen*	19.05	36.48	73.53	93.28	6.18	102.53	1,230.32

Province	Min. Temp (Celsius)	Max. Temp (Celsius)	Relative Humidity (%)	Wind speed (km/day)	Sun hours (hrs/day)	Amounts of rainfall (mm/month)	Amounts of rainfall (mm/year)
Kalasin	18.86	35.71	74.52	154.47	No data	114.09	1,369.09
Loei	17.83	36.14	76.73	63.22	6.06	106.47	1,277.64
Mukdahan	19.04	36.60	72.77	71.66	6.39	124.13	1,489.55
Maharakham	19.11	37.06	74.14	108.78	No data	111.86	1,342.28
Nongbua Lamphu	19.04	36.85	74.05	83.90	No data	107.90	1,294.78
Nong Khai	18.98	36.28	73.60	78.67	No data	145.31	1,743.66
Nakornpanom	17.79	35.58	74.88	60.13	6.10	180.37	2,164.46
Nakornratchasima*	19.63	35.63	72.70	130.00	5.89	94.08	1,129.01
Roi Et	19.06	35.84	73.41	125.07	7.27	117.78	1,413.31
Sakonnakorn*	18.09	35.78	75.04	55.40	6.97	137.09	1,645.09
Surin*	19.34	36.19	73.91	73.49	6.76	121.46	1,457.58
Si Sa Ket	19.60	36.09	74.44	80.33	7.01	123.43	1,481.13
Ubonratchathani*	19.30	36.45	73.51	108.66	6.56	138.21	1,658.52
Udonthani*	18.75	36.42	71.75	86.83	6.06	120.00	1,440.01
Umnatcharoen	19.05	35.42	76.53	109.39	No data	144.33	1,587.65
Yasotorn	19.14	36.40	76.83	122.11	No data	121.50	1,336.45

Note: * represents provinces selected as the case study.

Data source: the TMD

7.2.2 Hydrological ecosystem service – water supply

Water is one of the key hydrological ecosystem services provided by forest ecosystems. Fresh water is essential for our well-beings, including drinking water, water supply for household uses and industrial activities, and water for agriculture. Ecological processes that help maintain hydrological ecosystem services are directly influenced by land use and land management practices in combination with other factors such as basin topography, soil properties and rainfall characteristics. For example, in a catchment, forest areas and their management regulate the entire water cycle by sustaining evapotranspiration, reducing surface runoff and modulating floods. Amounts of hydrological ecosystem service or water supply depend on climatic conditions, which to a certain degree associate with forestlands in such areas. This section presents relationships between forest areas (%) in the Northeast and the Central Plain and some key climatic factors affecting water supply in the two regions. Amounts of rainfall and relative humidity show positive correlations with forest areas (Figure 7.2: a-b), while minimum and maximum temperature reveal negative associations (Figure 7.2: c-d). These findings signalize that to maintain amounts of water supply, forest protection is necessary.

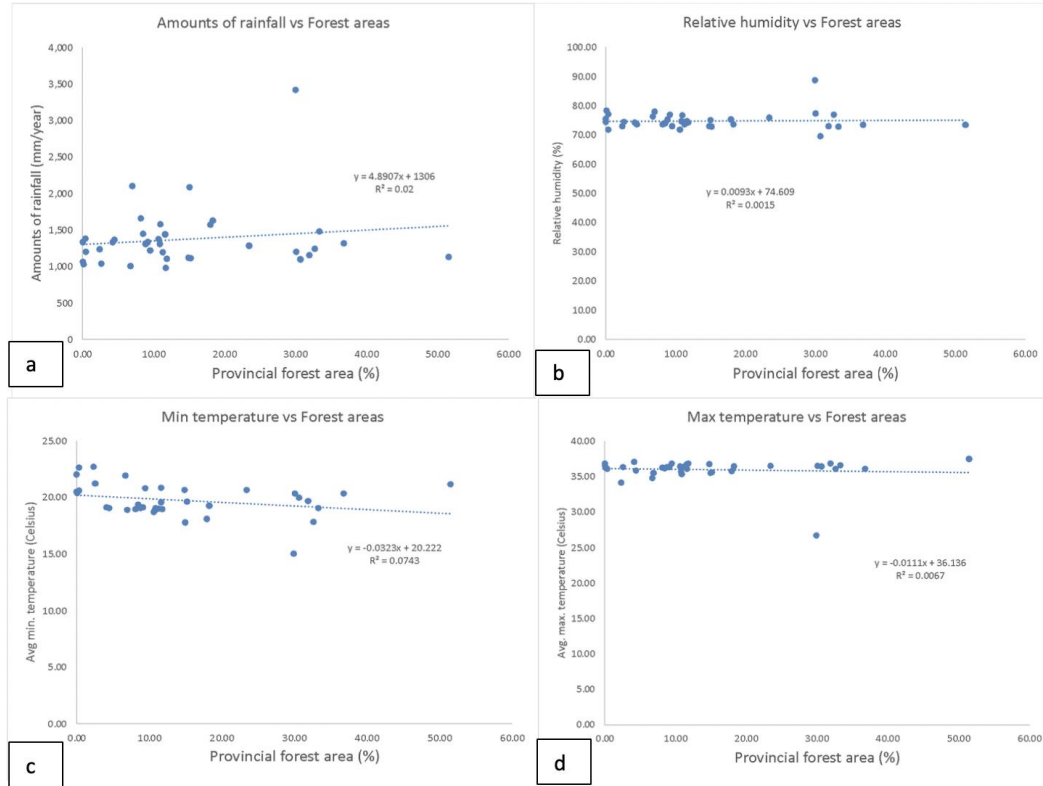


Figure 7.2. Correlations between forest areas (%) and some key climatic conditions i.e., amounts of rainfall (mm/year), relative humidity (%), minimum and maximum temperature (degree Celsius).

Water provisioning or water supply is defined as water storage in rivers, lakes and aquifers (De Groot et al., 2002). This ecosystem service is correlated to inflows into the water bodies and to the water harvesting systems and infrastructures (Nunez et al., 2006). Quantifying amounts of water supply can be expressed in different ways by combining the following terms: 1) the runoff (MEA, 2005), 2) the ratio between availability and demand for water resources (Boithias et al., 2014), and 3) the total volume of uptake water for different socio-economic purposes (Maes et al., 2016). In this study, we followed Mastrorilli et al. (2018) approach in which quantifying amounts of water supply is based on parameters that are generally available from meteorological and hydrological data, including precipitation water, evapotranspiration and environmental flow (EF). Moreover, secondary data from relevant authorities i.e., the RID and FAO, were retrieved to represent water supply available for use.

Table 7.4 summarizes amounts of rainfall and runoff water in Thailand's main river basins during 1995-2018. Averaged rainfall and stored runoff water in the Northeast's River basins (i.e., Kong, Chi and Mun) are approximately 1,246.04 mm/year and 253.44 mm/year, respectively.

Summed amounts of rain and stored runoff water in the three main basins are 219,439.95 million m³ and 43,916.59 million m³, respectively. Meanwhile, averaged amounts of rainfall for the Central Plain's River basins are smaller, except that the depth of runoff is higher, due to smaller basin areas (Table 7.5). Furthermore, Table 7.6 summarizes the average depth of rainfall during 1997-2021 and environmental flow (EF), which is the natural flow required to maintain the current conditions of aquatic ecosystems, specifically in the study provinces. Amounts of rainwater available for use were computed by subtracted EF out from the amounts of rainfall. Added this with amounts of natural annual runoff, amounts of available water for use can be estimated, which are 1,148.01 mm/year and 1,396.55 mm/year for the study provinces in the Central Plain and Northeast, respectively.

Table 7.4 Amounts of rainfall and runoff water in Thailand's main river basins during 1995-2018.

Region	Basin ID	Name	Basin areas (km ²)	Rainfall (mm/year)	Amounts of rainwater (10 ⁶ x m ³)	Amounts of stored runoff (10 ⁶ x m ³)	Depth of runoff (mm/year)
North	01	Salawin	17,918	1,169.08	20,947.58	8,797.98	491.01
North	03	Kok	7,895	1,288.53	10,172.94	3,509.67	444.54
North	06	Ping	33,896	1,020.13	34,578.33	7,157.71	211.17
North	07	Wang	10,792	967.84	10,444.93	1,566.74	145.18
North	08	Yom	23,616	1,080.74	25,522.76	4,083.64	172.92
North	09	Nan	34,331	1,182.52	40,597.09	10,555.24	307.46
NE	02	Kong	57,424	1,525.54	87,602.61	30,319.26	527.99
NE	04	Chi	49,477	1,106.69	54,755.70	6,351.66	128.38
NE	05	Mun	69,701	1,105.89	77,081.64	7,245.67	103.95
CP	10	Chao Praya	20,126	960.86	19,338.27	3,480.89	172.95
CP	11	Sakaekrang	5,191	1,055.13	5,477.18	1,204.98	232.13
CP	12	Pha Sak	16,291	1,093.63	17,816.33	2,316.12	142.17
CP	13	Tha Chin	13,681	946.94	12,955.09	1,243.69	90.91
CP	14	Mae Klong	30,837	1,296.84	39,990.66	17,395.93	564.13
CP	19	Petchaburi	5,603	891.68	4,996.08	2,148.32	383.42
CP	20	W. coast	6,744	1,112.81	7,504.79	2,101.34	311.59
East	15	Prachinburi	10,480	1,368.04	14,337.06	3,871.01	369.37
East	16	Bang Pakong	7,978	1,226.31	9,783.50	3,046.58	381.87
East	17	Tonelesap	4,151	1,267.53	5,261.52	2,002.01	482.30
East	18	E. coast	13,829	1,904.02	26,330.69	12,638.73	913.93
South	21	E. coast	26,352	2,080.18	54,816.90	23,571.27	894.48
South	22	Tapi	12,224	1,943.64	23,759.06	10,453.98	855.20
South	23	Songkla Lake	8,495	1,930.21	16,397.13	4,427.23	521.16
South	24	Pattani	3,857	2,556.89	9,861.92	4,339.25	1,125.03
South	25	W. coast	20,473	2,429.46	49,738.33	18,900.57	923.19

Region	Basin ID	Name	Basin areas (km ²)	Rainfall (mm/year)	Amounts of rainwater (10 ⁶ x m ³)	Amounts of stored runoff (10 ⁶ x m ³)	Depth of runoff (mm/year)
Total			511,362	1,322.72	680,068.09	192,729.48	376.89

Data source: RID (<http://water.rid.go.th/hyd/download/rainfall-runoff-25basin.pdf>), accessed date: January 30, 2023.

Table 7.5. Amounts of rainfall and runoff water in Thailand's main river basins grouped by regions

Region	Amounts of rain (mm/year)	Amounts of rainwater (10 ⁶ x m ³)	Amounts of stored runoff (10 ⁶ x m ³)	Depth of runoff (mm/year)
Central Plain	1,051.13	15,439.77	4,270.18	271.04
East	1,441.48	13,928.19	5,389.58	536.87
North	1,118.14	23,710.61	5,945.16	295.38
Northeast	1,246.04	73,146.65	14,638.86	253.44
South	2,188.08	30,914.67	12,338.46	863.81
Total	1,322.72	680,068.09	192,729.48	376.89

Data source: RID (<http://water.rid.go.th/hyd/download/rainfall-runoff-25basin.pdf>), accessed date: January 30, 2023.

Table 7.6. Depth of rainfall (during 1997-2021), environmental flow (EF), amounts of rainwater after subtracted by EF, natural annual runoff and available water for use in the study provinces.

Province	Rainfall (mm/year)	EF (%) ^a	Amounts of rainwater (mm/year) ^b	Amounts of natural runoff (mm/year) ^c	Available water for use (mm/year) ^d
Central Plain	1,039.79	20.38	832.51	315.51	1,148.01
Ayutthaya	1,080.47	13.72	932.34	389.27	1,321.61
Chainat	1,047.63	6.16	983.09	192.87	1,175.96
Supanburi	991.13	41.27	582.09	364.38	946.47
Northeast	1,426.79	45.41	761.35	635.21	1,396.55
Khon Kaen	1,230.32	51.56	595.97	359.96	955.93
Nakornratchasima	1,129.01	21.35	887.96	302.52	1,190.48
Sakonnakorn	1,645.09	48.47	847.72	842.90	1,690.62
Surin	1,457.58	34.61	953.26	550.31	1,503.57
Ubonratchathani	1,658.52	63.11	611.83	1,077.76	1,689.59
Udonthani	1,440.01	53.38	671.33	677.79	1,349.12
Total	1,297.79	37.07	785.07	528.64	1,313.71

Note:

^a. Environmental flow (EF) is the water requirement for maintaining the aquatic ecosystems. In this study, EF (% of the natural flow required to maintain the current condition of river) in each of the study provinces was acquired from the Global Environmental Flow Information System at <http://eflows.iwmi.org/>.

^b. Amounts of rainwater represent amounts of rainfall subtracted by the EF.

^c. Amounts of natural annual runoff were obtained from the Global Environmental Flow Information System at <http://eflows.iwmi.org/>.

^d. Available water for use is a sum of amounts of rainwater and natural annual runoff.

7.2.3 Water usage and farming practice in rice cultivation

7.2.3.1 Crop water requirement

Rice cultivation requires certain amounts of water from the beginning toward harvesting either from rainfall or irrigation water. In this study, we used CROPWAT 8.0 to estimate the crop water requirement (CWR), which is the water needed for evapotranspiration under ideal growth conditions, measured from planting to harvest. “Ideal conditions” refer to conditions when adequate soil water is maintained by rainfall and/or irrigation, so that it does not limit plant growth and crop yield. Basically, the CWR is calculated by multiplying the reference crop evapotranspiration (ET_0) by the crop coefficient (K_C). Assumably, the CWR is fully met, so that actual crop evapotranspiration (ET_C) will be equal to the CWR: $ET_C = CWR$. The K_C values for rice plants i.e., KDML 105 and RD varieties, were obtained from the RID published documents. Meanwhile, provincial climatic parameters from the TMD (Table 7.3) were used to estimate ET_0 , which expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors.

Subsequently, the CWRs from different water sources i.e., rainfall and irrigation, were computed by estimating “effective precipitation (P_{eff})” or “effective rainfall” in this study. The P_{eff} describes the total amount of precipitation retained by the soil so that it is potentially available for meeting the water need of the crop. Effective rainfall is computed based on total amounts of rainfall with various methods offered in CROPWAT 8.0. In this study, we used the USDA SCS method (the United States Department of Agriculture, Soil Conservation Service) as it does not take into account the soil type and the net depth of irrigation. The USDA SCS gives a lower estimation of effective rainfall compared to the water balance approach. But since the water balance approach is highly data demanding, the USDA SCS method is widely used in estimating the effective rainfall in agriculture water management (Chapagain and Hoekstra, 2010). The USDA SCS equations to estimate effective rainfall are:

$$\begin{aligned} P_{eff} &= P_{total} / 125 \times (125 - 0.2 \times P_{total}) && \text{for } P_{total} \leq 250 \text{ mm} \\ P_{eff} &= (125 + 0.1 \times P_{total}) && \text{for } P_{total} \geq 250 \text{ mm} \end{aligned}$$

where P_{eff} is the effective rainfall and P_{total} is the total rainfall in the concerned period.

The irrigation requirement (IR) is calculated as the difference between CWR and effective rainfall. The IR is zero if effective rainfall is larger than the CWR. It is assumed that the IR s are fully met. Green water evapotranspiration (ET_{green}), or evapotranspiration of rainfall, can be equated with the minimum of total crop evapotranspiration (ET_C) and effective rainfall (P_{eff}). Blue water evapotranspiration (ET_{blue}), or field-evapotranspiration of irrigation water, is equal to the

total crop evapotranspiration minus effective rainfall (P_{eff}), but zero when effective rainfall exceeds crop evapotranspiration. All water flows are expressed in mm/day or in mm per period of simulation (e.g. ten days) and summed up to the one-year period of cultivation (mm/year). Lastly, amounts of ET_{green} and ET_{blue} in the depth unit (mm/year) were converted to water volume per hectare (m^3/ha) by multiplying them with 10, and they are referred to as the crop water use (CWU). Figure 7.3 depicts a step-through diagram of crop water requirement and crop water use calculation.

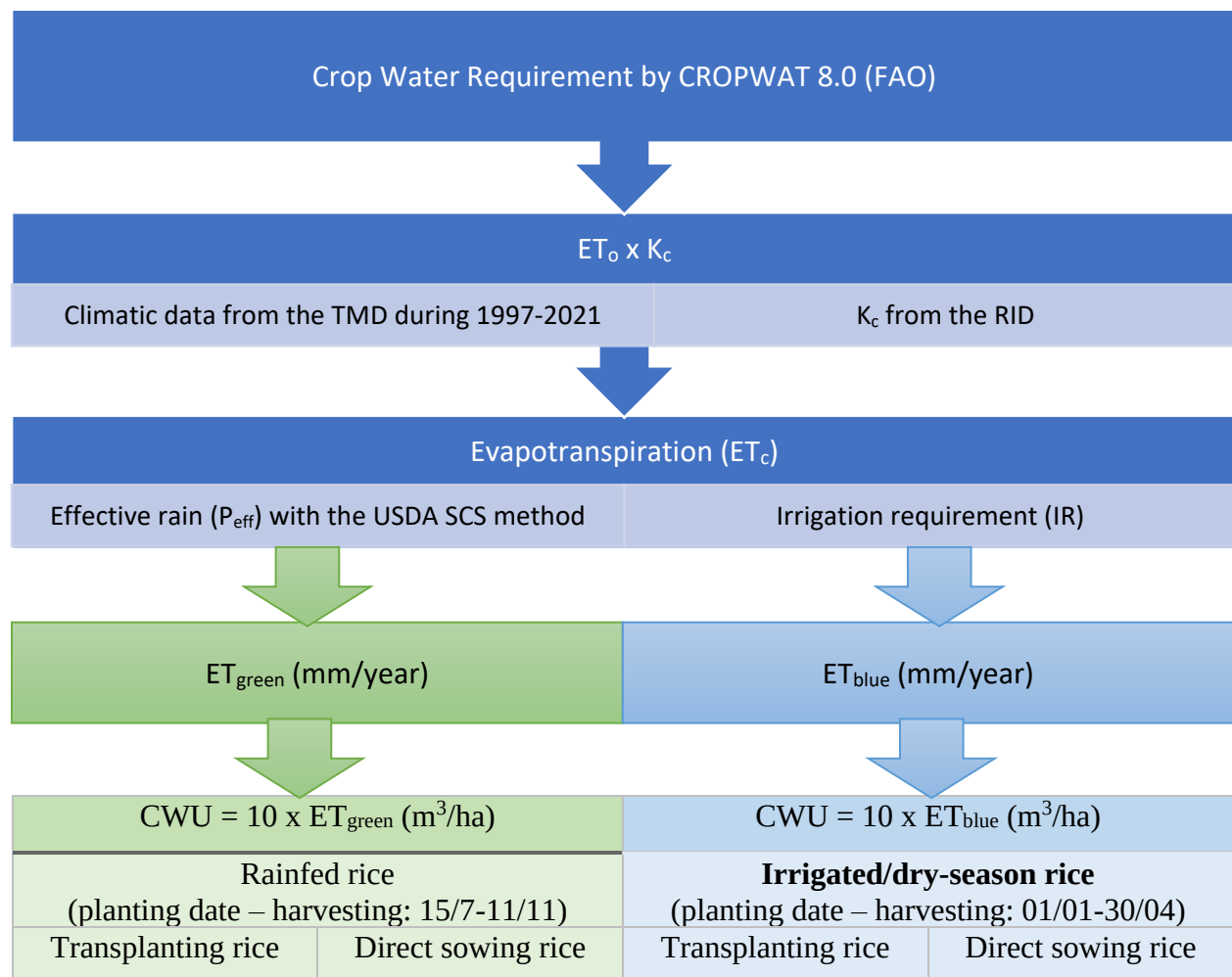


Figure 7.3. A step-through diagram of crop water requirement and crop water use calculation.

Table 7.7 summarizes CWR, effective rainfall, irrigation water requirement and CWU in the Central Plain and the Northeast. The two regions obtained similar amounts of ET_C , but the Northeast's effective rain depth is higher. Rice cultivation in the Central Plain depends more on

irrigation water, whereas the Northeast relies more on rainwater. Moreover, the rain-fed rice cultivation used less water than irrigated or dry-season rice planting. Direct sowing required less water than the transplanting method. Overall, averaged amounts of water use from rain (CWU-green) and irrigation water (CWU-blue) are 3,500.94 m³/ha and 5,914.03 m³/ha, respectively, or summed up to 9,414.97 m³/ha. Mungkung et al. (2019) reported that rice cultivation in Thailand normally requires water approximately 6,340 m³/ha.

Table 7.7. Crop water requirements (ET_c), effective rainfall (Pe_{eff}), irrigation water requirement (IR) and crop water use (CWU) by regions, cultivation seasons and planting methods.

Province	ET _c (mm/year)	Effective rain (mm/year)	IW (mm/year)	CWU-green (m ³ /ha)	CWU-blue (m ³ /ha)	Sum CWU (m ³ /ha)
Central Plain	707.23	316.65	605.14	3,166.50	6,051.42	9,217.92
1. Rain-fed rice	627.25	514.55	306.72	5,145.50	3,067.17	8,212.67
= Direct sowing	624.33	499.87	311.27	4,998.67	3,112.67	8,111.33
= Transplanting	630.17	529.23	302.17	5,292.33	3,021.67	8,314.00
2. Irrigated rice	787.20	118.75	903.57	1,187.50	9,035.67	10,223.17
= Direct sowing	783.73	116.07	903.60	1,160.67	9,036.00	10,196.67
= Transplanting	790.67	121.43	903.53	1,214.33	9,035.33	10,249.67
Northeast	708.01	367.93	584.53	3,668.17	5,845.33	9,513.50
1. Rain-fed rice	625.73	584.47	291.72	5,822.50	2,917.17	8,739.67
= Direct sowing	622.83	563.28	293.53	5,632.83	2,935.33	8,568.17
= Transplanting	628.63	605.65	289.90	6,012.17	2,899.00	8,911.17
2. Irrigated rice	790.29	151.38	877.35	1,513.83	8,773.50	10,287.33
= Direct sowing	786.90	149.95	879.22	1,499.50	8,792.17	10,291.67
= Transplanting	793.68	152.82	875.48	1,528.17	8,754.83	10,283.67
Grand Total	707.75	350.83	591.40	3,500.94	5,914.03	9,414.97

7.2.3.2 Water quality and grey water footprint

In this study, four provinces (i.e., Chai Nat, Suphanburi, Khon Kaen and Surin) with rice cultivation under the CON and SRP in the Central Plain and the Northeast were selected. Twenty water samples were collected from rice paddies in each of the selected provinces including both the CON and SRP rice cultivation practices. Eight parameters i.e., DO, pH, EC, Salinity, Turbidity, TDS, TP and NO₃ were measured to illustrate physical and chemical characteristics of water quality in rice paddies. They were compared against Thailand's water quality standard to examine water quality from different rice cultivation practices: SRP vs CON. Analytical methods

of all the parameters were based on the standard methods for water and wastewater examination (APHA, 2017).

For grey water footprint calculation in rice cultivation, nitrogen (N) was used as a representative element for estimation. The rate of nitrogen leaching is 10% of nitrogen-based fertilizer application rates and the permissible limit in surface water source of 5.0 mg/L NO₃-N was selected, followed Thailand's water quality standard for surface water to estimate the volume of water necessary to dilute leached nitrogen to the permissible limit. Data on average fertilizer application rates for all study sites were obtained from the household socioeconomic survey (Table 7.8). The equation for grey water footprint calculation is shown in Equation 5.

Table 7.8. Average fertilizer application rates and average rice yields for the rain-fed rice and irrigated rice cultivation.

Province	Rain-fed rice cultivation							
	CON				SRP			
	TP	AR	SW	AR	TP	AR	SW	AR
	Yield (tons/ha)	(kg/ha)	Yield (tons/ha)	(kg/ha)	Yield (tons/ha)	(kg/ha)	Yield (tons/ha)	(kg/ha)
Chai Nat	6.00	302.43	5.64	284.72	5.93	282.14	4.86	367.49
Suphanburi	5.77	262.50	5.00	278.79	8.44	481.25	4.97	274.14
Khon Kaen	1.97	113.94	2.12	147.82	1.96	80.00	1.98	79.05
Surin	2.74	151.34	2.65	273.62	1.97	143.75	2.58	154.80
	Irrigated rice cultivation							
	CON				SRP			
	TP	AR	SW	AR	TP	AR	SW	AR
	Yield (tons/ha)	(kg/ha)	Yield (tons/ha)	(kg/ha)	Yield (tons/ha)	(kg/ha)	Yield (tons/ha)	(kg/ha)
Chai Nat	6.24	335.00	5.32	349.00	5.65	326.25	4.70	546.88
Suphanburi	5.22	150.00	5.85	355.93	8.44	200.00	5.37	358.24
Khon Kaen	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Surin	n/a	n/a	3.53	153.13	n/a	n/a	2.15	200.00

Note: n/a = Not available, CON= conventional practice, SRP= suitable rice practice

TP = Transplanting planting method, SW = Sowing planting method,

AR = amount of fertilizer applied per hectare

$$WF_{grey} = \frac{(\alpha \times AR)}{Y(C_{max} - C_{natural})} \quad \text{(Equation 5)}$$

Where α is the leaching-runoff fraction for Nitrogen (0.1)

AR is the amount of fertilizer applied per hectare (kg/ha)

$C_{\max}$ is the maximum acceptable concentration of $\text{NO}_3\text{-N}$ (5.0 mg/L) for the receiving water body

C_{natural} is the natural background concentration in the receiving water body, which was zero in the current study

Y is the rice production yield (ton/ha)

Water quality from the selected paddy fields in this study is shown in Table 6.9. Fluctuation of EC, Turbidity and TDS values were observed. They pointed out that a number of appropriated sampling points are necessary for monitoring of water quality in the rice field. According to the report from the Pollution Control Department of Thailand (2011), average concentrations of pollutants contaminated in rice paddies, including the total nitrogen, the total phosphorus and the suspended solids are 4.3, 1.0, 96.0 mg/L and 4.3, 0.16, 382.0 mg/L for the transplanting method (TP) and direct sowing method (SW), respectively. The concentration of total phosphorus from the TP method was slightly higher than the SW method similar to this study's findings.

Table 7.9 Average concentrations of water samples from sampled paddy rice fields.

Parameters	Chai Nat [CON]	Suphanburi [SRP]	Khon Kaen [CON]	Surin [SRP]
DO [mg/L]	5.96 [0.88]	1.43 [0.92]	8.40 [0.78]	8.27 [1.37]
pH	7.33 [0.48]	6.88 [0.10]	6.05 [0.40]	7.31 [0.68]
EC [$\mu\text{S}/\text{cm}$]	166.31 [25.11]	177.38 [11.47]	472.37 [443.74]	85.07 [81.70]
Salinity [ppt]	0.08 [0.01]	0.09 [0.01]	0.23 [0.22]	0.05 [0.04]
Turbidity [NTU]	45.33 [70.83]	80.46 [92.39]	20.29 [14.72]	69.83 [80.67]
TDS [mg/L]	117.75 [17.08]	160.00 [28.29]	300.83 [272.21]	102.25 [55.68]
TP [mg/L]	1.31 [0.35]	<0.75	<0.75	1.16 [0.10]
NO_3 [mg/L]	ND	2.13 [1.50]	ND	1.65 [0.00]

Note: ND = Not Detected, the number in the brackets = standard deviation (SD) of the water quality from all sampling sites [N = 20 samples/study site [province]], CON= conventional practice; SRP= suitable rice practice

We also analyzed the obtained water quality from the rice fields by comparing of two different rice cultivation areas in the Central Plain and the Northeast. Independent t-tests indicated that pH, EC, Salinity, Turbidity, and TDS of the water samples from the CON and SRP in both regions were significantly different ($p \leq 0.05$), whereas DO and NO_3 showed significant difference only with the water samples from the Central Plain. However, the amount of nutrient – total phosphorus has no significant difference in all study sites (Figure 7.4).

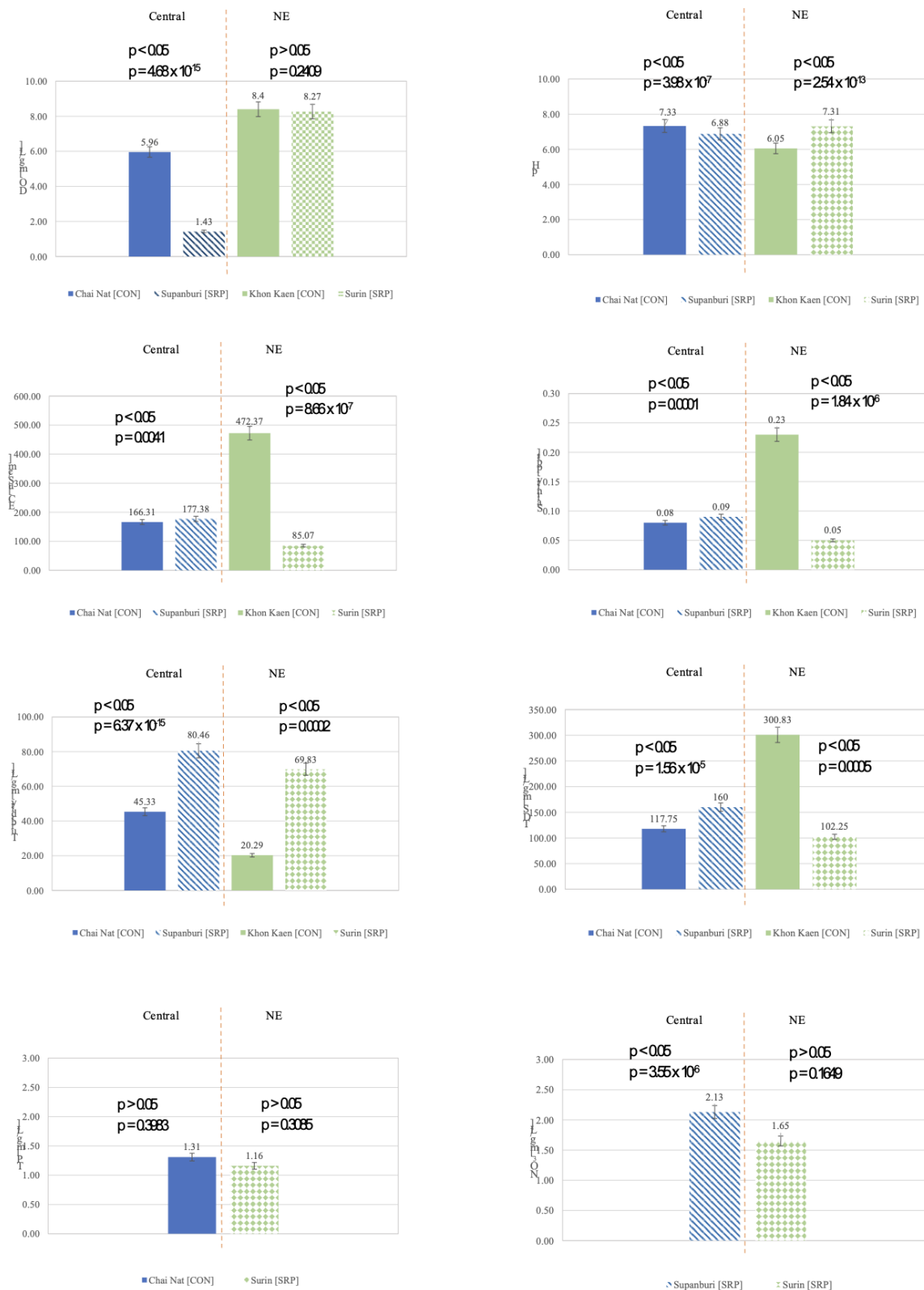


Figure 7.4. Water quality in the sampled rice paddies in the Central Plain and the Northeast.

Excessive use of N-based fertilizers resulted in large amounts of nitrogen deposition in surface and ground water. In this study, a size of WF_{grey} represents NO_3 -N dilution to a natural stage. The lowest and highest amounts of WF_{grey} per hectare from rain-fed rice cultivation were recorded in the Northeast under the SW method at 799.02 m^3/ton (Khon Kaen: SW with the SRP) and 2,061.34 m^3/ton (Surin: SW with the CON), respectively. The lowest WF_{grey} of 474.07 m^3/ton was estimated in the Central Plain under the irrigated rice cultivation with the transplanting method (Supanburi: TP within the SRP), whereas the largest amount of 2,329.17 m^3/ton was found in Chai Nat under the SW method under the SRP (Table 7.10). These findings suggest that low amounts of WF_{grey} from rain-fed rice cultivation can be achieved under the SW within the SRP practice. Meanwhile, for the irrigated rice cultivation, the transplanting method with the SRP resulted in low amount of WF_{grey} . This assumption pointed out that the amount of fertilizer applied per hectare (AR) is a limiting factor for WF_{grey} due to greater amounts and varieties of fertilizer application in the SW method compared to the TP method.

Table 7.10. WF_{grey} of the rain-fed rice and irrigated rice cultivation in the study provinces.

Province	$WF_{grey}-NO_3$ (m^3/ton)							
	Rain-fed rice cultivation				Irrigated rice cultivation			
	TP		SW		TP		SW	
	CON	SRP	CON	SRP	CON	SRP	CON	SRP
Chai Nat	1,008.91	952.37	1,009.94	1,512.95	1,073.71	1,154.19	1,310.97	2,329.17
Supanburi	910.36	1,140.74	1,114.80	1,103.84	575.00	474.07	1,216.38	1,335.30
Khon Kaen	1,154.98	814.53	1,391.46	799.02	n/a	n/a	n/a	n/a
Surin	1,102.68	1,457.03	2,061.34	1,199.69	n/a	n/a	866.78	1,859.65

Note: n/a = Not available, TP = Transplanting method, SW = Sowing planting method, CON= conventional practice; SRP= sustainable rice practice

In addition, the amounts of WF_{grey} from different cultivation types in the Central Plain and the Northeast were statistically analyzed. Independent t-tests revealed no significant difference between the two planting methods (TP vs. SW) in both cultivated regions (Figure 7.5). Concurrent analyzed results from rain-fed rice and irrigated rice cultivation were reported in this study. This refers to the importance of appropriated cultivation methods and amounts of fertilizer applied per hectare as mentioned above.

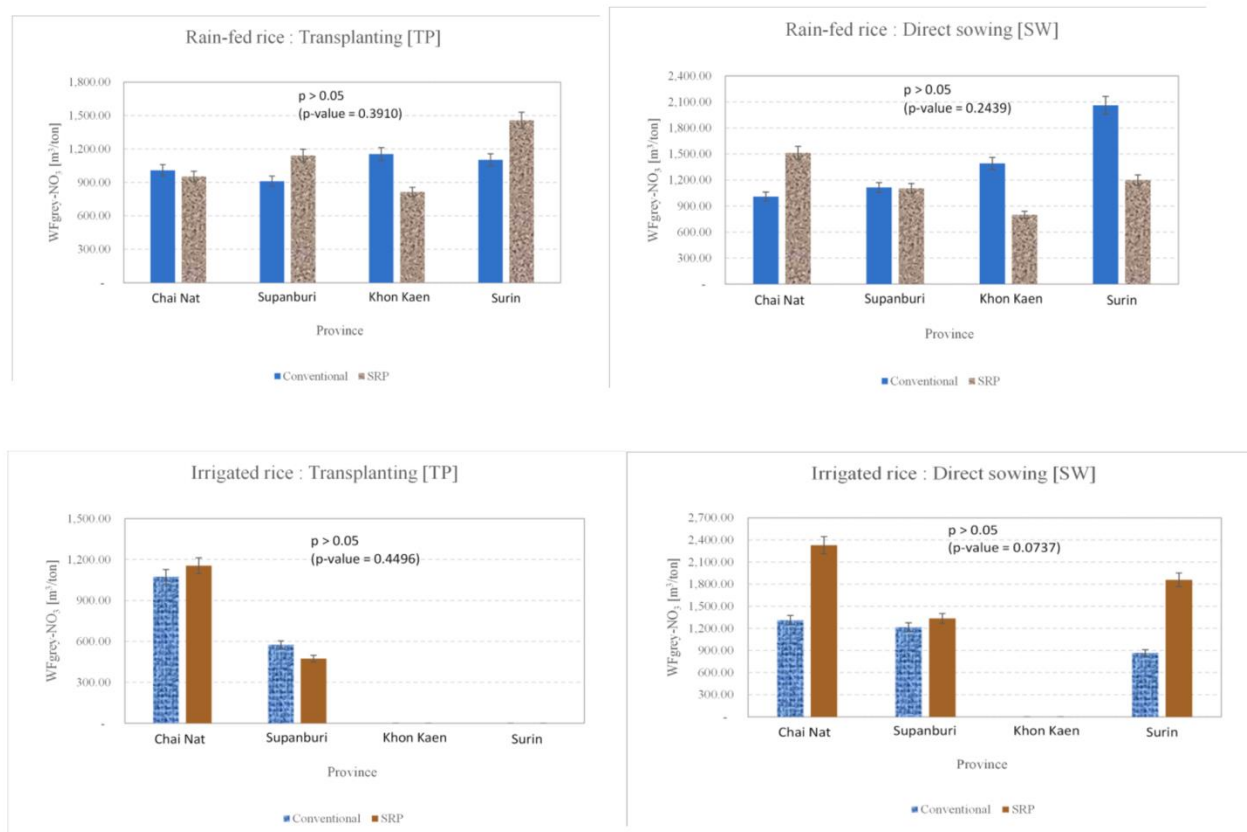


Figure 7.5. Grey water footprint with different crop seasons and planting methods.

In conclusion, water quality and WF_{grey} estimation emphasized on N element are expected to promote effective management of fertilizer applied per hectare in the paddy rice fields. Thus, appropriate cultivation methods e.g., the SRP will reduce amounts of WF_{grey} . However, the estimation of WF_{grey} based on both N and P elements is also interesting for further study. Nevertheless, the water quality standard for the receiving water body in each country is also a critical factor for the WF_{grey} of paddy rice cultivation.

7.2.3.3 Green, blue and total water footprints

Water footprint is an indicator of the human use of water, including green, blue and grey water footprints. A footprint size in agriculture is usually expressed in water volume per mass – m^3/ton , which is equivalent to liter/kg. Crop water use (m^3/ha) from rain and irrigation water were divided by rice yields (tons/ha) from different rice cultivation practices to estimate the green and blue footprints. The grey water footprint was calculated as the chemical application rate to the field per hectare (kg/ha) timed the leaching-run-off fraction divided by the maximum acceptable

concentration (kg/m^3) minus the natural concentration for the pollutant considered (kg/m^3) and then divided by the rice yields (ton/ha). The total water footprint of growing rice is the sum of the green, blue and grey components. And, the size of water footprints depends on amounts of rice yields from different cultivation practices. Higher yields will result in smaller footprints

Table 7.11 summarize rice yields, crop water uses and water footprints classified by regions. The Central Plain obtained significantly greater amounts of rice yields (5.79 tons/ha) than the Northeast, making their water footprints significantly smaller than the Northeast's footprints. The transplanting method gave slightly greater yields, but the rice consumed larger amounts of rainwater compared to the direct sowing (Table 7.12). The latter obtained $4,162.03 \text{ m}^3/\text{ton}$ of the total water footprint, larger than the transplanting method ($3,886.07 \text{ m}^3/\text{ton}$). The SRP, obtained greater yields with smaller green, blue and total water footprints but with no statistical significance when compared to the CON practice (Table 7.13). The green, blue and grey water footprints were accounted for 38%, 35% and 27%, and 37%, 32% and 31% for the CON and SRP practice, respectively.

Finally, Table 7.14 summarizes rice yields and amounts of water footprints across regions and cultivation practices altogether. The findings reiterate that the Central Plain obtained higher yields, resulting in smaller water footprints than the Northeast's footprints. Therefore, improving rice productivity is the key to reduce its water footprints. Since the Northeast's water availability is not that different compared to the Central Plain, its limiting factors are pointing to soil conditions and farm management. Nevertheless, the Northeast's rice agroecosystem illustrates quite environmental-friendly farm management. Thus, the priority remains at soil condition improvement as the key for water footprint reduction.

Table 7.11. Rice yields, crop water use and water footprints by regions.

Items	Region	N	Mean	Std. Deviation
Rice yields (tons/ha)**	Central Plain	20	5.79	1.03
	Northeast	25	2.37	0.49
ET_c (mm/year)	Central Plain	24	707.23	88.67
	Northeast	48	708.01	85.55
Effective rain (mm/year)	Central Plain	24	316.65	202.72
	Northeast	48	367.93	221.52
Irrigation requirement (mm/year)	Central Plain	24	605.14	306.20
	Northeast	48	584.53	298.18

Items	Region	N	Mean	Std. Deviation
CWU-green (m ³ /ha)	Central Plain	24	3,166.50	2,027.17
	Northeast	48	3,668.17	2,200.89
CWU-blue (m ³ /ha)	Central Plain	24	6,051.42	3,062.03
	Northeast	48	5,845.33	2,981.83
WF-green (m ³ /ton)**	Central Plain	20	553.25	369.02
	Northeast	24	2,301.28	747.03
WF-blue (m ³ /ton)*	Central Plain	20	1,062.87	556.83
	Northeast	24	1,601.84	1,127.12
WF-grey (m ³ /ton)	Central Plain	16	1,138.92	513.81
	Northeast	9	1,205.28	631.26
Total WF (m ³ /ton)**	Central Plain	16	2,755.04	716.97
	Northeast	9	5,108.39	1,155.04

Note: * and ** depict significant differences of the means from t-tests for the tested variables at 0.05 and 0.01, respectively.

Table 7.12. Rice yields, crop water use and water footprints by type of planting methods.

Items	Planting methods	N	Mean	Std. Deviation
Rice yields (tons/ha)	Transplanting	19	4.08	2.26
	Direct sowing	26	3.75	1.59
ET ^c (mm/year)	Transplanting	36	710.91	86.84
	Direct sowing	36	704.59	86.22
Effective rain (mm/year)	Transplanting	36	361.27	225.49
	Direct sowing	36	340.40	207.44
Irrigation requirement (mm/year)	Transplanting	36	589.41	301.43
	Direct sowing	36	593.39	300.56
CWU-green (m ³ /ha)	Transplanting	36	3,597.89	2,235.57
	Direct sowing	36	3,404.00	2,074.40
CWU-blue (m ³ /ha)	Transplanting	36	5,894.11	3,014.32
	Direct sowing	36	5,933.94	3,005.60
WF-green (m ³ /ton)	Transplanting	19	1,764.66	1,195.89
	Direct sowing	25	1,310.68	930.69
WF-blue (m ³ /ton)	Transplanting	19	1,136.53	411.45
	Direct sowing	25	1,524.30	1,183.37
WF-grey (m ³ /ton)*	Transplanting	12	984.88	1,061.03
	Direct sowing	13	1,327.05	541.90
Total WF (m ³ /ton)	Transplanting	12	3,886.07	2,396.02
	Direct sowing	13	4,162.03	1,401.71

Note: * depicts significant differences of the means from t-tests for the tested variables at 0.05.

Table 7.13. Rice yields, crop water use and water footprints by type of cultivation practices.

Items	Cultivation practice	N	Mean	Std. Deviation
Rice yields (tons/ha)	CON	23	3.72	1.68
	SRP	22	4.07	2.10
ET _c (mm/year)	CON	36	707.75	86.59
	SRP	36	707.75	86.59
Effective rain (mm/year)	CON	36	350.83	216.91
	SRP	36	350.83	216.91
Irrigation requirement (mm/year)	CON	36	591.40	301.00
	SRP	36	591.40	301.00
CWU-green (m ³ /ha)	CON	36	3,500.94	2,158.73
	SRP	36	3,500.94	2,158.73
CWU-blue (m ³ /ha)	CON	36	5,914.03	3,010.03
	SRP	36	5,914.03	3,010.03
WF-green (m ³ /ton)	CON	23	1,555.09	1,099.33
	SRP	21	1,453.74	1,050.15
WF-blue (m ³ /ton)	CON	23	1,449.53	1,095.81
	SRP	21	1,255.35	756.58
WF-grey (m ³ /ton)	CON	13	1,138.25	635.10
	SRP	12	1,189.41	1,013.92
Total WF (m ³ /ton)	CON	13	4,142.87	1,224.15
	SRP	12	3,898.50	1,392.65

Note: CON = conventional practice and SRP = sustainable rice practice. T-tests were conducted with no significant differences for all tested variables.

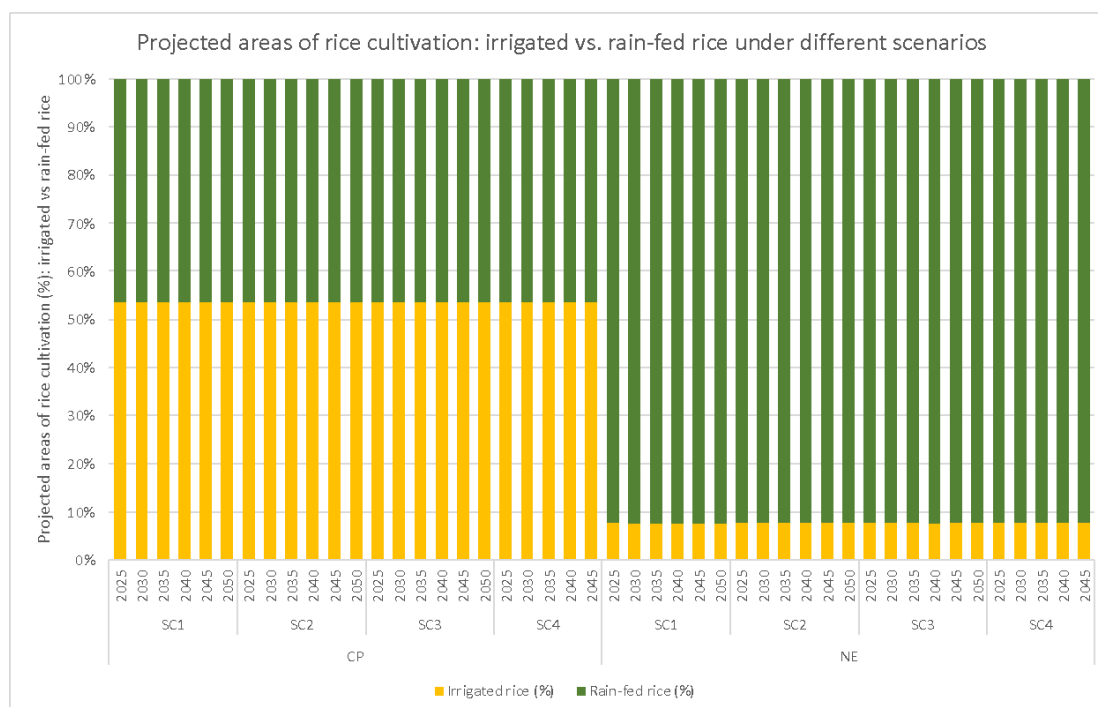
Table 7.14. Rice yields and amounts of water footprints by regions and cultivation practices.

Items	Central Plain			Northeast		
	CON	SRP	Overall	CON	SRP	Overall
Rice yields (tons/ha)	5.50	6.08	5.79	2.35	2.39	2.37
WF-green (m ³ /ton)	574.23 (21%)	532.27 (19%)	553.25 (20%)	2,309.60 (43%)	2,291.44 (48%)	2,301.28 (45%)
WF-blue (m ³ /ton)	1,095.79 (41%)	1,029.95 (37%)	1,062.87 (39%)	1,721.63 (32%)	1,460.26 (30%)	1,601.84 (31%)
WF-grey (m ³ /ton)	1,027.51 (38%)	1,250.33 (44%)	1,138.92 (41%)	1,315.45 (25%)	1,067.57 (22%)	1,205.28 (24%)
Total WF (m ³ /ton)	2,697.53	2,812.54	2,755.04	5,346.68	4,819.27	5,108.39

Note: CON = conventional practice and SRP = sustainable rice practice.

7.3. Scenario analysis of water footprint: Green, blue, and grey

Figure 7.6 depicts projected areas of rice cultivation in the Central Plain and the Northeast for irrigated and rain-fed rice under four different scenario models: SC1, SC2, SC3, and SC4²⁴. Only small changes in projected areas during 2025-2050 were observed. Clearly, the majority of rice planting areas in the Northeast were classified as rain-fed or non-irrigated paddies (~90% of the total projected planting areas). Meanwhile, approximately 55% of the projected planting areas in the Central Plain were classified as irrigated paddies. Rice cultivation in the Northeast is basically rain-fed, depending on the rain or green water, which is accounted for about 45% of a total water footprint. Farmers in the Central Plain, on the other hand, are able to grow irrigated or dry-season rice due to more extensive availability of irrigation areas. Subsequently, large proportions of the blue water use in the Central Plain were observed, especially for irrigated-rice cultivation i.e., ~88% of a total amount of water use (Figure 7.7).



²⁴ SC1 = Business as Usual (BAU), SC2 = Conversion from the CON to SRP practice is low (Moderate). SC3 = Conversion from the CON to SRP practice occurs at a medium rate (Enhanced), and SC4 = Conversion from the CON to SRP practice occurs at a high rate (Transformational).

Figure 7.6 Projected areas of rice cultivation: irrigated vs. rain-fed rice in the Central Plain and the Northeast during 2025-2050.

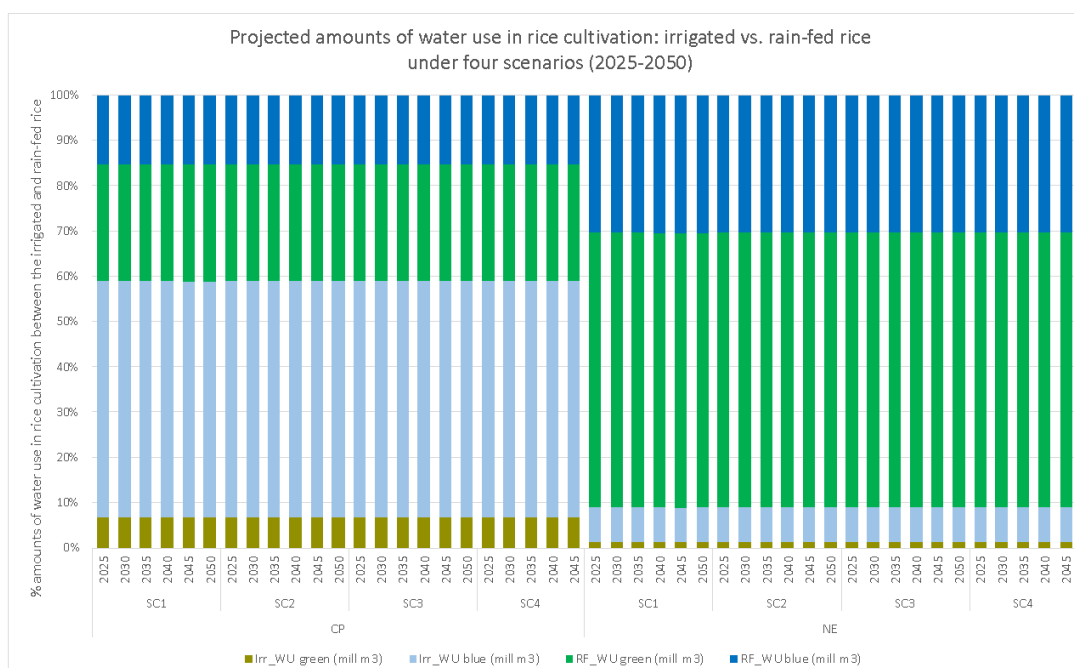


Figure 7.7 Projected amounts of crop water use (WU green = rainwater and WU blue = irrigated water) in rice cultivation: irrigated (Irr) vs. rain-fed (RF) rice in the Central Plain and the Northeast during 2025-2050.

Furthermore, Table 7.15 summarizes projected yields of rice under different climatic conditions (see details in the greenhouse gas emission section) and cultivation practices: CON vs. SRP in the two regions. The Central Plain was projected with higher yields (5.62 tons/ha) than the Northeast (3.44 tons/ha). Averaged amounts of yields under the SRP were projected higher than the CON practice in both regions, especially the Northeast (i.e., 3.87 vs. 2.56 tons/ha, respectively). By multiplying each of the water footprints (m^3/ton) with amounts of yields projected (tons/ha), we got amounts of water use per hectare (m^3/ha). The Northeast's total amounts of water use (green + blue + grey) are higher than the Central Plain due to larger water footprints, specifically the green and blue footprints, as a result of low yields. However, the Northeast's amount of grey water is smaller than the Central Plain since its grey water was accounted for the largest proportion of the region's total amount of water use (Figure 7.8). Rice cultivation in the Central Plain is relatively commercial-based, rather than for household

consumption as usually practiced in the Northeast. Farmers tend to apply greater amounts of (chemical) fertilizers to improve their productivity, leading to a larger size of grey water footprint.

Lastly, the SRP practice illustrates larger amounts of water use in both regions. This is perhaps due to large amounts of green and grey water usage and the projected yields. The larger projected yields, the greater amounts of water use. Nevertheless, even though under this projection the water use issue might portray the less environmental-friendly SRP, rice agroecosystems under it provide beneficial ecosystem services, including local biodiversity, food provisions and income generation.

Table 7.15. Projected yields and amounts of water use based on water footprints (2020-2050).

Items	Yield (tons/ha)	WU green (m ³ /ha)	WU blue (m ³ /ha)	WU grey (m ³ /ha)	WU total (m ³ /ha)
Central Plain	5.62	4,154.07	4,298.14	6,413.43	14,865.64
CON	5.61	3,895.43	5,165.24	5,729.85	14,790.51
SRP	5.63	4,283.39	3,864.59	6,755.23	14,903.20
Northeast	3.44	7,468.88	5,680.18	3,818.70	16,967.76
CON	2.56	5,169.17	5,733.94	3,400.51	14,303.62
SRP	3.87	8,723.27	5,650.86	4,027.80	18,401.93
Grand Total	4.17	6,321.45	5,201.78	4,791.73	16,314.95

Note: WU = water use, CON = conventional practice, SRP = Sustainable rice practice

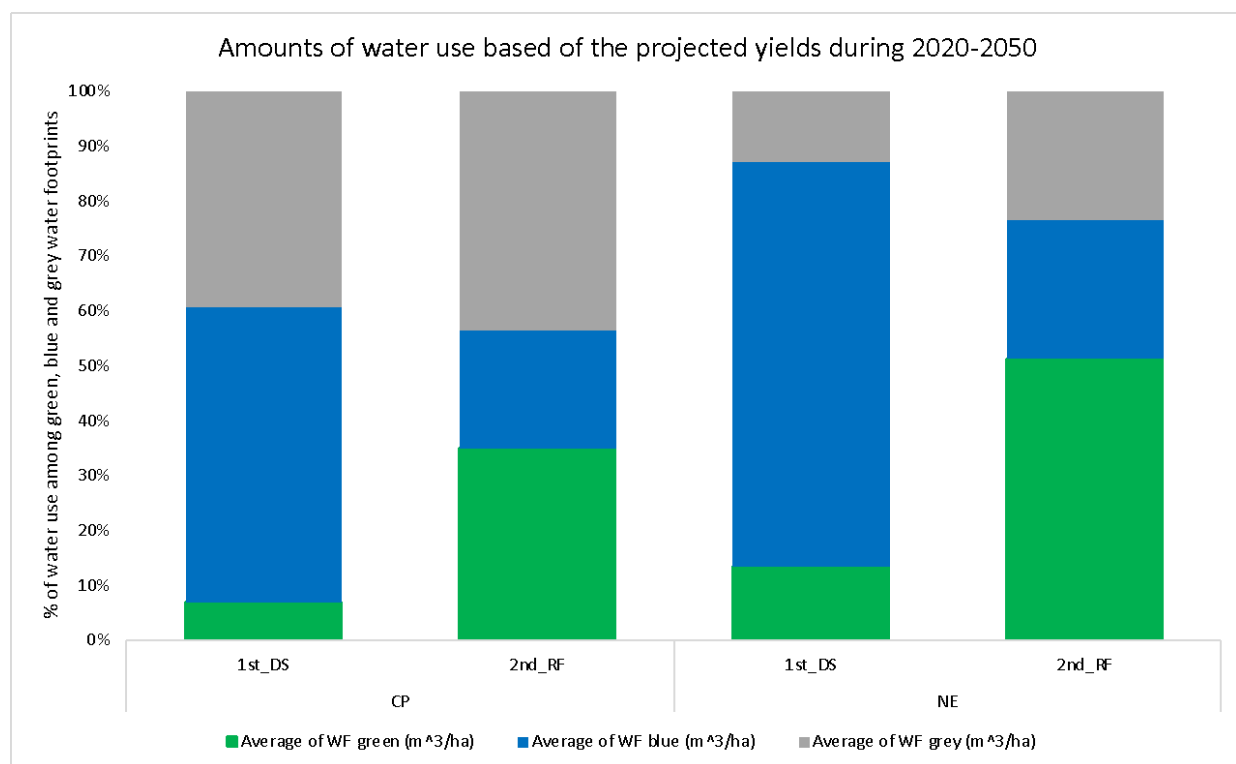


Figure 7.8. Amounts of water use (m^3/ha): green, blue and grey water based on the projected yields of dry-season (DS) and rain-fed (RF) rice in the Central Plain and the Northeast.

Gross amounts of water use were computed by multiplying amounts of water use per hectare (m^3/ha) with total projected yields i.e., yield (tons/ha) and projected planting areas (ha), under different scenarios during 2025-2050. Figure 7.9 depicts the gross amounts of water use (million cubic meters per year) in the Central Plain and the Northeast by cultivation practices and planting seasons. Across all four scenarios, the Northeast's rice cultivation exploited greater amounts of water than the Central Plain due to larger planting areas and bigger water footprints. Obviously, rain-fed rice cultivation is accounted for the greatest proportion of water use, especially in the Northeast. Decreases in rice planting areas projected under the SC1, SC2, SC3 and SC4 resulted in substantially declined amounts of water use with the CON practice in both regions, especially toward the SC4.

Conversely, planting areas under the SRP were projected increase from SC1 toward SC2, SC3 and SC4, respectively. These projections resulted in increased amounts of water use under the SRP in the two regions. Proportionately, the amounts of increases are small when compared to the amounts of water use projected under the CON practice both for rain-fed and dry-season rice cultivation. These findings signalize potential contribution of the SRP in helping reduce amounts of water use in rice cultivation. Figure 7.10 and Table 7.16 reiterate these findings with yearly data from 2025-2050. However, when amounts of water use under the CON and SRP were summed to project overall usage of water in rice cultivation, the summed amounts increased toward the SC4 even though this scenario with projected decreases in planting areas under the CON but vice versa for the planting areas under the SRP is expected to reduce amounts of water use. Adjustment of planting areas in each of the proposed scenarios is necessary to reconsider which one will perform the best in helping reduce amounts of water usage.

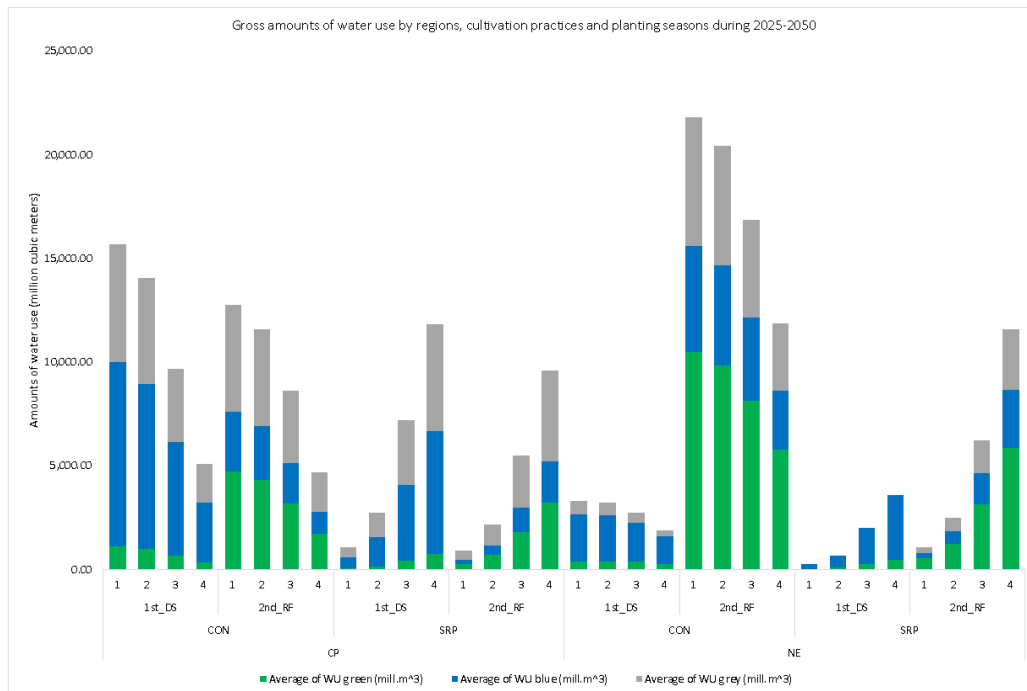


Figure 7.9. Amounts of water use in rice cultivation based on the projected yields under different scenarios: SC1-SC4 and cultivation practices: the CON and SRP practice during 2025-2050. Note: DS = dry-season rice and RF = rain-fed rice.

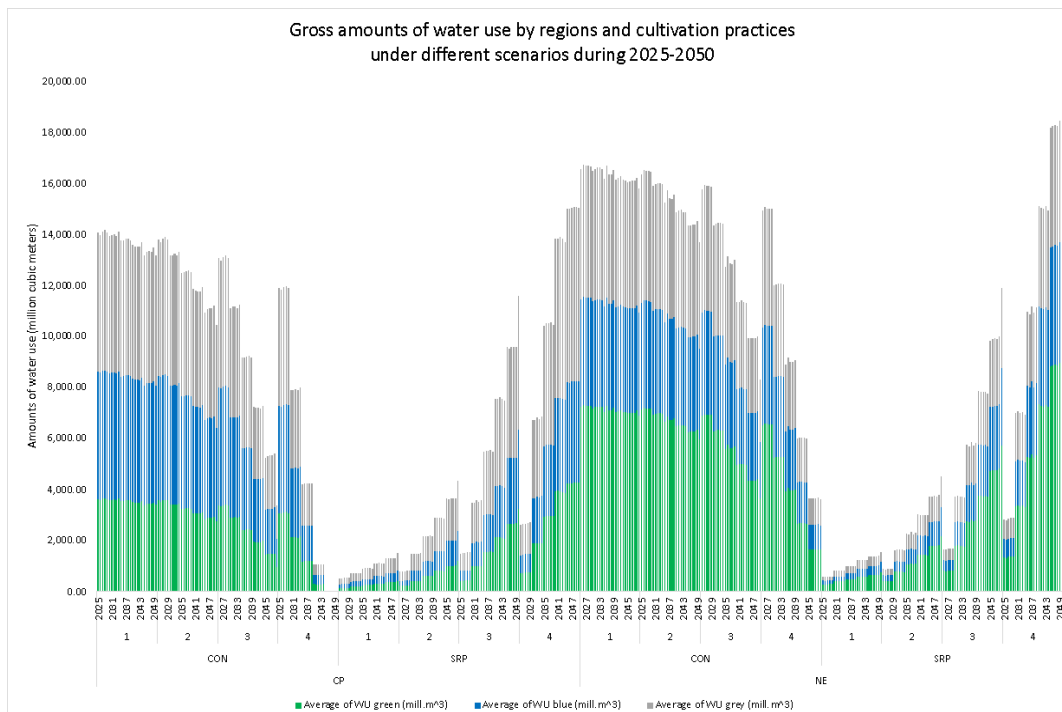


Figure 7.10. Amounts of water use based on the projected yields under different scenarios: SC1-SC4 and cultivation practices: the CON and SRP practice with yearly data during 2025-2050.

Table 7.16. Amounts of water use in rice cultivation under different scenarios and cultivation practices with summed amounts of water use in the CON and SRP practice.

Region-Practice-SC	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU-total (10 ⁶ x m ³)
Central Plain				
CON	2,611.91	3,514.24	3,869.75	9,995.90
SC1	3,551.24	4,875.53	5,314.72	13,741.49
SC2	3,226.98	4,391.55	4,808.22	12,426.75
SC3	2,378.62	3,121.59	3,481.03	8,981.24
SC4	1,290.81	1,668.31	1,875.01	4,834.12
SRP	1,338.50	1,258.78	2,149.15	4,746.42
SC1	270.32	247.47	428.99	946.78
SC2	643.69	607.00	1,034.76	2,285.45
SC3	1,618.97	1,545.30	2,616.50	5,780.77
SC4	2,821.02	2,635.34	4,516.34	9,972.69
CON+SRP	3,950.41	4,773.02	6,018.89	14,742.32
SC1	3,821.56	5,123.00	5,743.72	14,688.27
SC2	3,870.67	4,998.54	5,842.99	14,712.20
SC3	3,997.60	4,666.89	6,097.53	14,762.02
SC4	4,111.83	4,303.64	6,391.34	14,806.82
Northeast				
CON	5,843.33	3,442.97	4,077.02	13,363.32
SC1	7,143.45	4,169.34	5,066.73	16,379.52
SC2	6,713.70	3,947.88	4,724.74	15,386.32
SC3	5,574.35	3,311.16	3,851.60	12,737.10
SC4	3,941.81	2,343.49	2,665.02	8,950.32
SRP	2,480.31	1,301.01	1,364.46	5,145.78
SC1	496.85	256.76	270.09	1,023.70
SC2	1,150.69	596.49	650.28	2,397.47
SC3	2,892.49	1,518.92	1,616.43	6,027.84
SC4	5,381.21	2,831.86	2,921.04	11,134.10
CON+SRP	8,323.64	4,743.97	5,441.48	18,509.10
SC1	7,640.30	4,426.11	5,336.82	17,403.23
SC2	7,864.39	4,544.37	5,375.03	17,783.79
SC3	8,466.83	4,830.08	5,468.03	18,764.94
SC4	9,323.02	5,175.34	5,586.06	20,084.42

Note: WU = water use, CON = conventional practice, SRP = sustainable rice practice

Part 8 Social Capital

For household survey, we did not only ask for the household economic information but also questions related to social outcomes. This part reports the happiness information that covers the happiness level and factors influenced happiness of rice farmers. Then, the social outcomes of the different rice practices are reported. The social outcomes included in our analysis are social relation, gender perspective, and generous behavior toward others. In addition, this section provides the information of the density of social network, which is part of social capital. The social network is analyzed to identify the effects of different rice practices on farmers' network and distribution of information regarding to new technology. Finally, the adaptation of rice farmers to climate change is also explored in this part.

Note that the household survey is the same set of what presented in Part 5 “Production Economy and Livelihoods”. Please refer to the sampling method and other relevance information the survey in part 5.

8.1 Happiness information

In the household survey, we employed the happiness question that would reveals how famers satisfy their lives as a whole. The happiness question applied in this survey asked farmers to provide their happiness level based on evaluation of positive and negative things happening in their lives (Mahasuweerachai and Pangjai, 2019). The happiness question in this study uses 1-10 scale, which 1 means completely unhappy and 10 means completely happy.

Table 8.1 first reports the findings on the levels of happiness among conventional and SRP farmers. We test whether the happiness level between these three types of farmers in each region is different using t-test. The test result suggests that the happiness levels in Central region are little higher than that in Northeast region, 8.32 compared to 8.09 out of 10 scale. In the Central region, happiness levels of different rice farming practices are not statistically significantly different. However, the SRP farmers in the Northeast report statistically higher happiness level than that of other types of farmers by about 0.9 from 1-10 scale.

In addition, we also asked these farmers to rank the three most important factors that alter their happiness level. The results from survey reveal that in the Northeast region family is the most important factor to drive happiness level for farmers in all practices. The second most important factor that drives happiness level differs according to types of farmers. Namely, conventional and

GAP farmers identify income as the second most important factor to alter their happiness, but SRP farmers stated the land ownership. For the Central region, conventional and GAP farmers ranked health and family as the two most important factors. Meanwhile, the SRP farmers paid highly attention to family.

Table 8.1 The happiness level and factors influencing happiness of rice farmers

Variables	Practices					
	Northeast			Central		
	Convention	GAP	SRP	Conventional	GAP	SRP
Happiness information						
Average assessed happiness level	8.090	0.129 (0.342)	0.910** (0.028)	8.328	-0.135 (0.592)	0.172 (0.795)
Factors influencing happiness (Percentage)						
Family	33.87	30.47	31.25	27.78	34.16	41.67
Income	19.51	17.89	19.79	17.46	14.04	14.58
Health	23.86	25.28	15.63	29.89	22.20	10.42
Landowner	13.03	15.36	21.88	12.96	14.80	16.67
Occupation	9.73	11.00	11.46	11.90	14.80	16.67

Note: Numbers in parentheses are p-value. ***, **, and * indicate the significance level at 1%, 5%, and 10%, respectively

8.2 Social capital

We also asked set of questions that measure social relations of conventional, GAP, and SRP rice farmers in the two regions. This set of questions consists of five questions regarding how often farmers join activities in their community, including general activities, religious activities, cultural activities, governmental activities, and volunteering activities. Farmers were asked to provide an answer for each question based on 1-5 scale where 1 means not joining any activity at all and 5 means joining activities every times.

The answers provided by three types of farmers are tested using t-test to clarify whether levels of social ties are significantly different between these types of farmers. The results are presented in table 8.2. First, both Northeast and Central region farmers seem to have a high level of joining community activities, averaging above 4 on a 1-5 scale, suggesting that in general the social ties in the rural areas in Thailand is high.

However, when compared the levels of joining community activities between conventional and other types of farmers, the GAP farmers in the Northeast region have statistically significant higher the volunteering activities levels than that of conventional farmers. In addition, in the Central region, joining religious activity level of GAP farmers is statistically significantly higher than that of conventional farmers. For the SRP farmers, even though, the scores of activities from SRP farmers in both regions especially religious and volunteering activities seem to be higher than that of conventional counterpart, they all are not statistically significant different from those of conventional rice farmer. It could be because of the small number of samplings with only six and three farmers in these regions that prevent us to have power of test to distinguish the difference.

The results of social relation suggest that GAP farmers have some more social relation than conventional rice farmers especially in the volunteering and religion dimensions. This would be the part of social capital that sustainable rice farmers may have more prosocial behavior toward others in their community than conventional rice farmers. This behavior may be developed through group cooperation because sustainable rice farmers participate in group activities more than conventional farmers especially for female farmers, as presented in table 8.2 under “Number of groups joined by farmers”. On average, SRP and GAP female farmers in the Central and Northeast regions joined more groups than conventional rice female farmers. And, the difference of joining group activity between sustainable rice female farmers, SRP and GAP, and conventional rice female farmers is statistically significant different.

Table 8.2 the social relations among three types of rice farmers

Variables	Practices					
	Northeast			Central		
	Convention	GAP	SRP	Conventional	GAP	SRP
Social relations						
General activities	4.691	-0.009 (0.879)	0.184 (0.299)	4.609	0.107 (0.355)	0.016 (0.957)
Religious activities	4.674	0.073 (0.227)	0.201 (0.296)	4.375	0.284** (0.046)	0.500 (0.193)
Cultural activities	4.663	-0.004 (0.947)	0.149 (0.405)	4.438	0.165 (0.237)	0.188 (0.602)
Governmental activities	4.417	0.057 (0.475)	0.271 (0.265)	4.188	-0.074 (0.709)	-0.063 (0.895)
Volunteering activities	4.420	0.231** (0.002)	0.267 (0.289)	4.031	0.253 (0.216)	0.469 (0.369)
Number of groups						
Female farmer	2.038	0.265** (0.002)	0.562** (0.030)	1.571	0.472** (0.043)	0.429 (0.231)
Observations	186	162	10	35	46	5
Male farmer	2.176	0.069 (0.545)	0.324 (0.333)	1.759	0.313 (0.102)	-0.092 (0.846)
Observations	102	102	6	29	42	3

Note: Numbers in parentheses are p-value. ***, **, and * indicate the significance level at 1%, 5%, and 10%, respectively.

8.3 Social Network

To improve productivity and sustainability in Thai farming, it is essential to adopt new agricultural technologies. Despite the Thai government's efforts to provide information through agricultural extension services, the adoption rate remains low due to insufficient extension staff and sporadic support. To overcome this challenge, a new approach is necessary that capitalizes on social networks and social learning to promote technology adoption.

This study aims to observe the structure of the agricultural network available in Thailand and identify the characteristics and social status of individuals who would be most suitable to be role models for promoting sustainable rice practices. This information would help to develop targeted extension programs that respond better to farmers' needs, align with the local context, and leverage social capital and social learning to improve productivity and ensure sustainability.

Inquiring into agricultural network structure in Thailand, we collected social network data from a sample of farmers in nine Thai provinces. These provinces include Ayutthaya, Chai Nat, and Suphanburi in the central region, as well as Khon Kaen, Nakhon Ratchasima, Sakon Nakhon, Surin, Udon Thani, and Ubon Ratchathani in the northeast region. The villages in our sample predominantly engage in two rice-growing practices: sustainable rice practice (SRP) and conventional rice practice. In total, there are 1,458 villagers from 91 villages in our sample, with 16-18 participants from each village. Participants were asked to identify members of their village whom they had asked (provided) agricultural information from (to) in the previous 12 months. They were also asked to provide information on the characteristics and social status of these individuals. In addition, participants were asked to name the person from whom they most often adopt agricultural advice, along with information on the characteristics and social status of these individuals.

We analyze the overall structure of the agricultural network available in each village by examining the network density, based on questionnaire data regarding who villagers connect to for agricultural information. Network density is a measure of the degree of interconnection between nodes in a network. It is calculated as the ratio of the number of edges in a network to the maximum number of edges possible in that network, and ranges from 0 to 1. A high-density network consists of closely connected nodes, which allow for efficient communication and information flow. In

contrast, a low-density network has fewer connections, resulting in slower and less widespread information dissemination.

In this study, low network density was observed in both conventional and SRP villages. The degree of network density on average between these two types was also not significantly different (see Table 8.3). This suggests that there are few connections between nodes in these networks. This may be one of the reasons why new information introduced into the community by government sectors or extension staff does not spread well. Consequently, not many people are well-educated or informed about the information, let alone able to adopt it in practice.

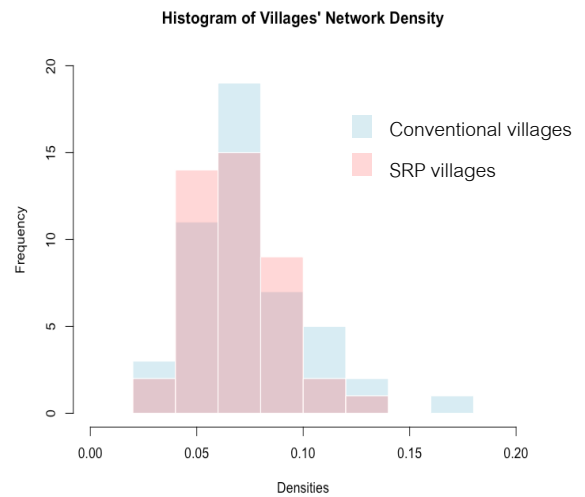


Table 8.3 Network Density Comparison between Conventional and SRP Villages

	Conventional (<i>N</i> =48)	SRP (<i>N</i> =43)	T-test (<i>p</i> -value <i>SRP</i> = <i>Conventional</i>)
Network	0.075	0.071	0.806
density	(0.027)	(0.022)	

Note: Standard deviations are in parentheses.

This result emphasizes the need for more agricultural nodes within the community. In particular, we need individuals who are well-connected to many people and are likely to be sought out for advice on agricultural subjects. Additionally, we should identify the characteristics and social status of the people in need to see if any specific traits or social statuses are likely to draw people in to follow them. By doing so, we can enhance connections and improve the dissemination of information within the community.

To this, we examine the eigenvector centrality of individuals within each village who are identified as sources of agricultural information or who have been giving agricultural advice to other villagers. Eigenvector centrality is a measure of the influence of a node (individual) in a network.

Specifically, it measures the importance of a node based on its connections to other important nodes in the network. A node is considered important if it is connected to other nodes that are also important. This analysis will help us identify nodes that have a significant impact in the network.

Eigenvector centrality is calculated by assigning an initial importance score to each node in the network based on its degree centrality, which measures its connections to other nodes. This score is then iteratively updated based on the importance of the nodes connected to each node. In other words, a node's score is influenced by that of its neighbors. The final scores obtained using this process are the eigenvector centrality scores for each node.

We further classify our samples who were agricultural nodes that other villagers follow for agricultural advice based on their social status (relative of a follower, friend/neighbor of a follower, community leader, agriculture group leader, agriculture group fellow member, government staff) and their characteristics that others attribute to them. These characteristics include:

- Openness(O): Individuals with an open, innovative, and sensitive mind. They embrace differences, enjoy the new and unknown, and thrive in agile environments that generate ideas through fast change.
- Conscientiousness(C): Individuals who often possess a high level of self-control and discipline, and are capable of planning and executing their life accordingly.
- Extraversion(E): Individuals who are gregarious, talkative, outgoing, seek interaction with other people, and stimulus from outer sources.
- Agreeableness(A): People who are humble, well-liked, helpful, and unselfish, with a strong social support foundation.
- Neuroticism(N): Individuals who are anxious, insecure, and prone towards sadness. They are often perceived as emotionally unstable and moody, and with a lack of confidence.

Table 8.4 The number of agricultural nodes that villagers follow for agricultural advice, categorized by trait and social status group.

	A	C	E	N	O	M	Sum
Relative	23	15	19	2	54	3	116
Friend/Neighbour	27	15	18	0	41	4	105
Community Leader	33	14	35	0	42	9	133
Agri Group Leader	5	8	22	1	31	8	75
Agri Group Member	1	0	6	0	9	4	20
Government staff	8	5	9	0	11	2	35
Sum	97	57	109	3	188	30	484

Table 8.4 provides insight into the distribution of personality traits among leaders in different social status groups. Overall, people in every social status tend to follow someone with an open personality. The community leader group has the highest number of individuals and includes individuals with high eigenvector centrality in the traits of Extraversion and Openness, as shown in Graph 1x. This suggests that leaders who are open and talkative tend to have a wide network, and people are more likely to follow them compared to leaders with other personality traits.

Meanwhile, people also tend to follow agricultural advice from those who are close to them, such as relatives, friends, or neighbors. However, when we consider social status and eigenvector centrality together, we can see that those in the "relative," "friend," or "neighbor" category have relatively low eigenvector centrality. This indicates that although many people choose to follow advice from these individuals, their networks are small, and they only exchange information with a few people in their connections.

Even though, these networks are relatively small, the close connections between relative, friend, and neighbor may be the potential and effective point for disseminating the information of new technology. This is because farmers would be more comfortable to talk, observe, and learn from peers who are really close to them (Villeval, 2020). This finding suggests that when choosing the role model farmers as the early adopters of new technology such as SRP, targeting on several small nodes, along with community leaders, in the communities may help to enhance dissemination of new technology.

Figure 8.1 Characteristics and Eigenvector Centrality of individuals who have been chosen as role models in different social statuses.



Figure 8.1 Characteristics and eigenvector centrality of individuals who have been chosen as role models in different social statuses.

8.4 Summary

The main purposes of this part are to reveal and analyze the social dimension that may be different by different rice practices. The happiness, social ties, and social network of conventional and SRP practices were examined. Data from household survey presents that farmers who practice sustainable rice practice would likely be happier than conventional rice farmers. When considering the factors that would drive the happiness of farmers, family and income are the first and second variables that determine the happiness level of both types of farmers.

We also analyzed the social ties situation of sustainable rice and conventional rice farmers. The results from our analysis suggest that generally sustainable rice farmers seem to have higher social ties than conventional counterpart especially for voluntary activity. In addition, female sustainable rice farmers seem to participate more in the farmer groups than female conventional rice farmers. The degree of participating in the groups between female and male sustainable rice farmers is the same, while the female conventional rice farmers participate in the groups less than male conventional rice farmers.

For social network, our results suggest that social network between conventional rice farmers and sustainable rice farmers are very similar in term of size of social network and characteristics of the nodes who are defined as the center of network. In addition to this finding, we also found that besides receiving information and observing from the nodes for new agricultural practices, farmers also receive information and follow the guidance regarding to the new agricultural technology from their relatives and close friends. These findings of social network study would be a starting point to the way of using social network information to select farmers who would be trained as early sustainable rice adopters. And, they could then spread information and lead others in their network to adopt sustainable rice practice.

This component of the study seeks to measure health impacts of different rice practices on farmers and general public. The health risks arising from rice production in this study include the potential health risks to farmers associated with the use and misuse of each of the agricultural pesticides applied to rice production, as well as the health risks to the broader population associated with air pollution from post-harvest rice straw burning.

9.1 Health-related economic costs of exposure to pesticides used in rice systems

While pesticides are used in rice cultivation for the purpose of increasing productivity, it also leads to higher health risks for people as pesticide concentrations in the environment increase.

In this study, we focus on farmers' practice. The health effects of pesticides are investigated on farmers and farm workers. Many farmers, both men and women, are directly exposed to pesticides. This includes farm workers who spray pesticides, those who mix and load the pesticides, sow pesticide-infused seeds, work on weeding and harvesting sprayed crops, and those who clean and dispose of the containers (Tago et al., 2014), as well as those who wash the clothes of the workers. Local communities, adjacent to rice fields, including homes, schools, restaurants, businesses, are also exposed to pesticide contamination, however impacts on these communities are out with the scope of the pesticide risks analysis in this study.

The health effects of pesticides depend on the amount and specific chemicals in the pesticides. In general, the main chronic health effects are cancer, neurological effects, diabetes, respiratory diseases, reproductive health, fetal diseases, and genetic disorders. Therefore, farming with non-chemical pesticides would certainly reduce the health risk for farmers. The main purpose of this study is to identify the effects of pesticide on farmers' health and to measure them in form of monetary value.

9.1.1 Methodology and results

To monetize the impact of pesticide on health of farmer, cost of illness (COI) and defensive expenditure (DE) concepts applied. The COI is defined as lost productivity due to illness plus the cost of medical treatment due to illness (Freeman 1993; Freeman et al., 2014). This method is often used to assess the health risk of pesticides because of its ease of use (EPA 2000). The COI is

composed of (1) the opportunity cost of days lost to pesticide-related illness and (2) the cost of medical treatment.

The defensive expenditure approach (DE) is used to evaluate the willingness to pay (WTP) for behavior to mitigate potential risks of pesticide exposure. Defensive expenditures include the cost of safety measures adopted prior to spraying to reduce the risk of pesticide exposure. The cost of illness and defensive expenditure may not capture all health effects. The chronic health effects may not be observed in such a small sample. In the final part of this section, we will attempt to evaluate potential chronic impacts using the benefit transfer method.

9.1.1.1 Pesticide uses and incidence of illness

Based on our survey of 728 farm households in the central and northeastern region, we divided the sample households into two groups based on their farming practices: 376 households with Sustainable Rice Platform (SRP) and 352 households with conventional practices (CP). We found that the most commonly used pesticides among the farmers surveyed were Phenoxycarboxylic acid, Chloroacetamide, and Isoxazolidinone + Anilide can cause symptoms such as nausea, vomiting, chest tightness, malaise, decreased urination, kidney failure, lung swelling, itchy rash, skin irritation, toxicity, and pulmonary fibrosis. Prolonged exposure to this substance has also been linked to Parkinson's disease. The fourth substance, Carbamate, can cause severe nerve irritation and can easily lead to death (Sangchom, 2013). Interestingly, the average expenditure on pesticides per hectare was lower in SRP than in CP, although the number of chemicals used was higher in SRP. The difference ranged from 5% to 78% of the average expenditure. This could mean that the amount of pesticides used in SRP was less than half of the amount used in CP (Table 9.A).

Table 9.A Frequency of pesticide commonly used and the average expenditure on pesticide by cultivation practice

Chemical Group	Number (plots)			Expenditure on pesticide (baht/hectare)		
	SRP	CP	Total	SRP	CP	Difference (%)
1. Chloroacetamide	56	40	96	625	656	31(5)
2. Phenoxycarboxylic acid	74	25	99	259	465	206 (57)

3. Isoxazolidinone + Anilide.	31	7	38	688	1,563	875 (78)
4. Carbamate	12	8	20	394	838	444 (72)

Note: Some plots were reported more than one pesticide

In our survey, each household was asked about the incidence of illness caused by chemicals used in rice fields, and only 88 households reported that their members' health was affected by pesticide use (Table 9.1), comprising 9.6% of SRP households and 14.8% of conventional households. A statistical test revealed a significant difference between the two proportions at a 5% level of significance. Table 9.2 provides a detailed breakdown of health symptoms by cultivation practice. The 10 common symptoms related to cultivation include headache, eye irritation, skin irritation/burn, fever, diarrhea, allergy, throat discomfort, joint pain, nausea, and muscle twitching/pain. Both household groups had the same proportion of each symptom. For each symptom pair, there were no significant differences between the two groups. Joint pain was the most frequently reported symptom, followed by headache and fever, among the households in the sample. Nevertheless, none of these were fetal or chronic health effects.

Table 9.1 Number of households that reported health effects from pesticides by cultivation practice.

Unit: households

	Health effects from pesticides		Total
	No	Yes	
Sustainable Rice Platform (SRP)	340 (90.4%)	36 (9.6%)	376 (100%)
Conventional Practice (CP)	300 (85.2%)	52 (14.8%)	352 (100%)
Total	640 (87.9%)	88 (12.1%)	728 (100%)
Statistical test for difference in proportion (z) (p-value)			-2.15 (0.03)

Table 9.2 Incidence of illness (percentage of households that reported health effects from pesticides) by cultivation practice

	Sustainable Rice Platform (SRP)	Conventional Practice (CP)
1. Headache	63.9%	75.0%
2. Eye irritation	44.4%	34.6%
3. Skin irritation/burn	41.7%	46.2%
4. Fever	55.6%	53.8%
5. Diarrhea	30.6%	30.8%
6. Allergy	30.6%	34.6%
7. Throat discomfort	30.6%	25.0%
8. Joint pain	77.8%	71.2%
9. Nausea	13.9%	13.5%
10. Muscle twitching/pain	19.4%	23.1%
Total number of households	36	52

a) The cost of illness (COI)

Table 9.3 presents the estimated cost of illness based on the survey data. The average health care costs, including direct costs such as medical expenses and indirect costs such as transportation costs, for SRP households and conventional households are 843.47 and 1088.07 baht/person/visit, respectively. This may be underestimated because some of the medical expenses were subsidized. The opportunity cost of time is assumed to be the cost of one day's medical visit to a hospital or clinic, which is proxied by the daily minimum wage of 335 baht in 2022. The total cost of illness is the sum of the healthcare cost and the opportunity cost of time, resulting in 1178.47 and 1423.07 baht/person/visit for SRP and conventional households, respectively.

Multiplying the total cost of illness by the number of medical visits and the number of household members affected, we obtain the annual cost of illness per household. While the annual illness costs for SRP households are slightly higher than those for conventional households, the probability of becoming ill is lower for SRP households. Therefore, the predicted cost of illness for SRP households is 397.69 baht/household, which is much lower than that for conventional households.

Table 9.3 The predicted cost of illness (COI) (Reported health care and opportunity costs) by cultivation practice

	Sustainable Rice Platform (SRP)	Conventional Practice (CP)
Health care cost (<i>baht/person/visit</i>) ¹	843.47	1088.07
Opportunity cost of time (<i>baht/person/visit</i>) ²	335	335
Total cost of illness (<i>baht/person/visit</i>)	1,178.47	1,423.07
Number of visits (<i>times/year</i>)	2.08	1.97
Average number of members with health effects (<i>persons/households</i>)	1.69	1.31
Annual illness cost (<i>baht per household</i>)	4,142.56	3,672.52
Sample probability of getting sick	0.096	0.148
Predicted cost of illness (<i>baht per household</i>)	397.69	543.53

Note: ¹not statistically different at 10%

²based on the announcement of daily minimum wage

9.1.1.2 The defensive expenditure (DE)

To collect information about defensive expenditure (DE), a smaller sample was selected for personal interviews after the main survey. According to systematic review by Sapbamrer, R., and Thammachai, A. (2020), common protective equipment used for chemical protection in agriculture practice includes gloves, boots, long-sleeved shirts, hats, rubber aprons, mask and goggles. The respondents in our sample did not mention using appropriate mask or eye goggles protection. Based on the review, the use of masks/nose cover are approximately 60% to 88%, while the use of goggles/glasses ranges from 0% to 88%. However, the studies in the review were not conducted in our study areas and most of them were not rice farmers. In our study, it was observed that farmers covered their nose with a cloth and did not use protective goggles/glasses.

The estimated costs of the protective measures are presented in Table 9.4. Most farmers utilize long-sleeved shirts, boots, gloves, and hats, but not rubber aprons. The expenses for each item vary based on the number of devices and reported prices. The probability-weighted expenditure for a SRP farmer and a conventional farmer for all protective items is 1,047.11 and 1,076.60 baht per year, respectively. The average defensive expenditure per household per year is approximately 3,370 baht and does not significantly differ between SRP and conventional groups. This may imply that the farmers' knowledge about pesticide use in both groups could be similar. This finding is consistent with the study by Siriuma et al. (2017), which examined users and non-users of synthetic pesticides.

Table 9.4 Defensive expenditure by cultivation practice

Devices	Sustainable Rice Platform (SRP)		Conventional Practice	
	Probability	Expenditure (baht/person/year)	Probability	Expenditure (baht/person/year)
1. Gloves	0.88	297.33	1	63.46
2. Long sleeve shirt	1	368.18	1	396.92
3. Boots	0.94	356.25	0.92	490.69
4. Hat	0.71	108.46	0.92	170.42
5. Rubber apron	0.12	45	0.08	100
Average probability	0.73		0.78	
All expenditures		1,047.11		1,076.60
Average number of HH members (persons)	3.6		3.5	
Defensive Expenditure (baht/household/year)	3,769.60		3,768.10	

The estimated health cost

The estimated total health costs for each group are summarized in Table 9.5. Although, the costs of illness of SRP group is lower, together with the defensive cost, the health cost of SRP farmers is slightly below that of CP farmers. With a similar average cultivated area of 3.4 ha, the average health costs per area for SRP farmers and CP farmers are 1,225.67 and 1,268.13 baht per ha, respectively.

Table 9.5 The estimated health cost from survey by cultivation practice

Costs	Sustainable Rice Platform (SRP)	Conventional Practice (CP)
Health cost (bath/ household/ year)		
Cost of illness	397.69	543.53
Defensive expenditure	3,769.60	3,768.10
Total	4,167.29	4,311.63
Total cultivated area (ha/ household)	3.4	3.4
Average health cost (baht/ha)	1,225.67	1,268.13

Our estimates of rice farmers' health costs are higher than those of Praneetvatakul et al. (2013). In their study, they estimated the total health costs of farm workers using Pesticide Environmental Accounting (PEA) at 811 baht/ha (adjusted from 22.42 USD/ha in 2010). This could be because we include defensive expenditures in health costs. However, when we exclude defensive spending, our estimates are much lower. In addition to the subsidy to health costs, the possible reasons for the decline in health costs over time are (1) farmers' growing awareness of the health effects of pesticide use and (2) regulation of some hazardous pesticides.

However, our health care costs may be underestimated because the illness in our study were based on self-report. A study by Lee et al. (2012) found that only 12% of pesticide poisoning cases resulted in medical care. Most of farmers may only consider the short-term effects after acute poisoning and not the serious diseases such as cancer, diabetes, depression, or blindness potentially triggered by chronic pesticide exposure. Some farmers may also consider poisoning symptoms to be "normal" and not pay much attention (Bourguet, D., & Guillemaud, T., 2016). In addition, fatal cases

of pesticide exposure were not included in the survey study because it is difficult to estimate the number of cases directly attributable to pesticide exposure and because survey studies, by definition, cannot account for fatalities (Bourguet, D., & Guillemaud, T., 2016).

The benefit transfer method can be used to estimate the monetary value of chronic health effects based on previous literature. Several studies found that the estimated cost of chronic pesticide exposure limited to cancer was at least four times greater than the estimated cost of acute poisoning events (Pimentel (2005, 2009); Pimentel and Burgess (2014)). In some studies, medical tests were performed or illnesses were diagnosed by a physician as a result of pesticide exposure, but because of the small number of observations, long-term illnesses might not be adequately assessed. One possible approach to assess chronic health effects is the stated preference approach such as the contingent valuation method. This method asks respondents how much they are willing to pay to reduce health risks associated with pesticide use. A study in Nicaragua showed that farmers' estimated WTP for the chronic effects of long-term exposure to chemical pesticides was \$25.8 per person (Garming, H., & Waibel, H., 2009).

The estimated health costs, which include the costs of chronic exposure, could then be approximated using information from the above studies. Table 9.6 shows two approaches (1) using four times the cost of illness in Table 9.3 and (2) using the value of Garming, H., & Waibel, H. (2009), which is 2,869.2 baht/person in 2022 (the original value was adjusted with GDP per capita in PPP and CPI) or converted to 10,329.12 baht/ha and 10,042 baht/ha for SRP and CP, respectively. Then, health costs including chronic effects range from 1,693.54 to 11554.79 baht/ha for SRP and from 1,907.58 to 11,310.33 baht/ha. However, the values from this method should be used with caution. The benefit transfer method has the disadvantage that the costs could not be comparable because they are influenced by several factors, such as the type of pesticide used, the number of treatments, the degree of protection of the farm personnel spraying the pesticides, etc., which can vary greatly from country to country, with particularly large differences between countries.

Table 9.6 The estimated health cost from survey and benefit transfer, by cultivation practice

Unit: Baht per ha

Costs	Sustainable Rice Platform (SRP)	Conventional Practice (CP)
-------	---------------------------------	----------------------------

	Approach (1)	Approach (2)	Approach (1)	Approach (2)
Chronic Exposure health cost	467.87	10329.12	639.45	10,042.20
Non-chronic Exposure health cost	1,225.67		1,268.13	
Total	1,693.54	11,554.79	1,907.58	11,310.33

9.2 Health-related economic costs of exposure to PM 2.5 from rice burning.

This section of the study focuses on the negative impacts of burning related rice residues on human health. According to the SRP Standard²⁵, one of the core requirements to be able to claim “Sustainably Cultivated Rice” is that rice stubble (or rice straw) is managed in a sustainable manner to reduce greenhouse gas emissions, reduce environmental impacts, and maintain or improve soil quality. Thus, SRP certified farmers must avoid burning rice stubble under harvest and post-harvest. The standards of GAP rice production and Thai agricultural products' food safety standards²⁶ do not restrict the post-harvesting practice of rice open field burning.

One recommendation of the GAP food crop standards is that the soil quality for the next cultivation should be maintained in the area. This could mean that burning in open fields should be avoided because it can damage the soil properties. Up to date, the sustainable rice practice in Thailand has officially stated that open field burning of rice residue (i.e., rice straw and rice stubble) is prohibited for sustainable rice practice cultivation.

This study assumes therefore that the source of residue burning on rice fields is not the sustainable rice practice area. Thus, the area of conventional rice production is the possible source of residue burning, which is used to estimate the health cost of rice production.

To begin with, open field burning is used to assess rice residue burning. The emission in this paper is based on a field experiment done in Thailand (Junpen et al., 2018). The assessment of rice residue burning is subject to open field burning. In this study, the emission is based on the field experiment conducted in Thailand (Junpen et al., 2018). Using Equation 9.2.1, we calculated the emissions from biomass open-burning as follows:

²⁵ Sustainable Rice Platform Standard for Sustainable Rice Cultivation (version 2.1, 2020) <https://www.sustainablerice.org/wp-content/uploads/2021/10/103-SRP-Standard-Version-2.1.pdf>

²⁶ Rice department, MoAC. <http://e-gap.ricethailand.go.th/page2.html> and the National Bureau of Agricultural Commodity and Food Standards(ACFS) (<http://e-book.acfs.go.th/backend/uploads/Download/103a14f76c65cc5236b44dd0c174fe9f.pdf>)

$$E_i = M \times EF_i \times 10^{-3} \quad (9.2.1)$$

where E_i is the air pollution emission; M denotes the mass of dry matter burned (t of dry matter); and EF_i is the emission factor of the air pollutant i (g/kg of burned dry matter). The value of emission factor in this study is used as $EF_{PM2.5} = 8.3$

Next, the study focuses on the emission of PM_{2.5} concentrations caused by rice straw burning. According to Junpen et al. (2018), calculating the dry mass burned of rice straw in a field (M) is dependent on the amount of rice residue subjected to open field burning. Estimation requires three components: the rice harvested area, the amount of rice residue per unit area, and the fraction of rice residue subject to open field burning. The burning scenarios are based on the transition of rice production from conventional rice production to sustainable rice practice production. Based on the early assumption, the rice harvest area in Equation (9.2.1) only yields values for the conventional rice production area. It should be noted that the data for the sustainable rice area defined by this study comes from a parallel study in which a pattern of land use change is predicted from 2030 to 2050. In the following step, the result of PM_{2.5} emission is used to assess the human health impacts.

The health impact of PM_{2.5} is calculated using an exposure-response function or a concentration-response function and the pollutant concentration. Depending on the health endpoint, health impacts can be classified into two types. It is divided into two categories: mortality and morbidity. Both concepts relate to the change in morality or mobility rates of health endpoints as a percentage change per 10g/m³. Either the occurrence of disease or the occurrence of mortality follows a conventional Poisson distribution presented by equation (9.2.2). To minimize duplication counting of health endpoints, The International Classification of Diseases report (ICD-10) considers the health consequences of various diseases and mortality. In this study, the health effects of PM_{2.5} will be calculated in terms of premature mortality due to respiratory system disease. In this respect, the valuation of premature mortality refers to a potential number of years of life lost before the age of 70 due to exposures to PM_{2.5} air pollution and is calculated in monetary terms. The population of each province will be projected ahead based on a 0.28 percent annual growth rate to quantify the health implications across the burning scenarios. Equations (9.2.2) and (9.2.3), which show the following, estimate the population exposure to PM_{2.5} and health damages caused by PM_{2.5} exposures.

$$ER_i = ER_{0i} \times e^{\beta_i(C-C_0)} \quad (9.2.2)$$

$$H_{ij} = P_j \times (ER_i - ER_{0i}) = P_j \times ER_{0i} \times [e^{\beta_i(C-C_0)} - 1] \quad (9.2.3)$$

where H_{ij} denotes the health impacts i in the province j under the level of PM2.5 concentration C . P_j is the exposed population in the province j . ER_i refers to the incidence of health end point under the level of PM2.5 concentration C . ER_{0i} is the baseline incidence of health endpoint i of the affected population. It represents the changes in incidence of a health impact per i $\mu\text{g}/\text{m}^3$ increments of PM2.5. β_i refers to the exposure-response coefficient of health endpoint. The exposure-response coefficient derived from the previous literatures (Yang et al, 2018; Yin et al., 2017). C refers to the concentration of PM2.5 from rice straw subject to open field burning, recalled from Eq.9.2.1. C_0 is the baseline PM2.5 concentration using the maximum value of recommended by WHO to avoid health problems.

The economic cost is estimated at this stage. The economic loss is calculated by developing a proxy monetary value for the risks associated with exposure to PM2.5.

Exposure to PM2.5 particles is used to determine the value of economic cost for each case scenario (Wang et al., 2020). The costs are estimated using the Amended Human Capital (AHC) technique in this study. AHC is calculated with reference to the loss of productivity of the entire society as a result of individual absence from work, and then corrected with the gross domestic product per capita, depending on the health implications under consideration.

AHC is frequently used in conjunction with a statistical life value to value health impacts (VSL). The lower and upper bounds of calculating health expenditures are calculated using the AHC and VSL methods. The willingness to pay for a marginal reduction in fatal risk (Hammit, 2000) is used to calculate VSL, which is then converted to disposal income. VSL is frequently used to assess the cost of medical treatment, hospitalization, and lost productivity, as well as to calculate the cost of disease.

This study will not cover morbidity in terms of long-term diseases like chronic bronchitis, as there is a lack of information on medical expenses and productivity loss.

In epidemiology and economic literature, the AHC is frequently used to assess the loss of human capital value caused by air pollution, particularly fine particulate matter (Huang et al., 2012; Yin et al., 2015; Yin et al., 2017). The possible sickness induced by PM2.5 is drawn from Thai research initiatives (Jenwitheesuk, K., Peansukwech, U., & Jenwitheesuk, K. (2020)) as well as earlier evidence (Yin et al., 2015) based on ICD-10 reports. As a result, employing the AHC technique, this study focuses on the health effects of PM2.5, particularly premature mortality induced by PM2.5. According to the AHC, individuals are seen as the fundamental unit of human capital, providing goods and services. This method assesses the loss of life and health using a general criterion for assessing physical capital, which is typically represented as wage or labor capital. The HC method simply considers the predicted income loss as the loss from early mortality.

$$AHC = GPP_{j0} \cdot \sum_{k=1}^t \frac{(1+\alpha)^k}{(1+\gamma)^k} \quad (9.2.4)$$

The amended human capital per case is expressed in Eq. (4). It was calculated based on a gross provincial product (GPP) of province j in year k (GPP_{j0})²⁷, α is the per capita GPP growth rate, and γ is a social discount rate²⁸, t is the average number of life-years lost due to exposure to PM2.5 at a given concentration, which is assumed to be 10 years (Yang et al., 2015).

Based on rice production scenarios, the health cost related to exposure to PM2.5 from different rice practices production is assessed. We expect that as the area of conventional rice production decreases with the expansion of sustainable rice cultivation area, the health cost tends to extensively decline.

Results

The estimation of health impact using the human capital approach reveals that the negative externality of PM2.5 emissions from rice residue burning varies in both regions depending on conventional rice conversion to sustainable rice practice. The health impact is converted in monetary

²⁷ A based year is 2012. The statistic of GPP applied from the Office of the National Economic and Social Development Council in 2018

²⁸ Social discount rate refers to a present value on cost and benefits for economic evaluation that will occur in the future. The social discount rate usually use between 3%-7% in developed countries and between 8%-15% in developing countries (Medalla, 2014). In the context of health impact, the parameters values of the social discount rate are 8%.

value taken premortality of all-causes. The spatial distribution of economic health costs is illustrated at the provincial level in 2021. The largest economic health cost, ranging from 8 to 27 million USD, was discovered in the southwest of the region, in the provinces of Khon Kaen, Nakhon Ratchasima, Buri Ram, and Roi Et. Surin, Maha Sarakham, and Amnat Charoen, for example, have a vast area of conventional rice cultivation, but their health costs are quite modest, ranging from 4-6 million USD. In certain provinces, the percentage of sustainable rice to conventional rice is high, which may imply a decreased public health impact. For the central region of country, the highest public health cost of PM2.5 from rice residue burning found in Kamphaeng Phet, Nakhon Sawan, Suphan Buri, Ayutthaya, Nonthaburi, and Pathum Thani provinces. A similar tendency also found in the central region, where a large proportion of sustainable rice land is associated with lower health expenditures. For example, over 20% of rice agriculture in Chai Nat, Sing Buri, and Saraburi provinces is sustainable rice production. The estimated public health cost is in a relatively low range for these provinces, ranging from 2–4 million USD.

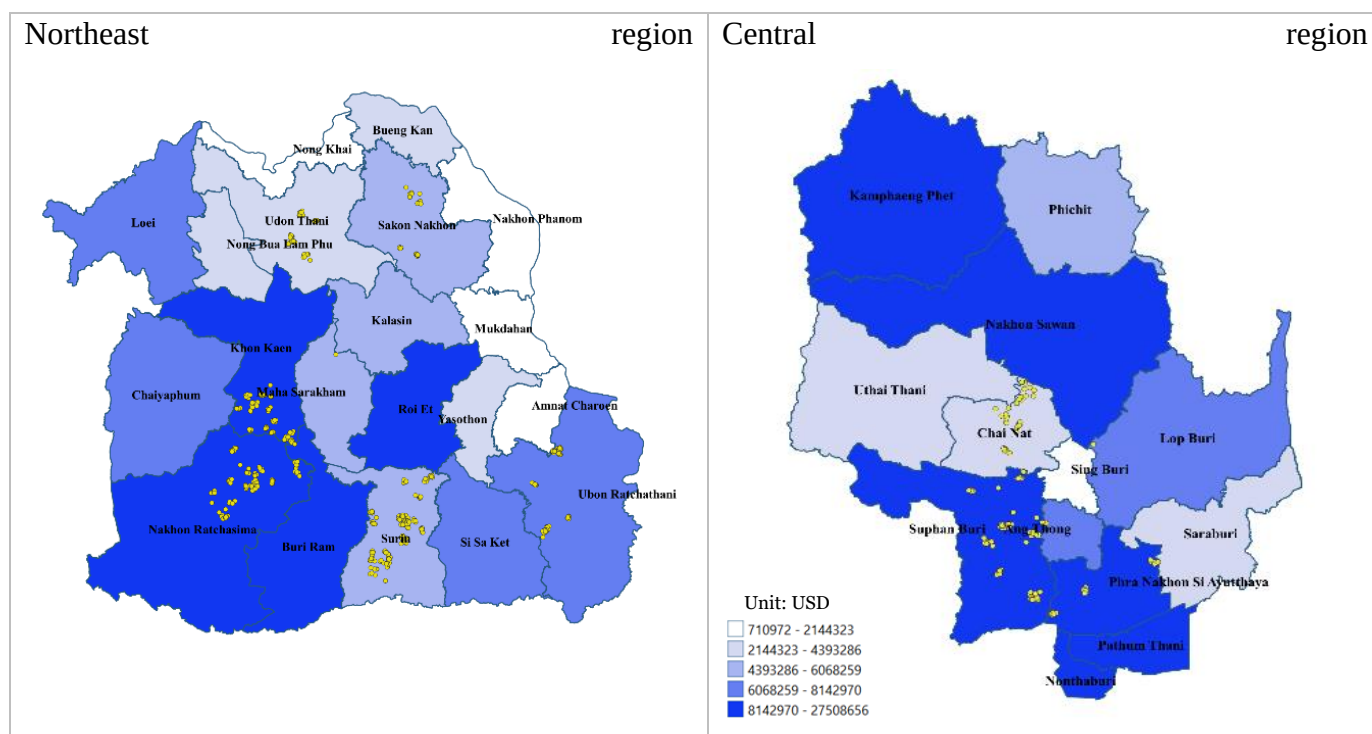


Figure 9.1 Spatial distribution of provincial economic health cost in 2021 assessed by AHC method. The northeast region is on the left panel and central region is on the right panel. The yellow dots indicate paddy fields from the household survey.

Table 9.7 Estimated Health Cost based on the AHC approach 2021

Regional zone	Province	PM2.5 ($\mu\text{g}/\text{m}^3$)	Health cost (thousand USD/Year)		Percentage in rice production cost (%)	
			All-cause mortality	Respiratory and lung cancer	All-cause mortality	Respiratory and lung cancer
NE Up	Sakon Nakhon	35.738	3,013 (105,463) ^a	1,407 (49,252) ^a	19.77%	9.23%
NE Up	KhonKaen	35.048	8,550 (299,246) ^a	3,990 (139,658) ^a	44.70%	20.86%
NE Up	Udon Thani	17.744	1,859 (65,075) ^a	854 (29,881) ^a	9.70%	4.45%
NE Low	Nakhon Ratchasima	36.405	15,956 (558,458) ^a	7,456 (260,968) ^a	71.02%	33.19%
NE Low	Surin	34.252	3,472 (121,512) ^a	1,619 (56,667) ^a	21.29%	9.93%
NE Low	Ubon Ratchathani	30.493	4,554 (159,379) ^a	2,116 (74,063) ^a	19.70%	9.16%
Central	Chai Nat	36.849	1,548 (54,164) ^a	723 (25,321) ^a	44.19%	20.66%
Central	Suphan Buri	36.221	5,117 (179,093) ^a	2,391 (83,676) ^a	69.73%	32.58%
Central	Phra Nakhon Si Ayutthaya	20.810	8,209 (287,329) ^a	3,780 (132,312) ^a	245.10%	112.87%

Note: 1USD = 35 BTH, ^a Thousand Baht/Year indicates in parenthesis.

9.2.1 Health cost caused by PM2.5 analysis according to scenarios

This section examines the relationship between PM2.5 health costs and various policy scenarios. A setting of four pathways is based on policy aim and includes "business as usual", "moderate change", "enhanced changes", and "transformation change", as per the sustainable rice area expansion scenarios. According to multiple policy objectives, it is anticipated that the sustainable rice area will increase while the conventional rice area will decline overtime. Since

burning rice straw is forbidden in sustainable rice cultivation, it is considered that conventional rice cultivation regions are the only places where burning occurs, particularly before and after rice production. Therefore, when the conventional rice area decreases, we anticipate that the negative impact associated with high PM_{2.5} levels would go down. The conventional rice area is regarded as the main source of PM_{2.5} emissions in this analysis because sustainable rice fields and other agricultural residue burning sources aren't included in the list of potential emission sources.

To assess the health-related expenses linked to the emission of PM_{2.5} from the combustion of rice straw, it is imperative to transform the PM_{2.5} emissions amount computed in the GHG emissions section (Eq.1) into a PM_{2.5} concentration in the environment. Figure 9.2-A and -B display the PM_{2.5} concentration from residue burning in each scenario of NE region and central region, respectively. For the NE region, the forecast annual average PM_{2.5} concentration of BAU during 2025-2050 is approximate 30 mg/m³. The highest PM_{2.5} concentration in the northern NE region is over 40 mg/m³, including Loei and Roi Et provinces. Once the policy is promoted at moderate change (Scenario 2), it reveals that the PM_{2.5} concentration tends to decrease in the southern NE, such as Surin, Si Sa Ket, Ubon Ratchathani provinces. In the same region of NE, the dramatic change relative to the BAU scenario is in the enhanced and transformative change of SRP promotion (Scenario 3 and 4) in Roi Et and Yasothon provinces.

For the central region, we found that the highest PM_{2.5} was found in Ang Thong province, at nearly 63 mg/m³, where the regional mean is at 30.9 mg/m³ of the baseline. The implementation of the SRP conversion policy can stimulate a reduction of PM_{2.5} from rice residue burning. If an enhanced conversion of the SRP program is implemented, Lop Buri, Chi Nat, Nakhon Sawan, Uthai Thani, and Suphanburi will see a decline in the level of dust. (As can be distinguished by a sawtooth on the bar chart in each province). The significant decrease in PM_{2.5} present in scenario 4 of an annual average of 11.8 mg/m³.



Figure 9.2-A PM2.5 concentration from residue burning in each scenarios of NE region, Thailand.

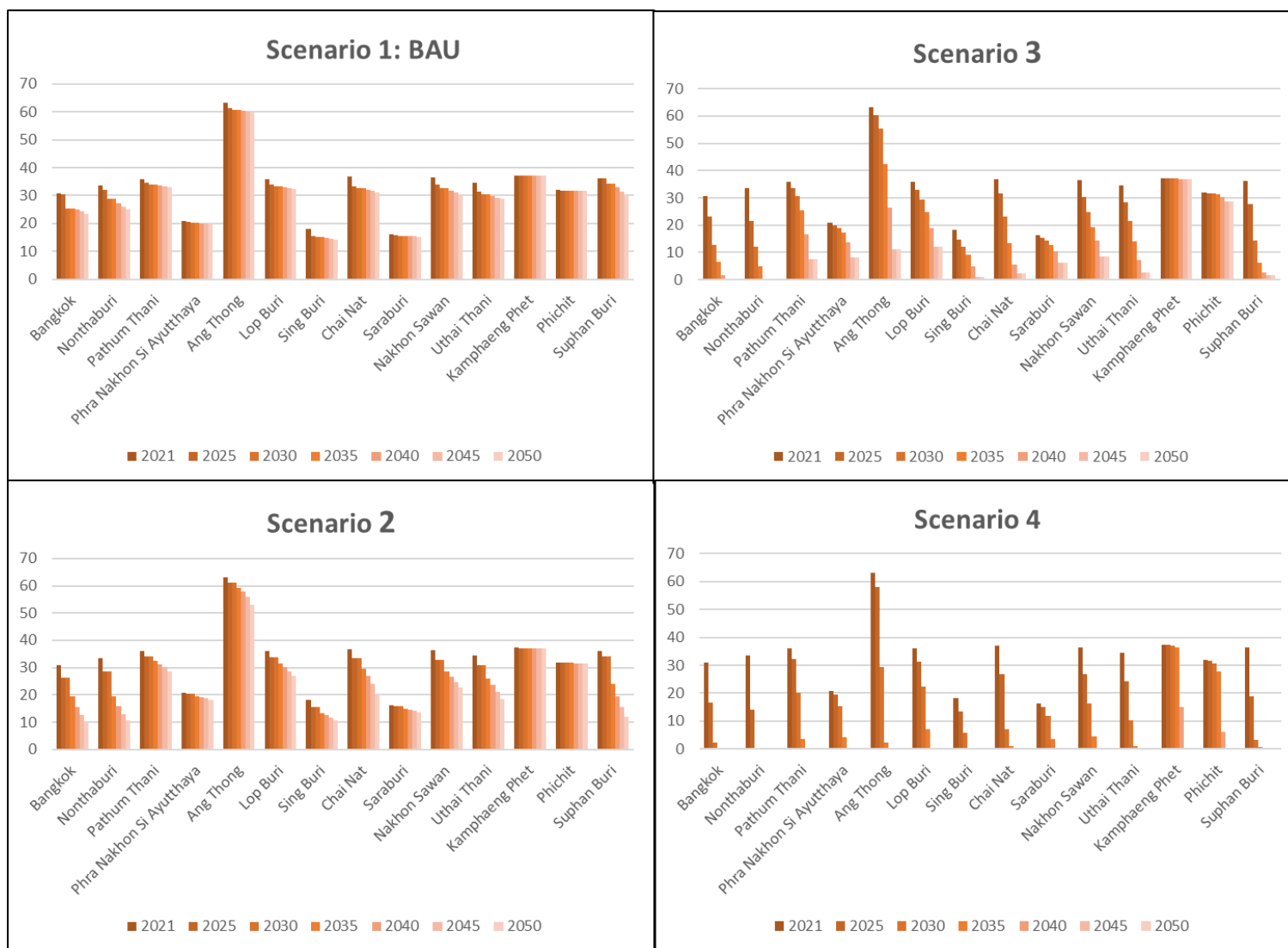


Figure 9.3-B PM2.5 concentration from residue burning in each scenarios of central region, Thailand.

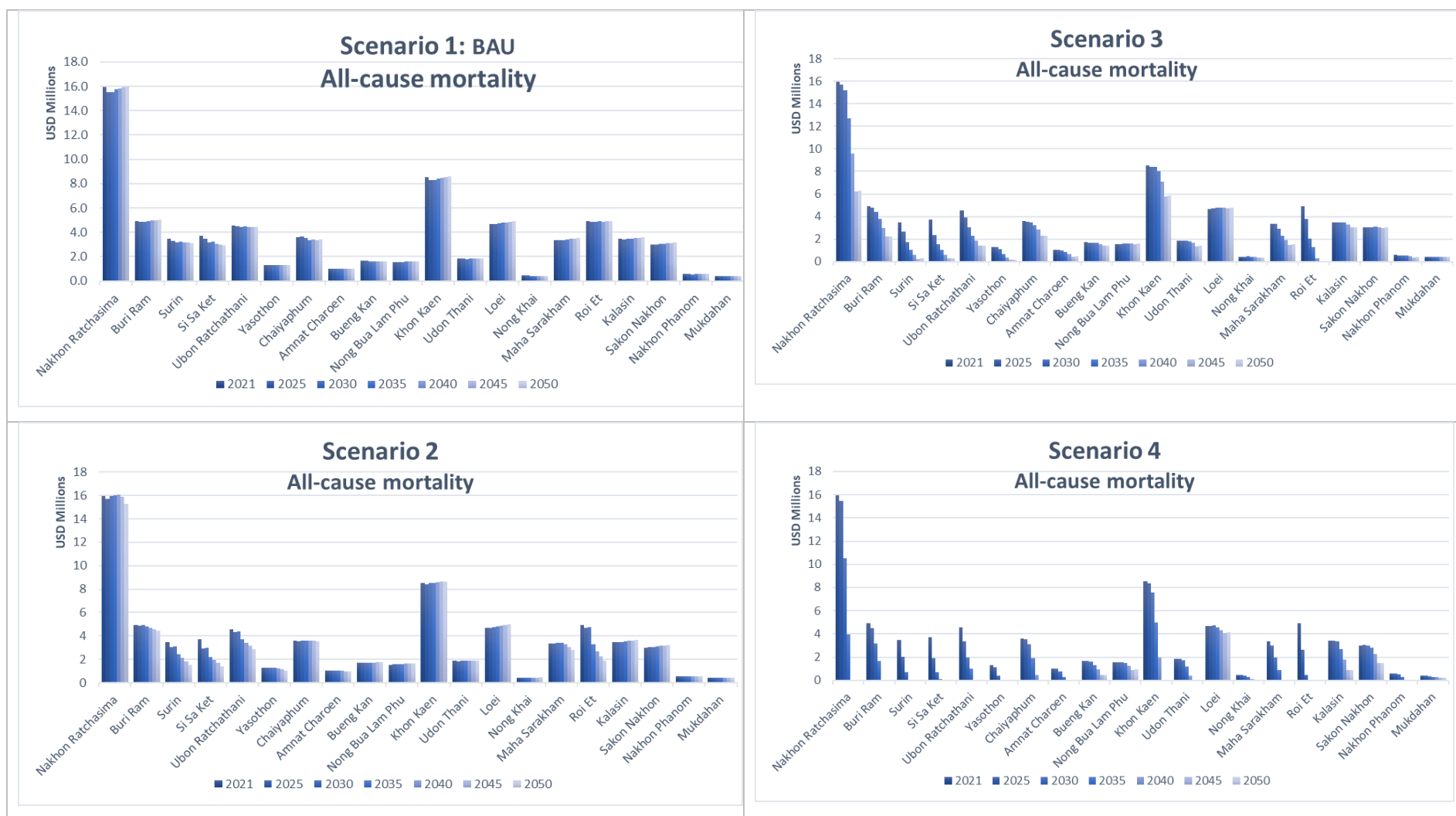


Figure 9.4. Comparison of Economic cost for all-cause mortality related to PM2.5 from rice burning according to the four scenarios for years from 2021 to 2050, in all provinces of NE Thailand.

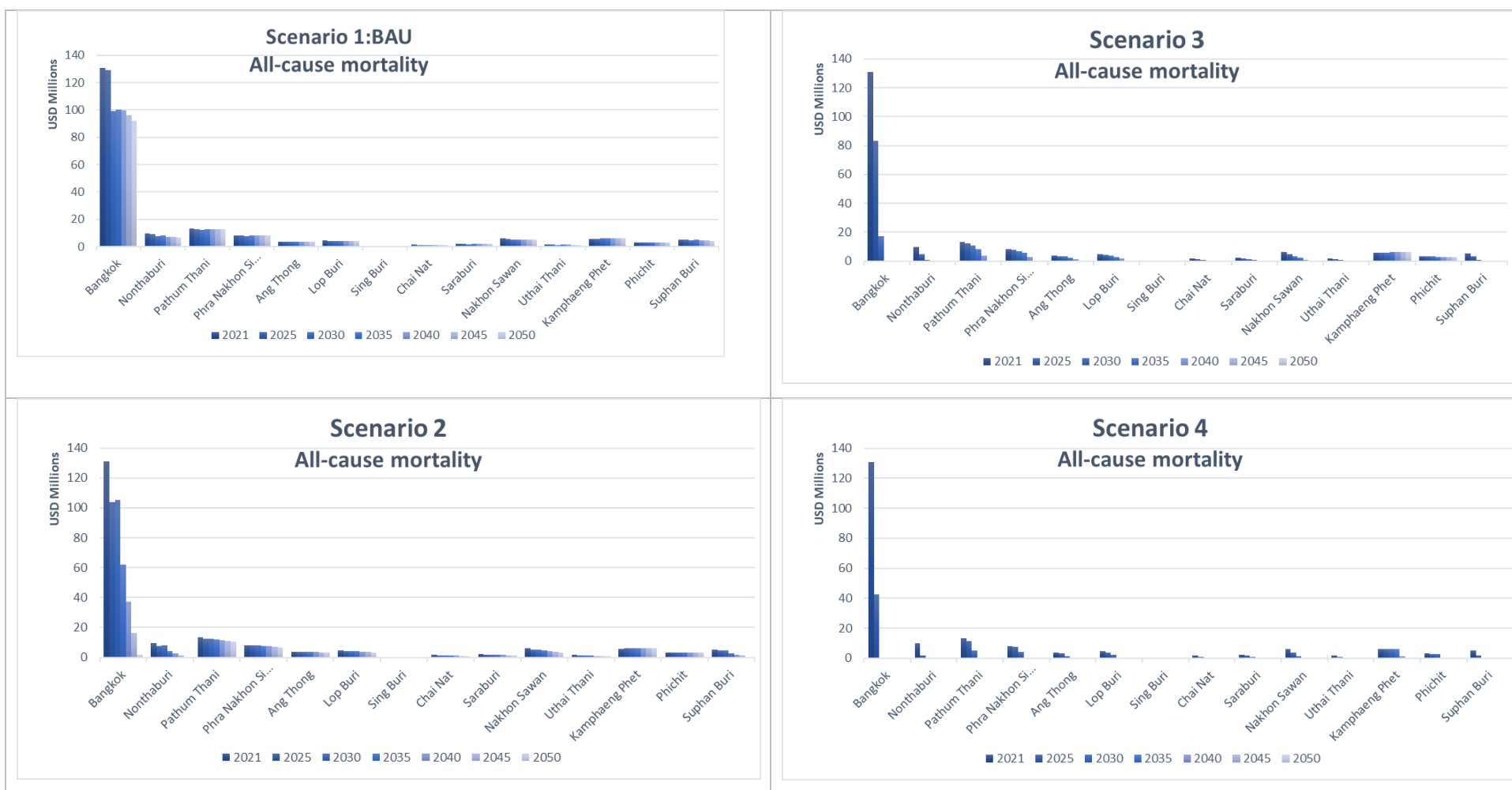


Figure 9.5 Comparison of Economic cost for all-cause mortality related to PM2.5 from rice burning according to the four scenarios for years from 2021 to 2050, of a central region, Thailand.

The health impacts of PM2.5 is estimated based on the human capital approach. To prevent double counting of health endpoints, the effects of various disorders on health were determined with respect to PM2.5 levels. Specifically, the rising risk of death from cardiovascular disease, lung cancer, and respiratory disease as well as cause-specific mortality (Yin et al., 2017). The World Health Organization (WHO, 2018) has stated that PM2.5 concentrations exceeding 10 mg/m³ are deemed to have health impacts, and our study follows this recommendation. The population of all provinces in both regions was retrieved of 2021²⁹ and each province was extrapolated forward using a 0.28% exponential growth rate to estimate the health effects across the four future scenarios. It produces a large number of instances brought on by PM2.5 pollution. The results are organized by health implications in Table 9.7. The disparity in population distribution across these provinces has an impact on the outcomes for all health consequences. According to the estimates shown in Table 9.7, there is a link between the amount of conventionally cultivated rice in a province and the number of residents who experience health effects from PM2.5 exposures. The large number of affected people health consequences in the northeast region are noted in Nakhon Ratchasima, Loei, Khon Kaen Si Sa Ket, Buri Ram, Surin, Ubon, and Ratchathani.

To investigate the overall health impact over time, a comparison of the average health costs across different scenarios is presented for two regions (Fig.9.6). The average health costs in each region cover health specific disease, all-causes mortality of all provinces in the study area is applied. It is obvious that an intensive conversion to sustainable rice production (Scenario 3 and 4) has potential to reduce the health impact comparing to BUA by over a million USD starting in 2035 for the northeast, but it is substantial for the central region over ten million USD in 2035.

²⁹ Department of Provincial Administration, Bureau of Registration Administration (BORA), Thailand 2021.

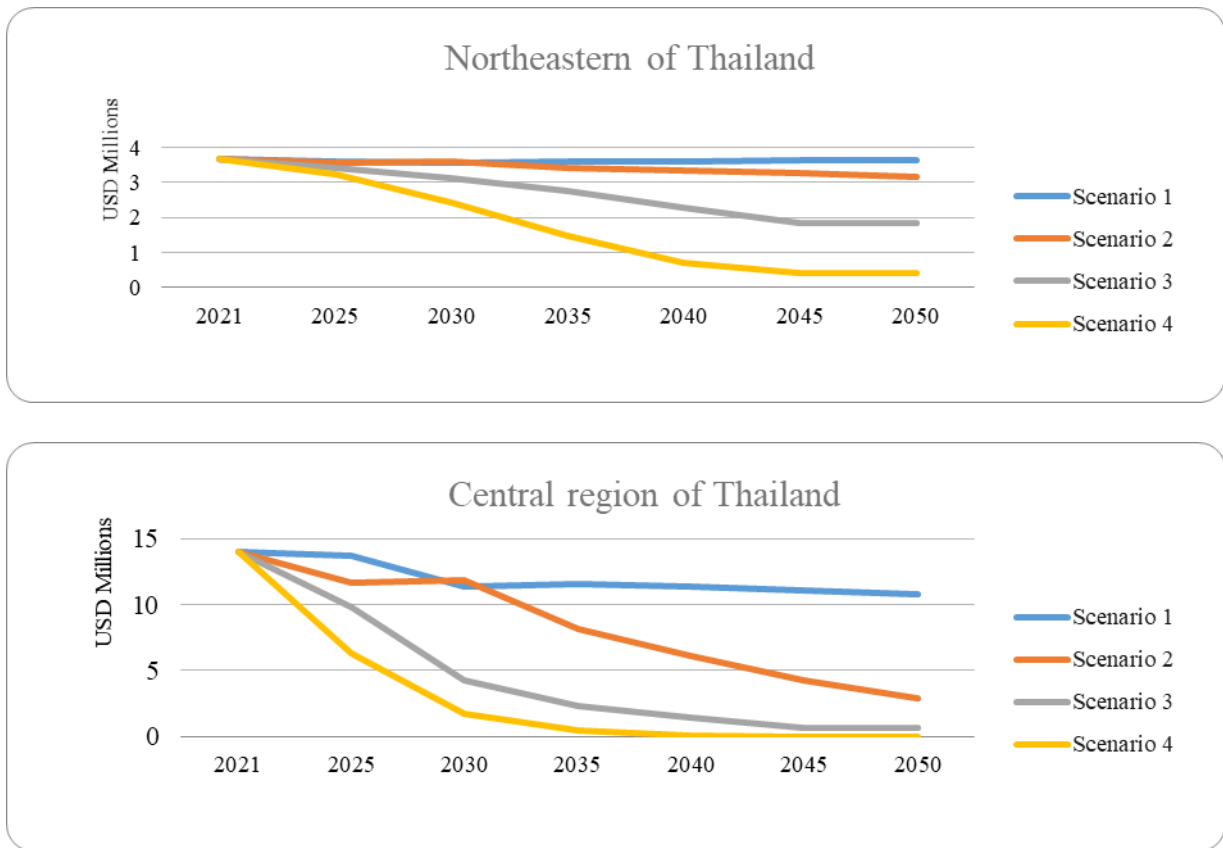


Figure 9.6. Average health costs caused by all-cause mortality from exposure to PM2.5 from rice residue burning.

9.3 Summary

In this section, we explore the public health risks associated with the burning rice straw. Converting rice production from conventional methods to SRP rice practices has the potential to mitigate the negative externality to the public. In Thailand, the sustainable rice practice prohibits the burning of rice residue (straw and stubble) in open fields. This study assumes residual rice field burning is not caused by sustainable rice practices. Thus, residue burning in traditional rice cultivation was employed to assess the benefits of SRP rice production. In the words, conventional rice cultivation and burning rice straw determined the health risk of conventional rice production. The open-field burning method is used to estimate the release of PM2.5 concentrations from burning rice straw. The health impact is assessed by measuring premature mortality using the

exposure-response function. This measurement is then used to calculate health costs using the capital approach. The main findings suggest that as the conversion of SRP rice area increases, the public risk decreases significantly. The health cost accounts for an average of 30 percent of rice production in the northeast region, while it is over 100 percent in the central region due to a strike in Ayutthaya province. The future scenarios of health costs over time show that an intensive conversion to sustainable rice production (Scenarios 3 and 4) has the potential to reduce health impacts comparing to BAU by over a million USD in 2035 for the northeast and over ten million USD in 2035 for the central region.

Part 10 Scenario Analysis

Introduction

The rice sector plays an important role in the social, economic, and environmental development of Thailand. The main purpose of this study is to assess the responses of various variables in rice system based on different scenarios, which focus on different degree of landscape changes between conventional rice and sustainable rice areas in the Central and Northeast region of Thailand from 2022-2050. There are four scenarios differed by the proportion of conventional and sustainable rice areas. The business as usual (BAU) scenario reveals the situation in which the sustainable rice area will increase to 640,000 hectares in 2050 or just about 7.58 percent of total rice area of these regions. For scenario 2, the sustainable rice area will increase to 1,961,600 hectares in 2050 or 18.19 percent of total rice area in both regions. For scenario 3 with enhancing sustainable rice promotion, this scenario projects the total of sustainable rice area in 2050 by about 4,672,000 hectares or 55.33 percent of total rice area in both regions. For the final scenario, scenario 4, the sustainable rice area will increase to 6,997,000 hectares or 82.86 percent of total rice area in these regions.

We analyze variables that response to the land use changes under different proportion of sustainable rice and conventional rice areas from these scenarios. The variables affected by different rice practices focus in this study related to natural capital, human capital, and social capital. For the natural capital, this study focuses on greenhouse gases emissions, biodiversity, and water footprint from conventional and sustainable rice practices. Impacts on human health from pesticide poisoning and air pollution due to PM2.5 caused by rice field burning from different rice cultivations are explored for measuring change in human capital. In addition, rice yield and cost of cultivation, which represent profit gained by farmers, between conventional and sustainable rice practices are also estimated as part of human capital. We also qualitatively explore the effects of different rice practices on social capital. The main focuses are cooperation and social relationship among farmers when performing different cultivation practices. In addition, we also explore the characteristics of social network, which is part of social capital, between these two practices to better understand how the information of new agricultural practice such as sustainable rice practice can be wildly diffused using social network and social learning, which later would lead to more

efficiency of increase sustainable rice practice adoption. Most of these measures, except for social capital, are quantified and predicted based on land use changes under each scenario.

We perform benefit-cost analysis to estimate the net benefit from each scenario compared to BAU scenario. The information from benefit-cost analysis reveals the best scenario that provides the highest net benefit when all measures are considered together. In addition, the information from benefit-cost analysis is also used to identify trade-offs and synergy points that would be important for policy design. Specifically, we present the net changes projected to occur in each measurement under each scenario, and analyze the trade-offs and synergy points that may occurs under each scenario and across scenarios.

To perform benefit-cost analysis, the changes that can be quantitatively measured are converted to monetary values. These variables include greenhouse gases emissions, biodiversity, water footprint, health costs caused by pesticide poisoning and air pollution. In addition, rice yield and cost of cultivation, which represent profit gained by farmers, are included to analysis. The details of financial proxies applied for each variable are explained in the next part following by the results of scenario analysis.

10.1 Financial proxies

The measures that could be quantified, which include rice yield, cost of rice cultivation, greenhouse gases emissions, and health impacts, were monetized to calculate relative benefits and costs generated under each scenario to identify the direct and indirect impacts of conventional and sustainable rice areas changes. The prices of rice output were identified as a value change based on scenarios. However, there are two rice prices varying on the regions. The northeastern rice is the premium rice, Hom Dok Mali, which the price is higher than that in the central region, 374.59 and 235.40 \$/ton respectively. The sustainable rice practice could provide less production cost than that from conventional rice practice, mostly saving from land preparation and fertilizer cost in the central, and from pesticide and fertilizer cost in the northeast.

The impact on human health were captured by two effects. The first one was from the impact of PM_{2.5} on public health estimated based on Exposure-response function model depending on scenarios. The second impact was health cost from pesticide on farmers' health calculated by the defensive expenditure approach. The sustainable rice practice could save the health cost from pesticide about \$38.22 per hectare. Finally, the value of GHG emission was represented by average

closing spot prices of European Emission Allowances (EUA) from 2019 to 2022 average price of carbon credit at about \$38.19 per ton of carbon. Moreover, the alternative prices from carbon credit price of voluntary program in Thailand by Thailand Greenhouse Gas Management Organization (TGO) \$5 and social cost of carbon as mentioned by US EPA \$51 per ton are calculated and reported in the appendix.

Moreover, the biodiversity and water are two more impacts that were not been accounted into the monetary value based on different rice practices in each scenario. Due to the fact that the biodiversity was represented by insects. Both practices commonly apply the chemical fertilizer and pesticides. The results from biodiversity analysis emphasized that biodiversity index between these two practices within each region were not significantly different. The price of water for agricultural sector were obscure. The water price cloud be reflected to water scarcity. However, the opportunity of water for rice cultivation is unclear in the study area. The blue and gray water for rice cultivation in various different scenarios were report in term of water per ton of rice production instead.

Table 10.1 The monetary proxy per unit of factors

Variables	Monetary Proxy	Unit	Value (Northeast region)	Value (Central region)
Rice production	Rice price	\$/ton	374.59	235.40
cost of production	Cost	\$/hectare	21.56	55.38
Health cost from PM2.5	PM 2.5 Health cost	\$/year	Cost	Cost
health cost from pesticide	value approach	\$/hectare	38.22	38.22
GHG emission (EU Emissions Trading System)	Carbon Price	\$/ton	38.19	38.19
GHG emission (Thailand Greenhouse Gas Management Organization price)	Carbon Price	\$/ton	5	5
GHG emission (US EPA)	Social cost of carbon	\$/ton	51	51

10.2 Scenario analysis

The benefits or losses in various capital dimensions between the two rice practices are calculated based on the different value of the three option scenarios compared to BAU scenario. In each scenario, three options of cultivation patterns are set. The first set assumes double crops of rice per year in the irrigated area and single crop of rice per year in non-irrigated area (*rice-rice option*). The second option is based on the assumption of single crop of rice per year in both irrigated and non-irrigated areas in rainy season. During the dry season, farmers in irrigated area grow maize, later called *rice-maize option*. The last option is the same as second option in term of rice cultivation where there is only one crop of rice per year for both irrigated and non-irrigated rice areas. However, farmers in both irrigated and non-irrigated rice areas grow sunn hemp during dry season, later called this option as *rice-sunn hemp option*.

Before going to trade off analysis based on scenarios by regions, we present the total value of benefit impacted by land pattern change from conventional to sustainable rice practice with each option. Starting with the *rice-rice option*, figure 10.1 represents the total net benefit generated from both regions. The fourth scenario provided the highest net benefit compared to BAU during 2021 to 2050 with the value about \$49,460 million accumulatively. Most of the overall net benefit came from environmental externality dimension, the more detail in figure 10.2. The second-high value comes from environmental issue including GHG emission reduction and soil organic carbon with the value of \$25,826 million. Although, the GHG emission value form rice cultivation is negative about \$7,697 million in figure 10.2, the net benefit value in environmental dimension is still high. The last net benefit value is human health dimension, which provides the net benefit about \$4,823 million. The net benefit value in the fourth scenario is higher than that in the second and third scenario about 4 and 1.5 folds, respectively. In the *rice-rice option*, the potential positive value is generated from the value of rice production because the yield under sustainable rice practice of the northeast region is on average double when compared to that of conventional rice practice.

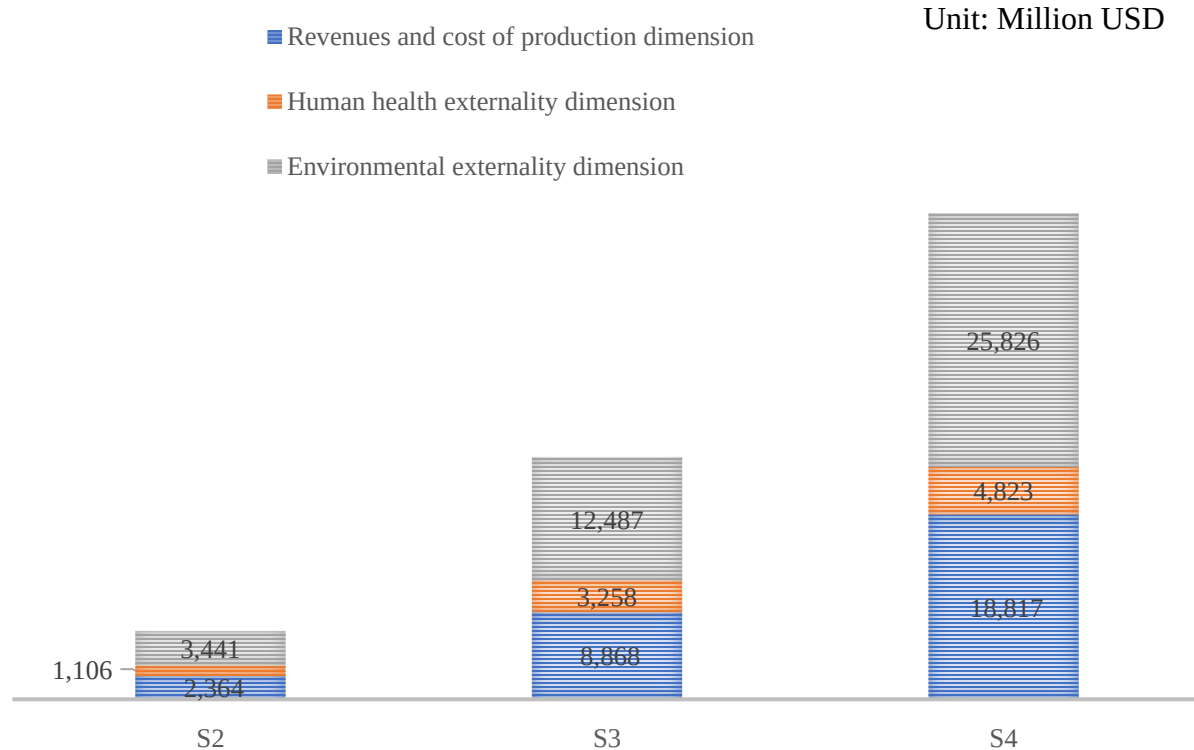


Figure 10.1 the overall benefit values of double crops option in each scenario from 2021 to 2050 compared to BAU

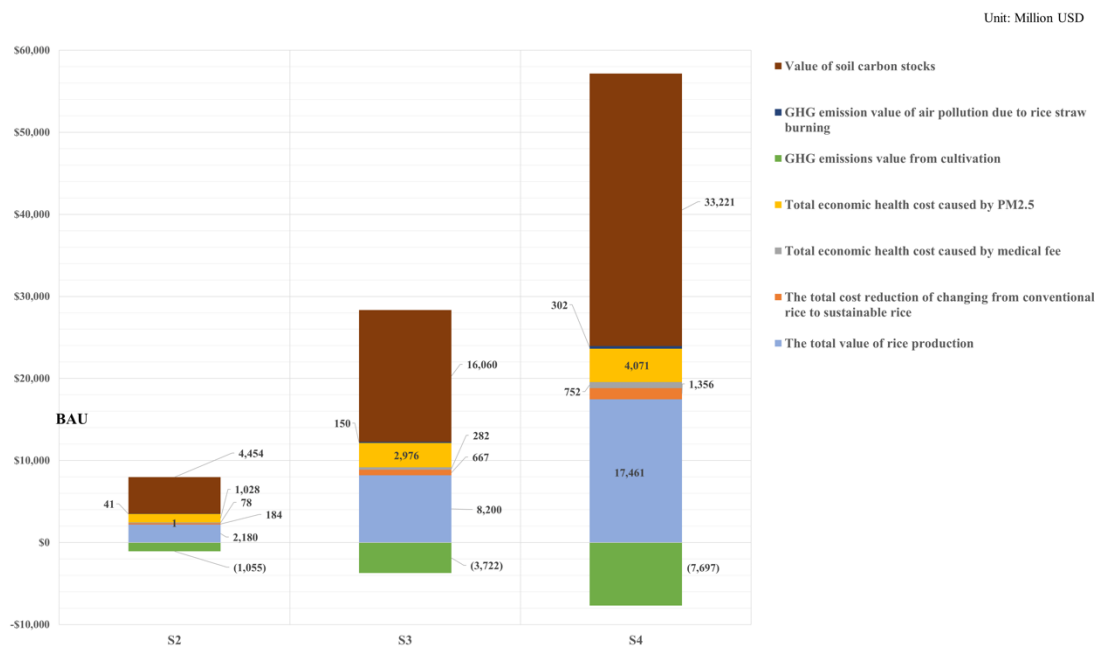


Figure 10.2 the overall benefit values of double crops option in more details in each scenario from 2021 to 2050 compared to BAU

The national net benefit values of rice-maize option with the same land pattern change in each scenario are shown in Figure 10.3. The fourth scenario still presents the highest net value with about \$39,339 million as well as the same pattern comparing among three scenarios. The value of human health dimension is increased by expansion of SRP area. In addition, the expansion of SRP area induces more net benefit value of environmental issue such as GHG emissions as well as significant increase in net benefit of rice production. However, the rice production value could be slightly negative in the second scenario due to switching of dry season rice to maize in central region, although the rice production in the northeast would increase heavily.

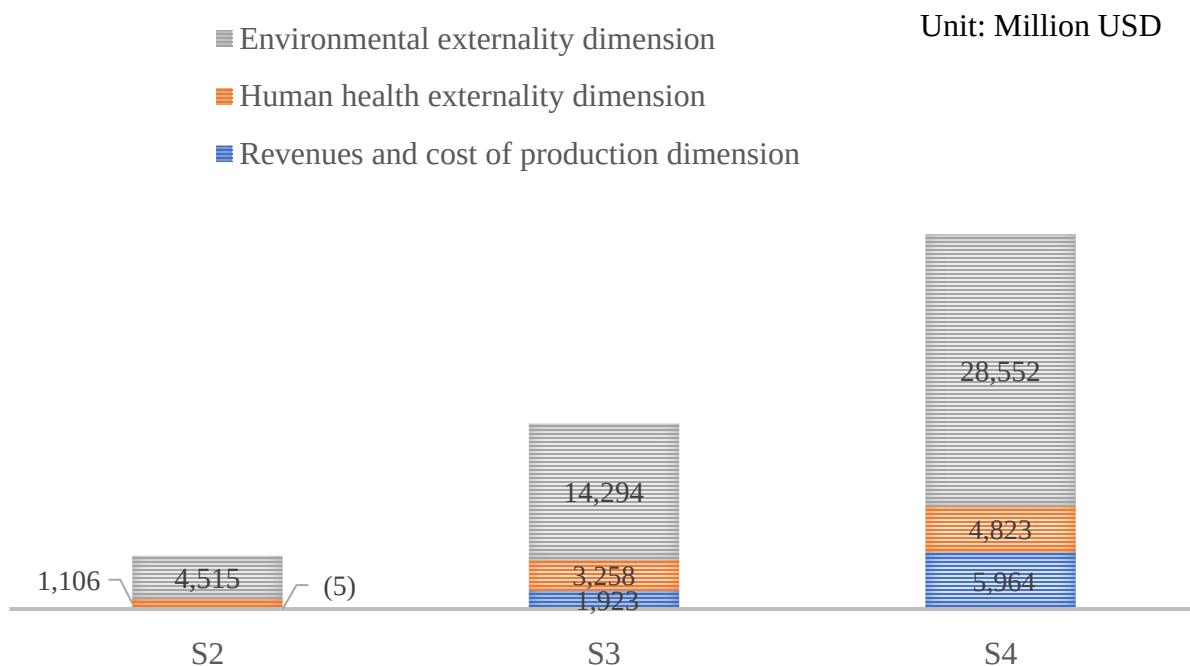


Figure 10.3 The overall benefit values of rice-maize option in each scenario from 2021 to 2050 compared to BAU

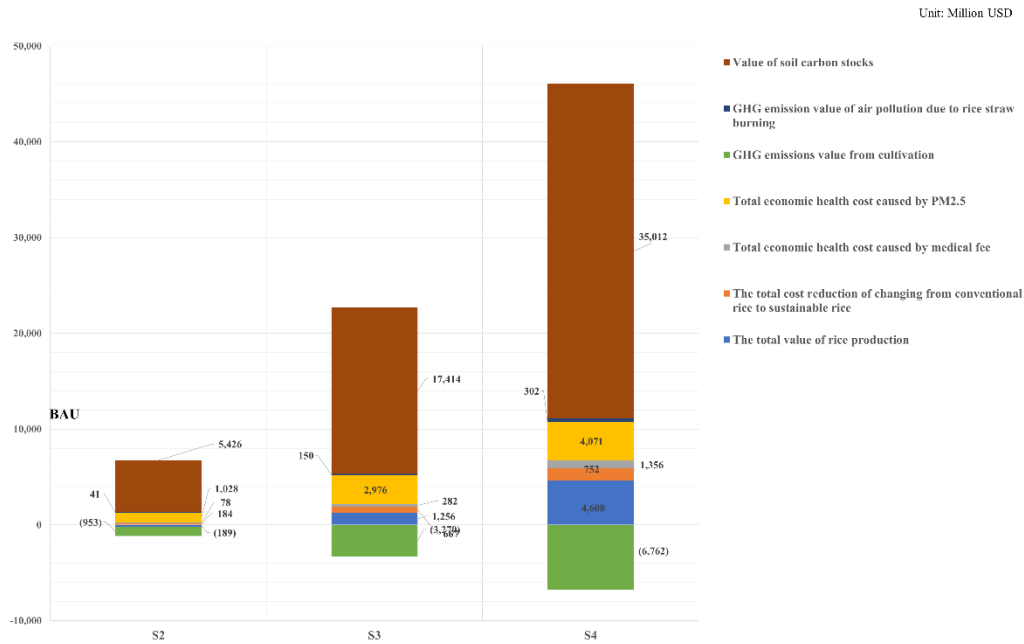


Figure 10.4 the overall benefit values of rice-maize option in more details in each scenario from 2021 to 2050 compared to BAU

The last option with rice-sunn hemp generated the same pattern with rice-rice and rice maize option. The highest net benefit value comes from the fourth scenario, figure 10.5, which contains the highest area of SRP. The environmental issue benefit slightly decreased when compared to the maize option, meanwhile the value of rice production decreased about half of the value in rice-rice option due to loss of rice production. The more detail of all impacts was shown in figure 10.6.

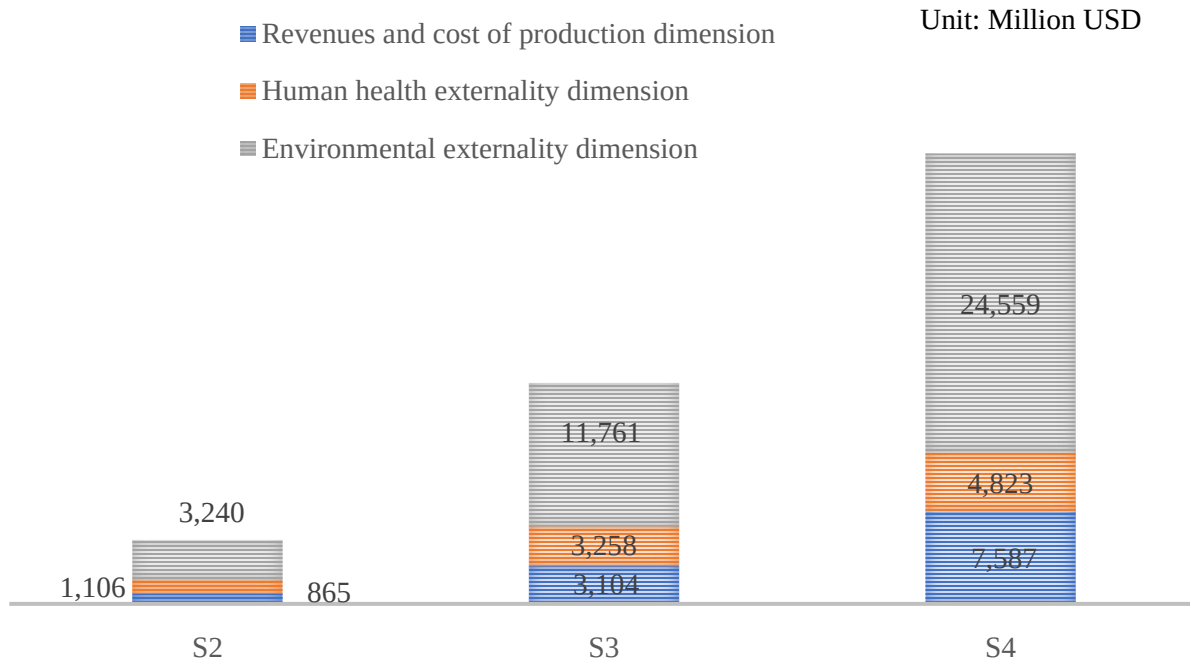


Figure 10.5 the overall benefit values of rice-sunn hemp option in each scenario from 2021 to 2050 compared to BAU

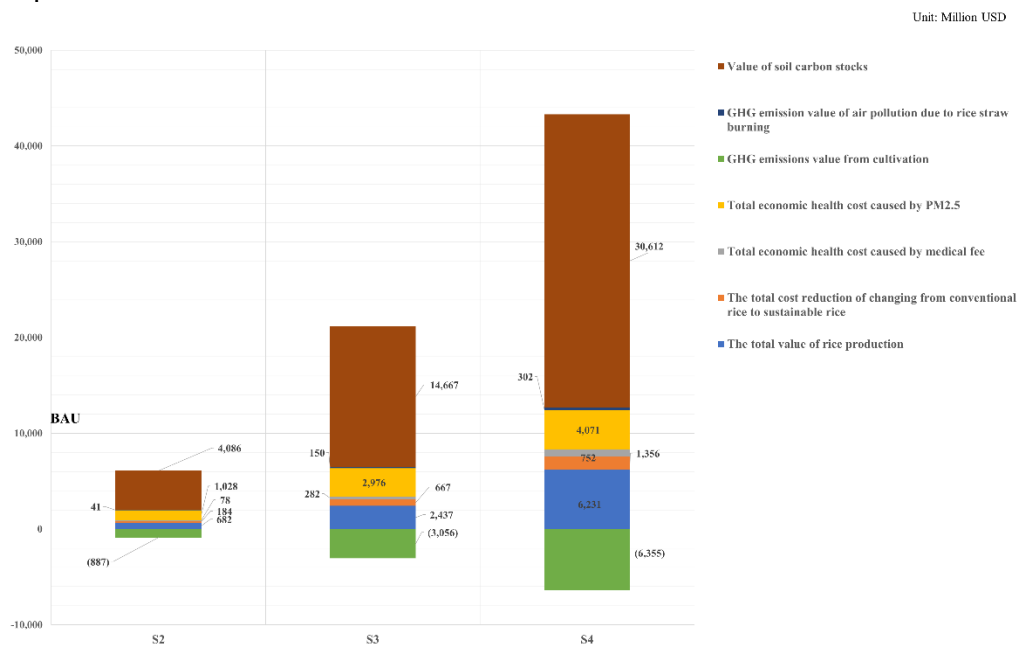


Figure 10.6 the overall benefit values of rice-sunn hemp option in more details in each scenario from 2021 to 2050 compared to BAU

When we consider the changes between the northeast region and the central region, the result in *rice-rice option* showed that net benefit especially from rice production value in the northeast region is much higher than that in the central region, figure 10.7. This is due to the fact that yield

improvement under SRP in the northeast region is much higher than that in the central region, which our model predicts a small improvement of rice yield under SRP in the central region. The net benefit of environmental impact shares the similar pattern with rice production value, whereas human health values in the central region are much higher than that in the northeast region when the SRP area increase. This is because currently farmers in central region have extensively and significantly applied insecticides and pesticides more than those in the northeast region. Therefore, the higher the expansion of SRP in central region is the more benefit from health cost reduction due to insecticide and pesticide poisoning.

The results of *rice-sunn hemp option* and *rice-maize option* are similar to the *rice-rice option* result. Moreover, the values of rice production in central region of these two options are negative, figure 10.8 and figure 10.9, respectively. The negative values of rice production in the central region directly come from our scenario analysis assumption in these two options. Currently, about 50 percent of rice area in the central region cultivate rice twice a year. When we assume that this area under SRP grows rice only one a year during raining season and during the dry season this area grows maize or sunn-hemp, about half of the rice yield disappears. However, our analysis does not include the benefits of maize and sunn-hemp, which could be in forms of farmers' income for maize and reduction of fertilizer cost for sunn-hemp.

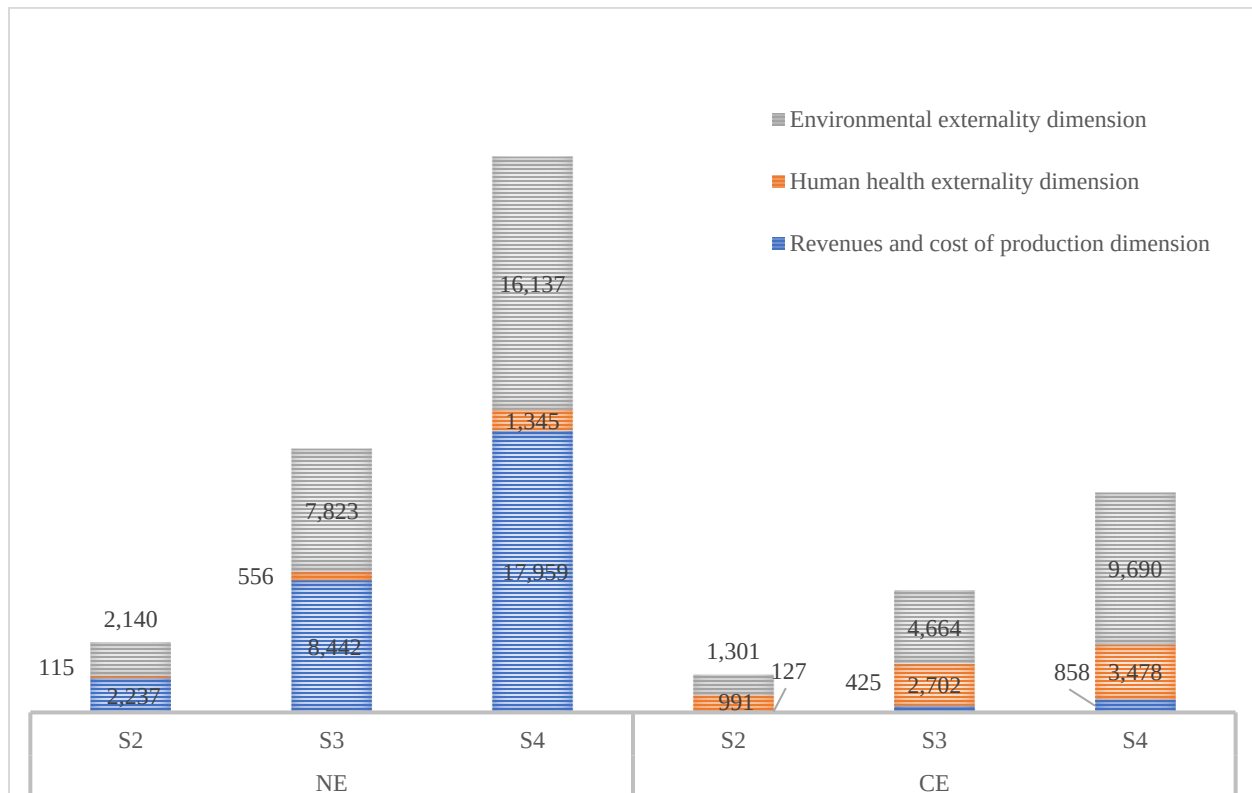


Figure 10.7 the net benefit values of double crops option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU

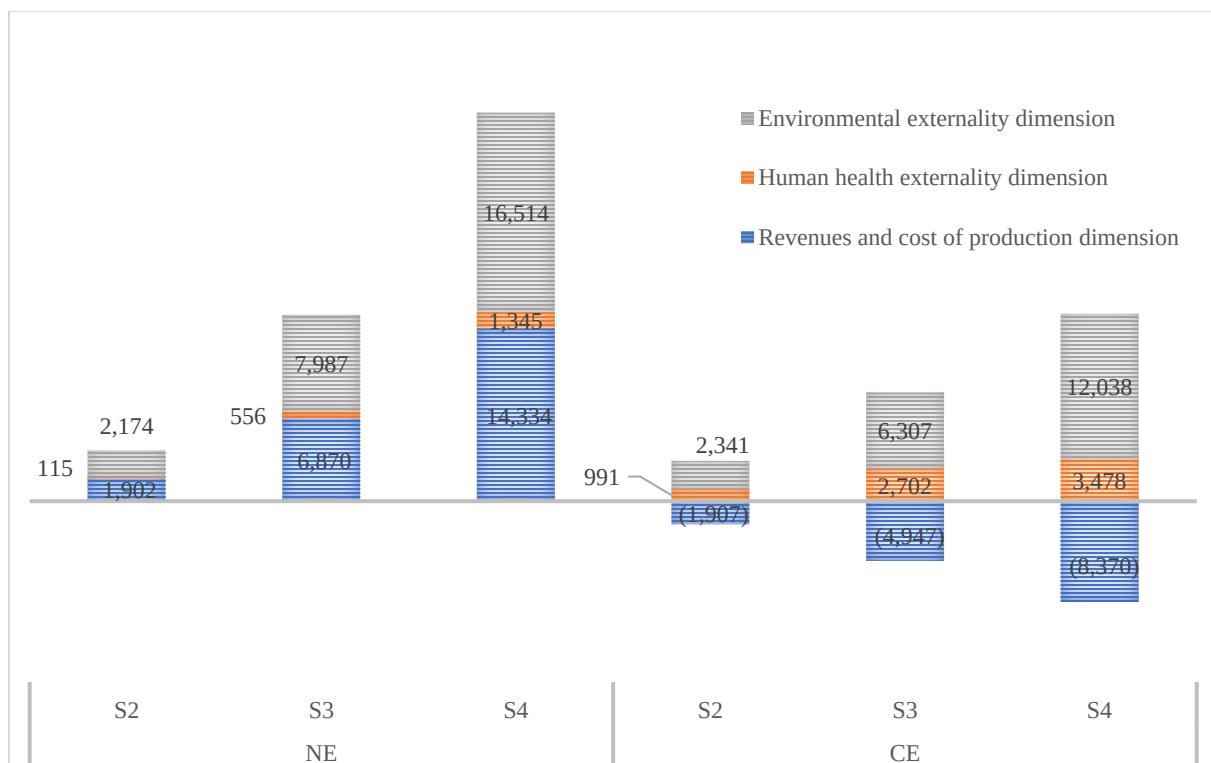


Figure 10.8 the net benefit values of rice-maize option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU

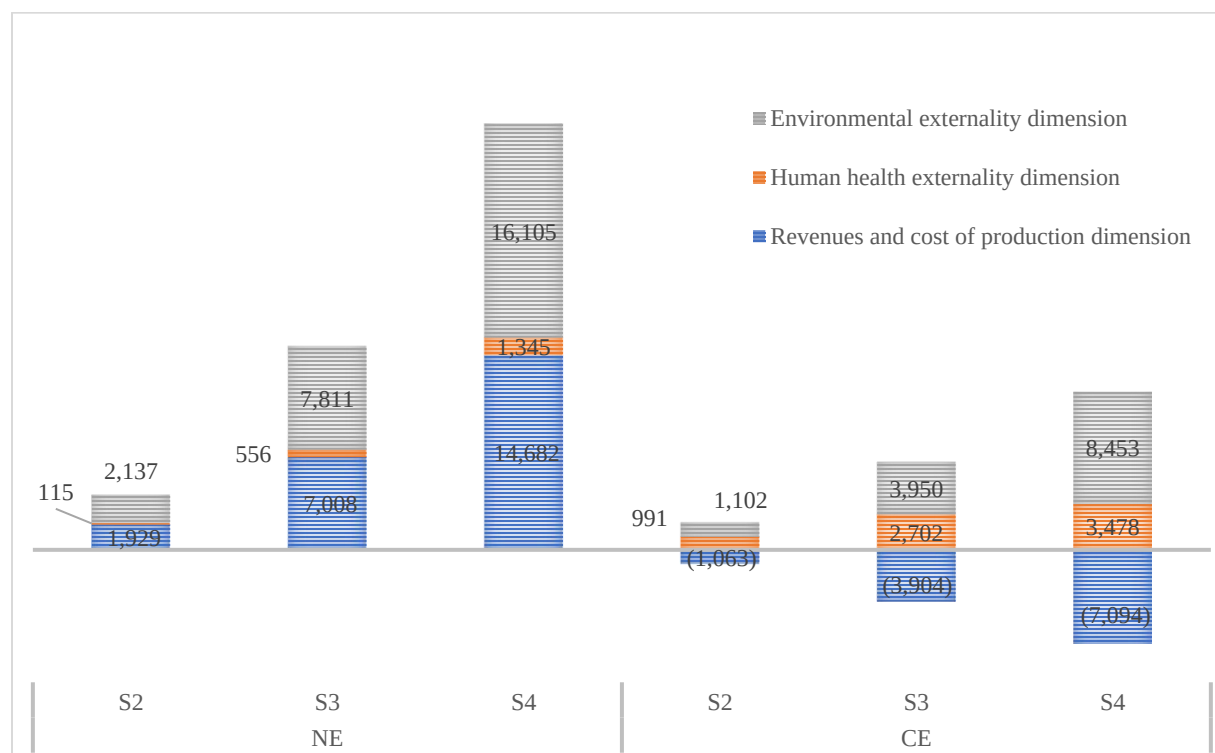


Figure 10.9 the net benefit values of rice-sunn hemp option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU

Scenario analysis by regions

Next, we move to the trade-off analysis when sustainable rice practice is promoted based on scenarios within the regions and options. These two regions are separately explained since many factors such as rice varieties, rice yields, irrigation areas, farmer practices, and climate conditions are quite different. The monetized values of seven factors, related to human health, environment, and economics, as well as volume of gray and blue water are explained together. It should be noted that water plays an important role in rice cultivation, but its value is ambiguous depended on what it could be used for or cost of accessibility. So, the quantities of gray and blue water consumptions comparing to BAU (line chart), are employed instead of monetary value like other measures. Moreover, the water efficiency in term of rice production (kilogram) per cubic meter of water was showed by the bar chart. The higher bar is the more water consumption efficiency.

Starting with the central area, the *rice-rice option* shows that the higher the area of sustainable rice practice is the better benefits gained from health cost reduction from decreasing of PM2.5 and an increase in soil carbon stock dimension, figure 10.10 and figure 10.11. The other dimensions, which are the benefits from an increase in rice production, reduction of cultivation cost, and reduction of health cost caused by pesticides, see the benefits of expansion of sustainable rice practice. However, gray water consumption is slightly poorer in the fourth scenario comparing to BAU, which means expansion of sustainable rice practice area would induces more water to dilute water pollution from rice cultivation. In term of gray water use efficiency, one cubic meter of gray water is compatible with 1.31 kilogram of rice in the fourth scenario, which is slightly lower than that of the BAU where one cubic meter of water would generate about 1.47 kilogram of rice. On the other hand, expansion of sustainable rice practice in the central area would reduce demand for blue water when compared to conventional rice practice. The blue water from irrigation system is better in the fourth scenario, which generate about 1.44 kilogram of rice per cubic meter of blue water when compared to 1.36 kilogram of rice per cubic meter of blue water for the BAU. The sustainable rice practice is more efficient in term of blue water consumption than that from conventional rice practice. Therefore, the expansion of sustainable rice practice in the central region could obviously generate the benefits from health cost reduction due to PM2.5 and pesticides, soil organic carbon stock, rice production, and blue water. However, the main trade off is gray water, which is used for resolving the chemical input contaminated in water. The higher the expansion of sustainable rice practice in central region would require more water to dissolve the chemical input. Nevertheless, the total benefit of expansion of sustainable rice area under *rice-rice option* in this region still outweighs this cost.

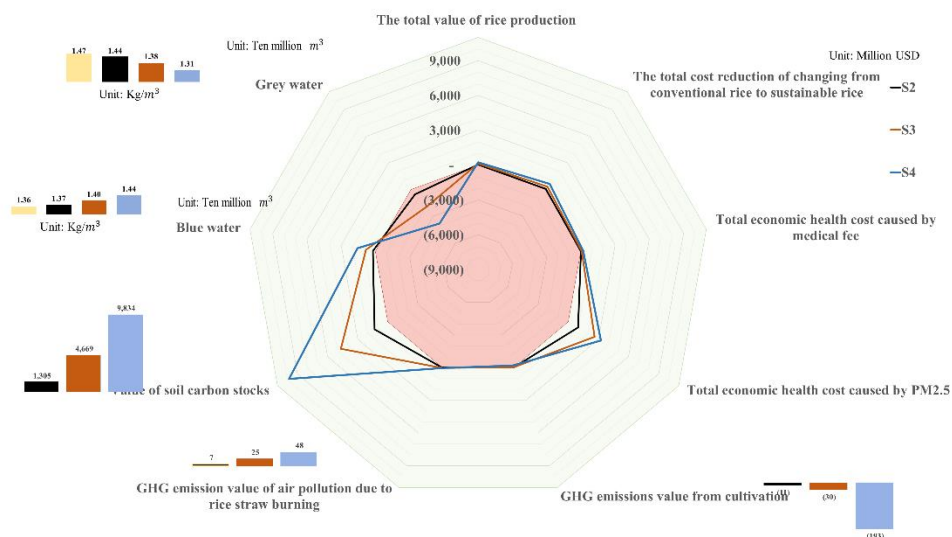


Figure 10.10 The shapes of trade-off chart with rice-rice option in central region in each scenario from 2021 -2050 compared to BAU

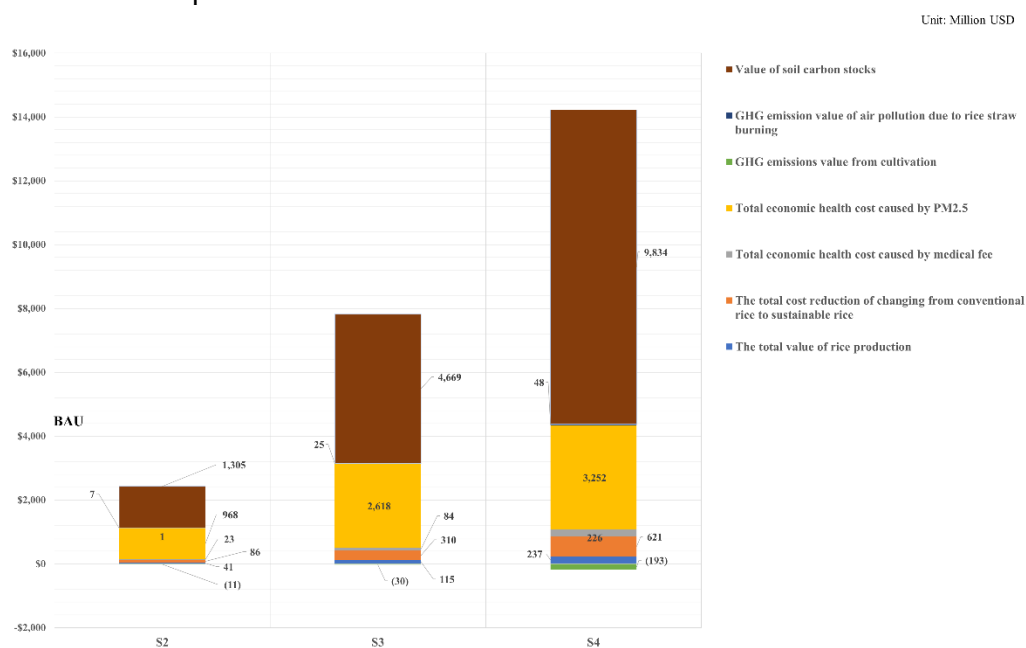


Figure 10.11 The scenario analysis based on values with rice-rice option in more details in central region in each scenario from 2021 -2050 compared to BAU

The central area with *rice-maize* and *rice-sunn hemp* options shows the same trade off pattern, figure 10.12 and figure 10.13. Moreover, most dimensions among these options were quite similar to *rice-rice* option. The blue water in the fourth scenarios is much better for both *rice-maize* option and *rice-sunn hemp* option comparing to BAU due to the significant less consumption of water in dry season. However, the huge loss generated under these options comes from loss of rice production value. Comparing to BAU, the fourth scenario induces loss of \$8,991 million and \$7,715 million in the *rice-maize* option and *rice-sunn hemp* option, respectively, figure 10.14 and figure 10.15. However, as mentioned above, there are other benefits, which are the income from maize for the *rice-maize* option and fertilizer cost saving from *rice-sunn hemp* option, that are not included in this analysis.

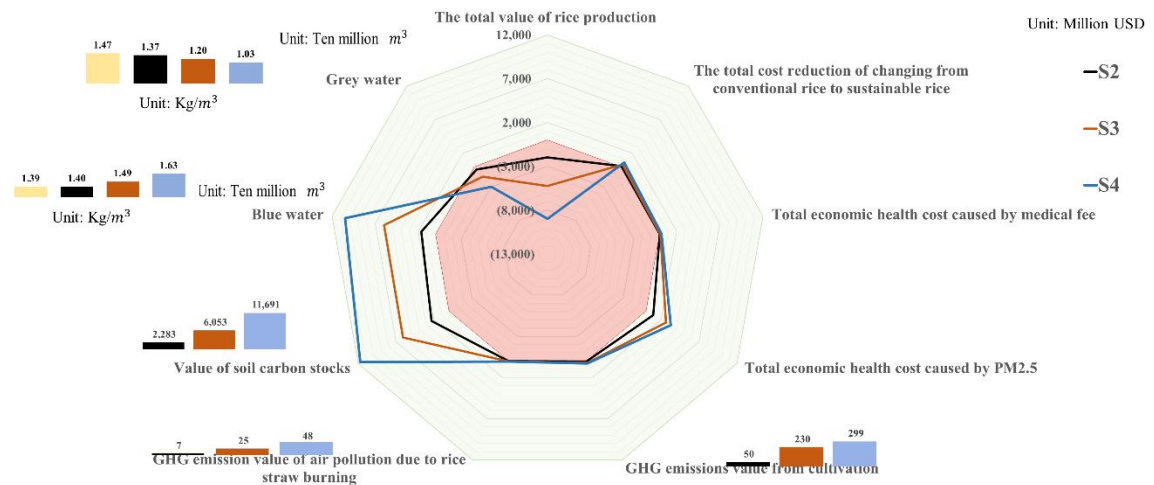


Figure 10.12 The shapes of trade-off chart with rice-maize option in central region in each scenario from 2021 -2050 compared to BAU

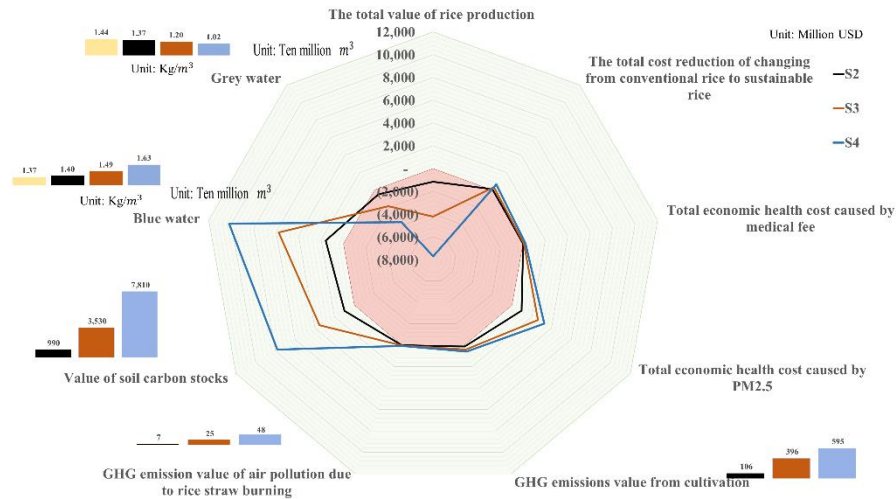


Figure 10.13 The shapes of trade-off chart with rice-sunn hemp option in central region in each scenario from 2021 -2050 compared to BAU

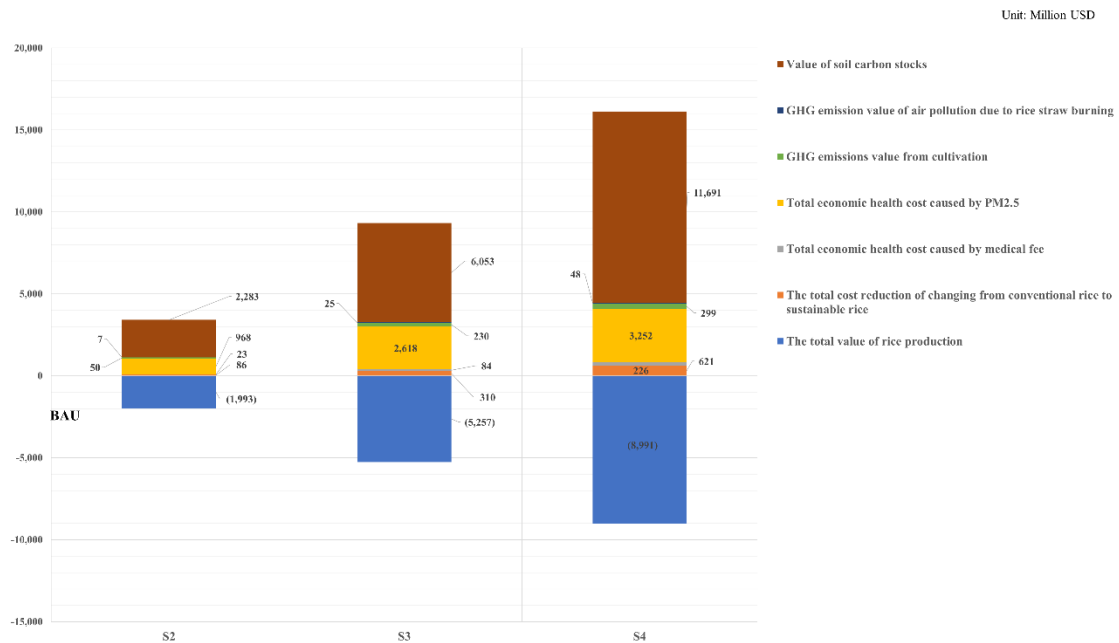


Figure 10.14 The scenario analysis based on values with rice-maize option in more details in central region in each scenario from 2021 -2050 compared to BAU

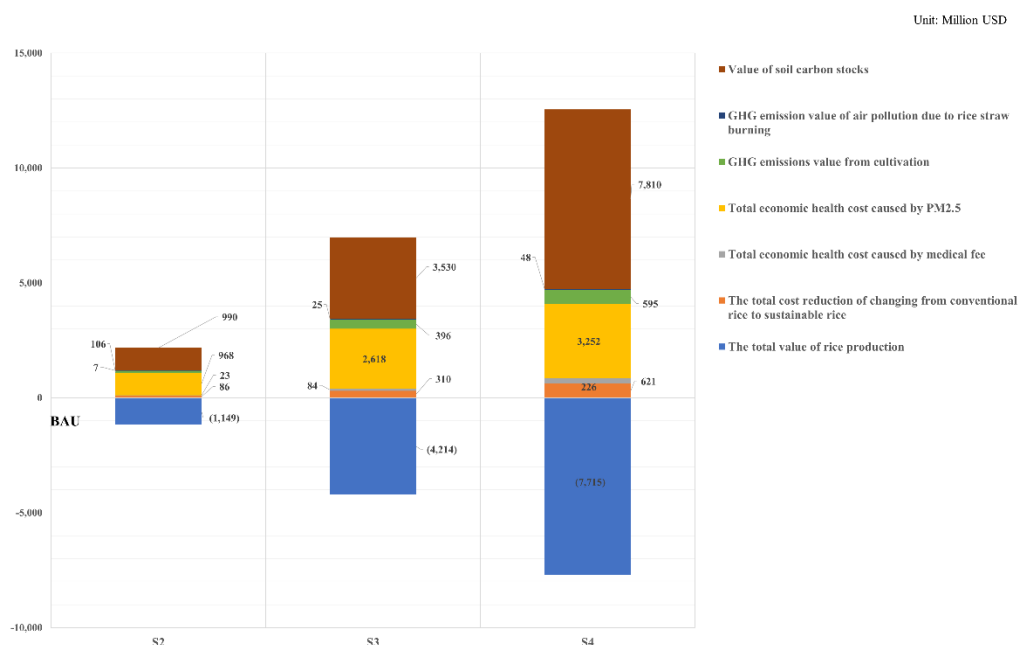


Figure 10.15 The scenario analysis based on values with rice-sunn hemp option in more details in central region in each scenario from 2021 -2050 compared to BAU

For central region, it seems to be clear from our analysis that the *rice-rice option*, assuming two crops of rice per year in irrigation area, provides the highest total net benefit value of an expansion of sustainable rice area when compared to the *rice-maize option* and *rice-sunn hemp option*. The main trade off under the *rice-rice option* is gray water because under this circumstance expansion of sustainable rice area in the central region would require more water to dilute the water pollution from rice cultivation. However, the difference between amounts of water required to dissolve the pollution from sustainable rice practice and conventional rice practice is marginal.

Next, we move to the results of the northeast region. The shapes of trade-off charts from three options in the northeast area are somewhat different from those in the central region. Meanwhile value of PM2.5 health cost and soil carbon stock are the main positive impacts on the central region, the values of rice production and soil carbon stock play an important role in the northeast region, figure 10.16, figure 10.17, and figure 10.18.

The *rice-rice option* showed that intensive sustainable rice promotion in the fourth scenario could provide total net benefit by about \$35,442 million, figure 10.19. The benefit from soil organic carbon is about \$23,387 million, while the loss from GHG emission in cultivation is about

\$7,504 million. Thus, net benefit in the environmental issue is still positive. For the water measure, the fourth scenario would require more blue water than that in BAU (line in radar chart) due to adding the second crop in irrigated area. In addition, when consider the water use efficiency measured by yield per cubic meter of water, scenario 4, presented the highest area of sustainable rice practice, provides the highest efficiency of blue water when compared to that of BAU, 0.765 kilogram per cubic meter versus 0.757 kilogram per cubic meter. However, the total blue water in the fourth scenario is higher than that when compares to BAU as negative value in the line chart. This negative effect come with much higher rice production in this area. For gray water, expansion of sustainable rice area would generate some negative to total water quality comparing to BAU. This is because the amount of gray water required for dissolving the pollution in water caused by rice cultivation in scenario 4 is higher than other scenarios including BAU. However, the efficient water use in the fourth scenario is the highest. One cubic meter of gray water would generate 0.86 kilogram of rice in scenario 4 comparing to 0.76 kilogram of rice for BAU. It could be stated that the higher the sustainable rice area the higher water required to dilute pollution due to the much higher rice production.

The tradeoffs in *rice-maize option* and *rice-sunn hemp option* show very similar pattern with that of *rice-rice option*. The details of both options are presented by figure 10.20 and figure 10.21, respectively. The main difference is the gray water, which *rice-rice option* provides slightly better than that in other options. The value of rice production is still positive and very high for *rice-maize option* and *rice-sunn hemp option* because the yield improvement from adopting sustainable rice practice in this region is on average almost double when compared to conventional counterpart. Therefore, even there are rice production losses in *rice-maize option* and *rice-sunn hemp option* due to no second crop in irrigated area, which covers just 13 percent of agricultural area in the region, this yield improvement can cover such loss resulting in net gain from yield improvement of sustainable rice practice.

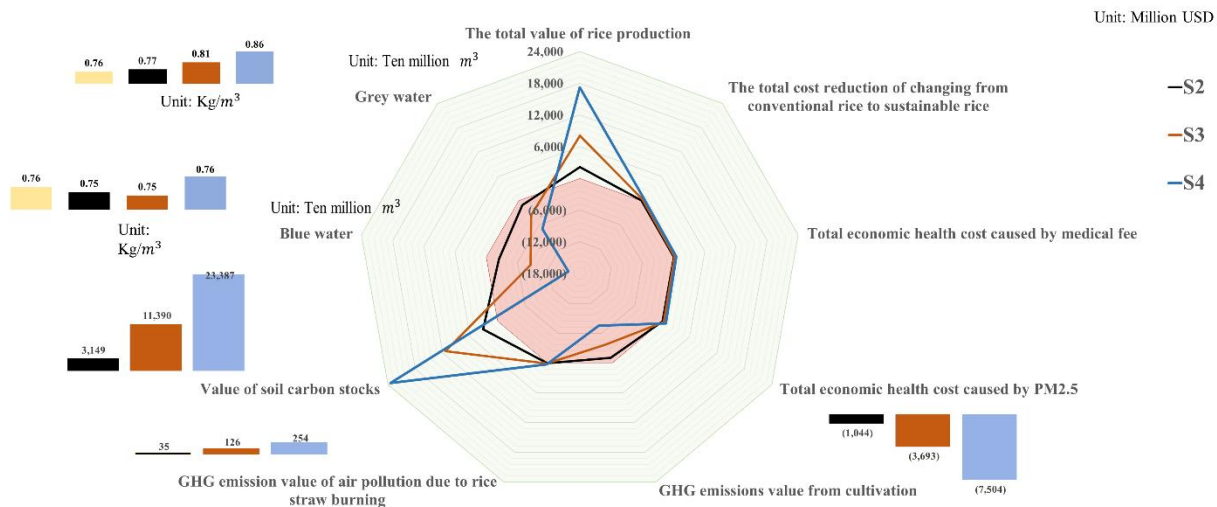


Figure 10.16 The shapes of trade-off chart with rice-rice option in the northeast region in each scenario from 2021 -2050 compared to BAU

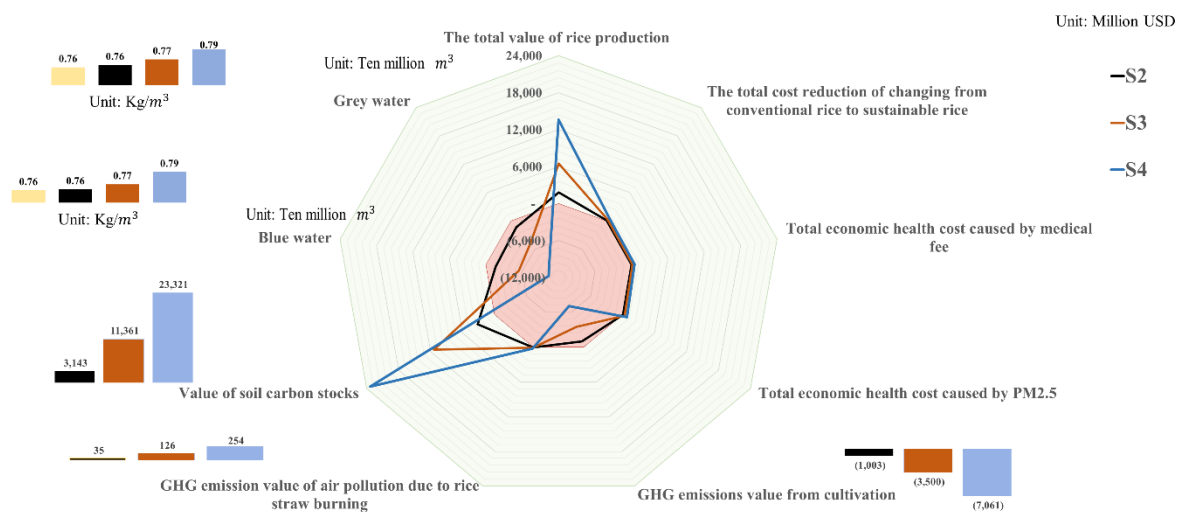


Figure 10.17 The shapes of trade-off chart with rice-maize option in northeast region in each scenario from 2021 -2050 compared to BAU

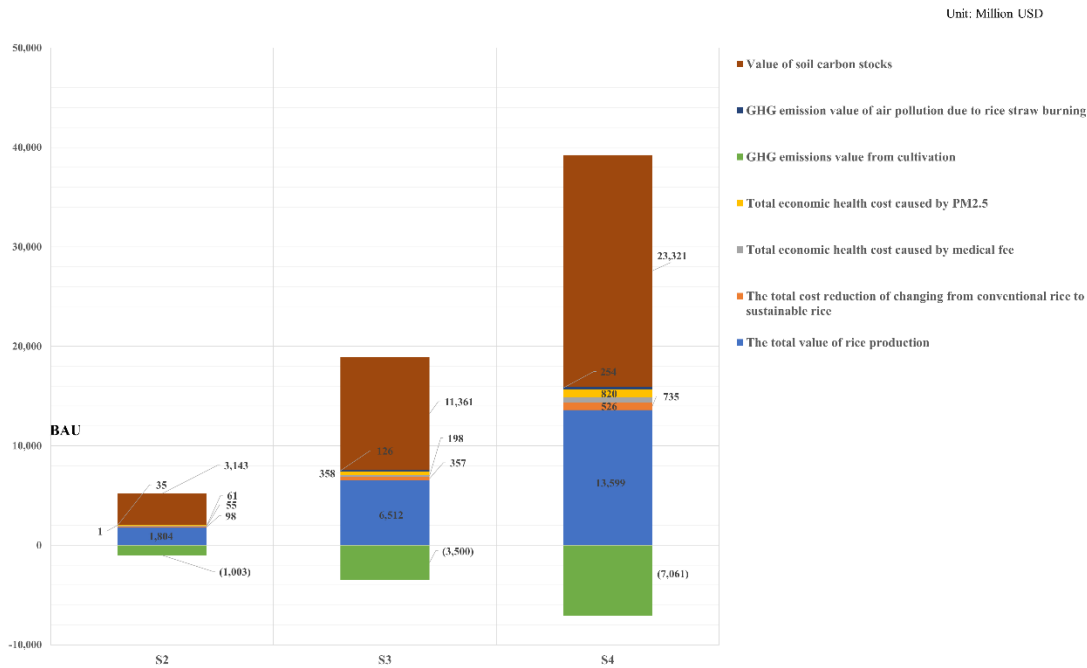


Figure 10.20 The scenario analysis based on values with rice-maize option in more details in northeast region in each scenario from 2021 -2050 compared to BAU

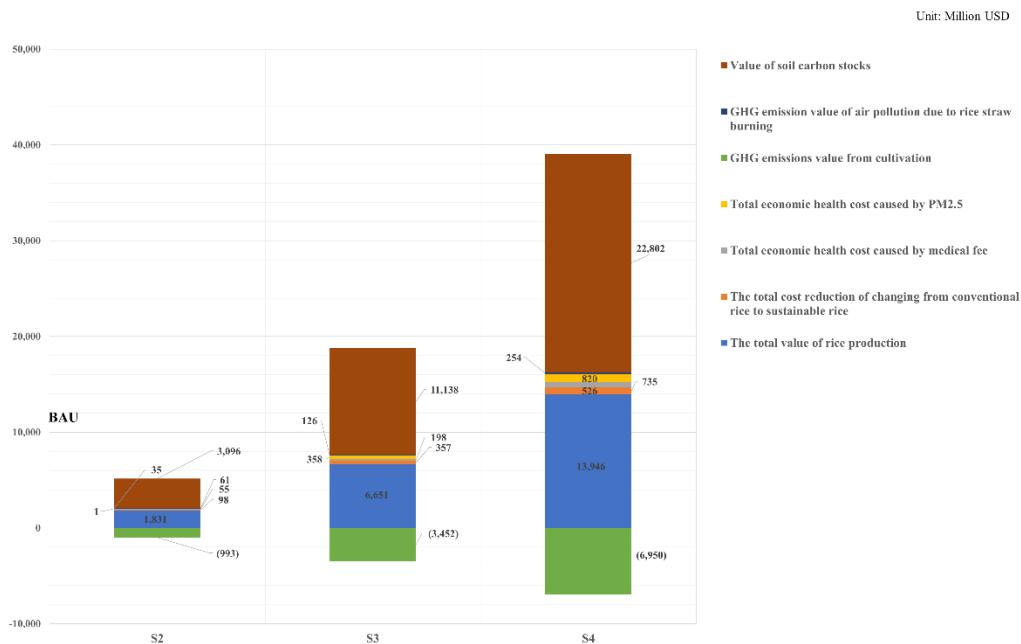


Figure 10.21 The scenario analysis based on values with rice-sunn hemp option in more details in northeast region in each scenario from 2021 -2050 compared to BAU

The distributional accumulated value in the fourth scenario of *rice-rice option*, figure 10.22 showed that about 60 percent of all benefits are on public sector, covering GHG emission and health cost from PM2.5. On the one hand, about 40 percent of all benefits levies on private or

farmers which are mostly from value of rice production. The *rice-maize option* provides the slightly higher distributional accumulated value on public than that on private, in figure 10.23. Meanwhile, in figure 10.24, the distributional accumulated value in *rice-sunn hemp option* quite lower on farmers' benefit, about 23 percent of all benefit. However, in term of value, the farmers could have more private benefit in the *rice-sunn hemp option* comparing to *rice-maize option* with the value of \$ 8.3 and \$6.7 billion respectively. The sustainable rice practice not only mainly generates public benefit as some friendly environmental practice, but also contributes a high distribution on private which is play an important role for technology adoption.

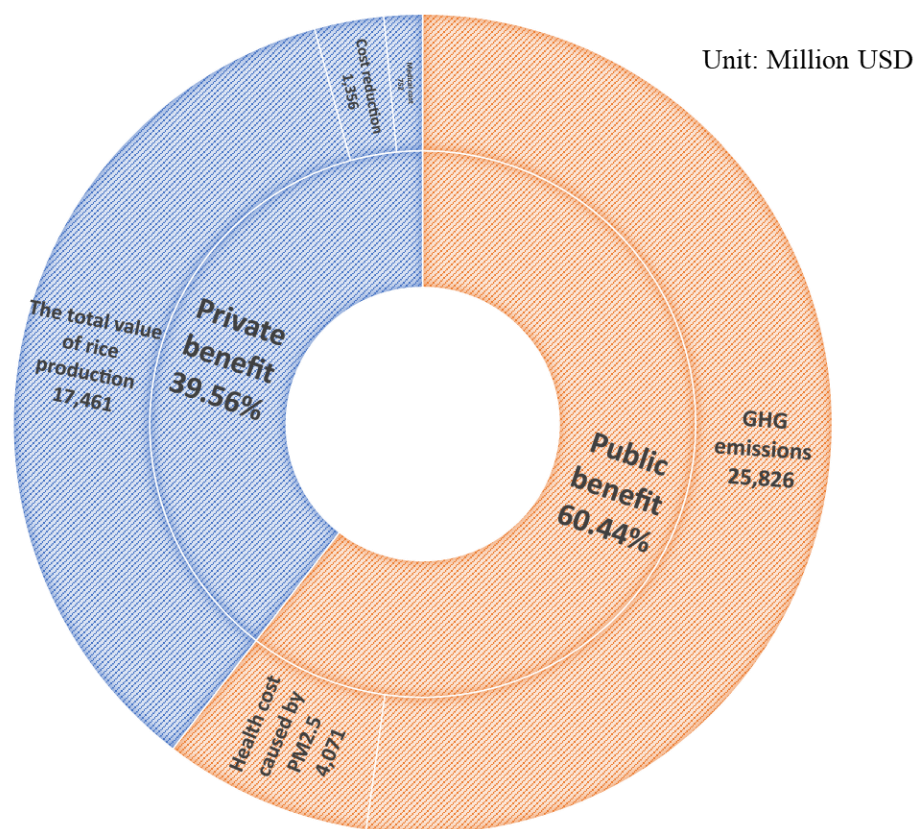
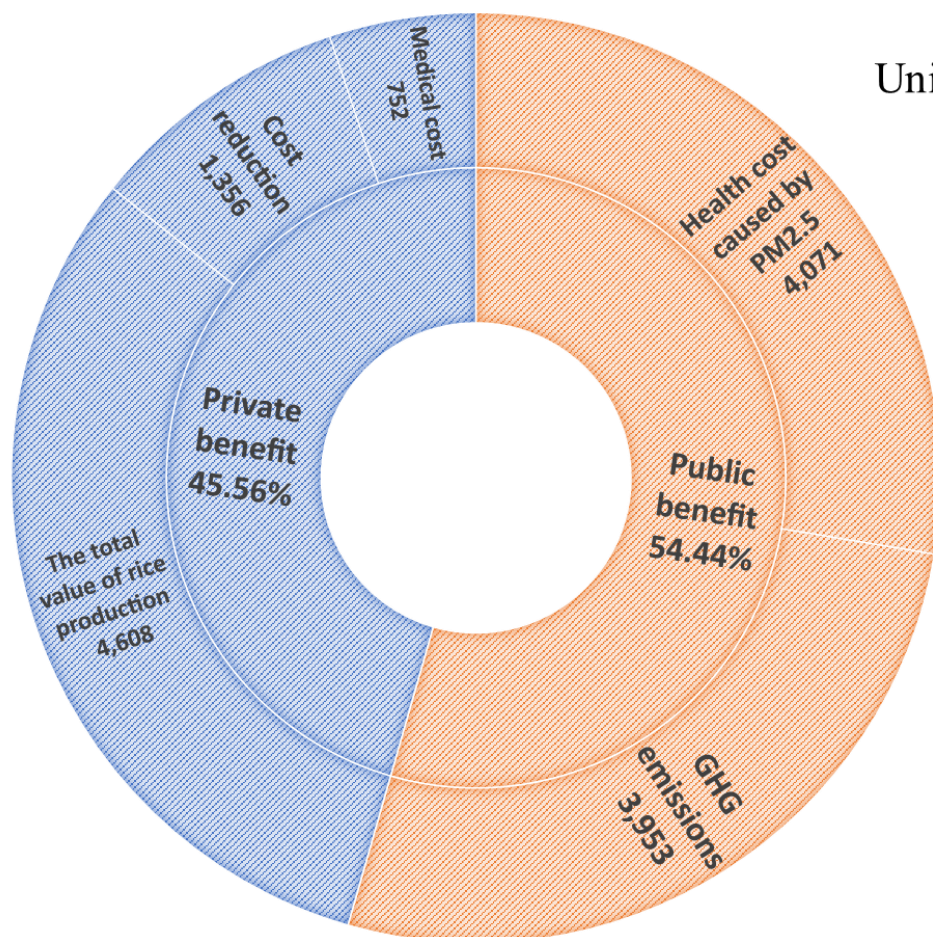


Figure 10.22 The distributional accumulated value in rice-rice option from the fourth scenario, 2021 to 2050



Unit: Million USD

Figure 10.23 The distributional accumulated value in rice-maize option from the fourth scenario, 2021 to 2050

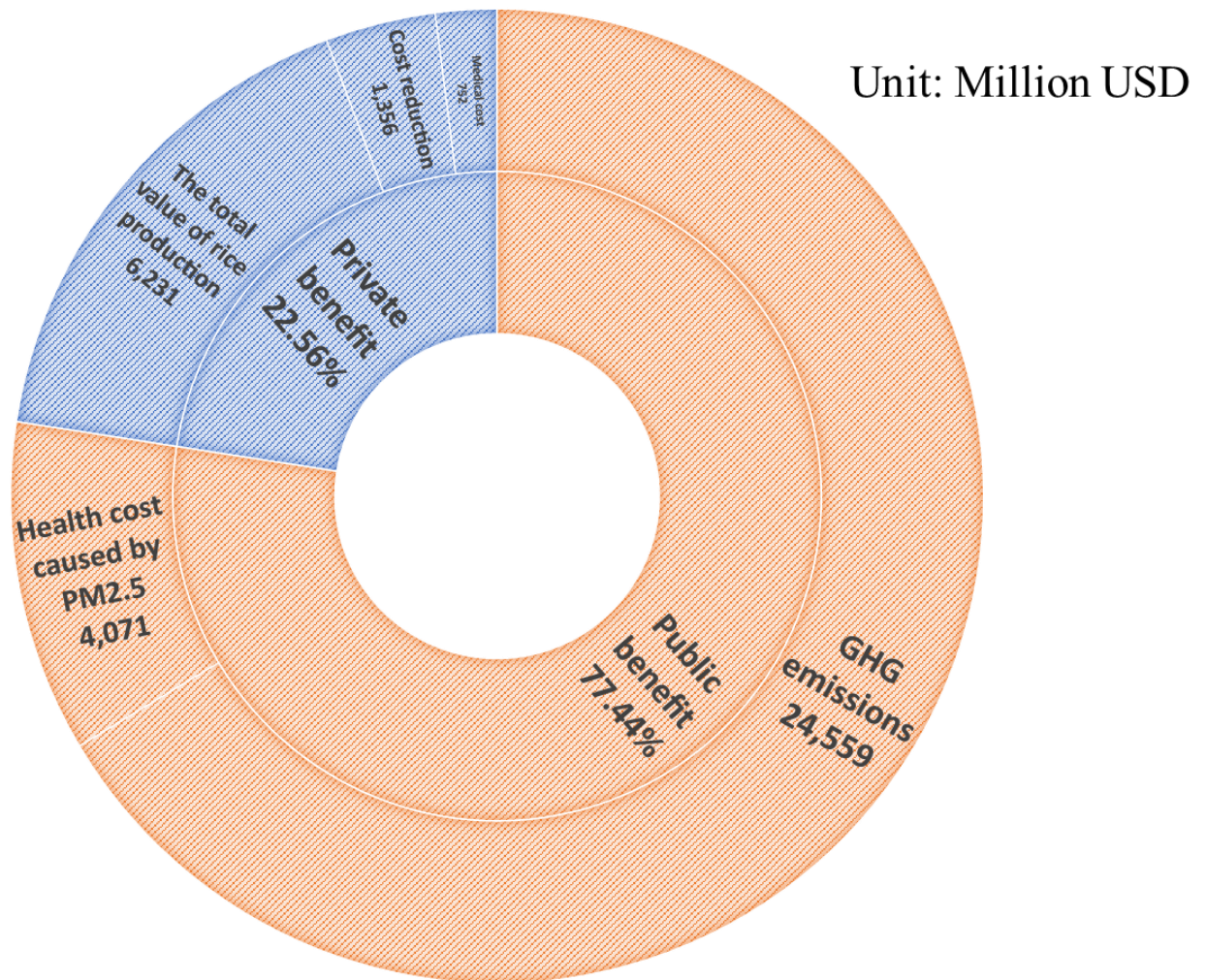


Figure 10.24 The distributional accumulated value in rice-sunn hemp option from the fourth scenario, 2021 to 2050

Finally, the previous accumulated value from 2021 to 2050 has showed that all dimensions from all options in each scenario could generate net positive benefits. However, when consider the medium term, from 2021 to 2035, the trade-off in revenue and cost of production dimension from switching to sustainable rice practice was presented. These data were separately presented by region as in the figure 10.25 and 10.26. The northeast farmers' income had been net positive since switching to sustainable rice practice due to the double high yield and lower cost of production. However, in the central area where dry season rice could be generally produced, the negative values of rice production were presented in all options. Switching to one rice and maize or sunn-hemp rotation provided higher negative net benefit in the rice production due to loss of one crop of rice production in a year. Moreover, in the *rice rice option*, the revenue of rice production was

still negative, but it could all offset with cost reduction. The rice production analysis showed that this negative value was from much lower yield in dry season because of fertilizer reduction matching with crop requirement.

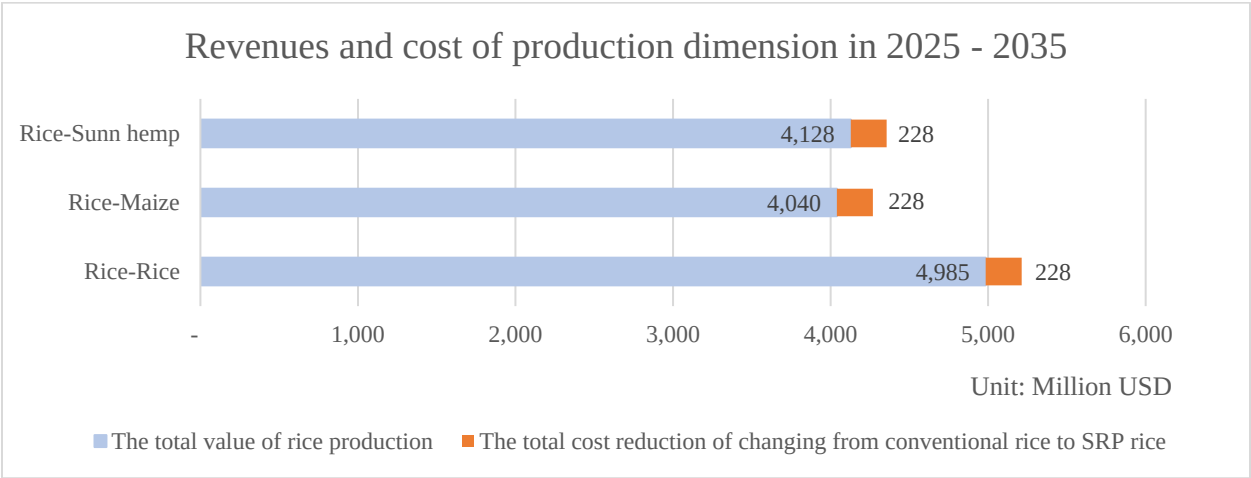


Figure 10.25 The fourth scenario middle term accumulated net benefit of revenue and cost of production dimension in northeast region during 2021 to 2035

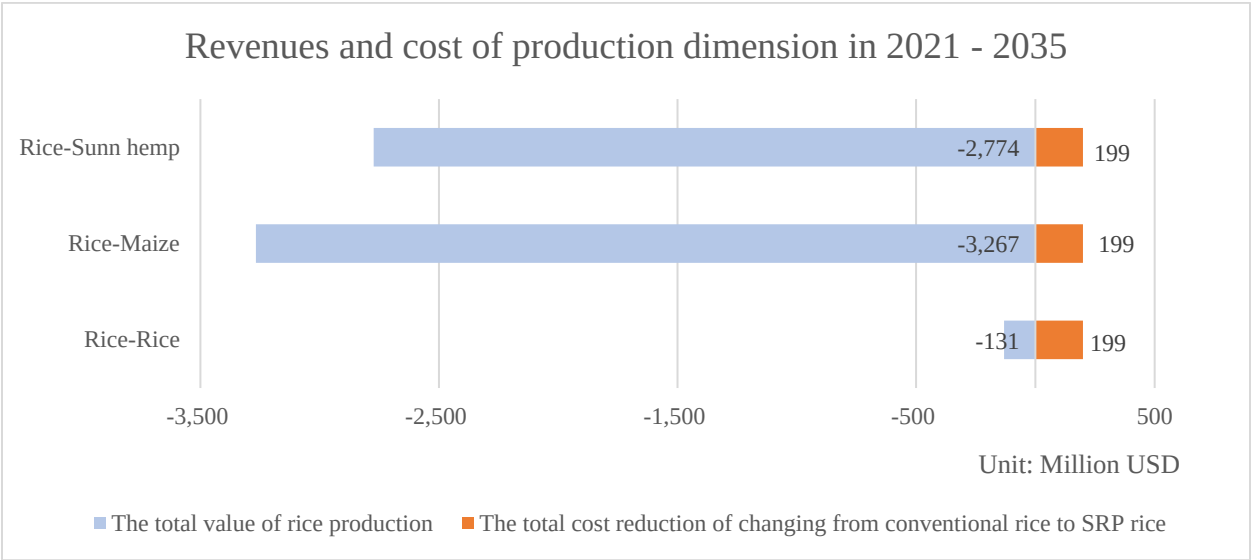


Figure 10.26 The fourth scenario middle term accumulated net benefit of revenue and cost of production dimension in central region during 2021 to 2035

Part 11 Conclusion and Policy Recommendations

This study investigates the direct and indirect effects of switching from conventional to sustainable rice practice in the Central and Northeast regions of Thailand. The rice area of these two regions currently covers more than 80 percent of rice cultivation area in Thailand. The TEEBAgriFood framework is applied to observe the change of natural, human, and social capitals on land pattern change based on four scenarios, which vary by the different proportion of conventional rice area and sustainable rice area. The timeframe for scenario analysis was 28 years, starting in 2022 and ending in 2050.

The measurements of these four capitals captured both direct effects and externalities. The natural capital consists of insect biodiversity, tree on farm, water use, GHG emissions, and soil carbon sequestration. Next, the human capital covers impact of air pollution due to rice field burning on human health and impact of pesticides on farmers' health. Then, rice yield and cost of rice cultivation are also measured to measure change of farmers' income. Finally, the social capital is measured through happiness, trust, gender equality, and social network.

Our scenario analysis is based on four scenarios, which are varied by the different proportion of sustainable rice practice and conventional rice practice. The first scenario, Business as Usual (BAU), predicts that the proportion of sustainable rice area will increase to just about 640,000 hectares by 2050 or cover around 7.58 percent of the total rice area. For scenario 2, the sustainable rice area will increase to 1,961,600 hectares by 2050, accounting for 18.19 percent of the country's total rice production area. For scenario 3 with enhancing sustainable rice promotion, the sustainable rice area will the total sustainable rice practice area would reach 4,672,000 hectares by 2050, accounting for 55.33 percent of the country's total rice production area. The final scenario, Scenario 4, the sustainable rice practice will increase to 6,997,000 hectares in 2045 and remain constant to 2050. This accounts for 82.86 percent of the country's total rice production area.

In each scenario, three options of cultivation are explored. The first option is assuming that for both conventional rice and sustainable rice practices, rice is grown twice a year in the irrigated area, and no rice and other crops are cultivated in non-irrigated areas during dry season, later called this option as *rice-rice option*. The next option is assuming that for sustainable rice practice, rice is grown only during raining season, and in the irrigated area during dry season farmers who apply sustainable rice practice grow maize, while those in non-irrigated areas grow no crops during dry

season. On the other hand, the conventional rice farmers still grow rice twice a year in the irrigated area, while those outside irrigated area do not grow any crops, later called this option as *rice-maize option*. The third option is assuming that rice is grown only during raining season in the irrigated areas for sustainable rice practice and follow by sunn hemp during dry season in both irrigated and non-irrigated areas, while for the area with conventional practice, rice is still grown twice a year in irrigated area and the lands outside irrigated area are left empty during the dry season, later called this option as *rice-sunn hemp option*.

The overall result in case of *rice-rice option* shows the effects of transferring from conventional rice practice to sustainable rice practice along 28 years in the Central and Northeast regions. The higher the areas of conventional areas transferred to sustainable rice practice areas generates the better benefits from various dimensions. This transformation would provide significant improvement in the net benefit resulting from improvement of private benefits to farmers, which include an increase in rice yield, cultivation cost reduction, and health cost reduction from pesticides. In addition, public benefits or positive externalities are visible from our analysis. The gains of public benefits cover the overall GHG reduction mainly from soil carbon sequestrations and GHG reduction from rice residue burning. Furthermore, the public health cost reduction from less air pollution from rice residue burning due to expansion of sustainable rice area is significant. For other two options, *rice-maize option* and *rice-sunn hemp option*, the patterns are similar in which an increase of sustainable rice practice generates net benefits. However, the main difference of these options to *rice-rice option* is the clear visible of tradeoff between reduction of demand for water in rice cultivation and reduction of rice production especially in the Central region where more than 50 percent of rice area of our study site is in the irrigated area. Specifically, the benefit gained from reducing number of crops from two crops a year in irrigated zone to one crop a year is the reduction of water demand for blue water and gray water. However, this comes with a cost of rice production reduction by almost half. This also implies that farmers' income from rice will be decreased by almost half too. Note that the income from maize is not included in the analysis. Therefore, the income loss due to reduction of rice production is upward bias as the substitute income from maize production is not included in analysis.

Due to the different environment and management conditions between the two regions, it is worth to analyze the results within the region. For *rice-rice option*, the Northeast region provided a huge change in value of rice production due to dramatically increase in yield from adopting

sustainable rice practice. On the one hand, the yield improvement in the Central region from adopting sustainable rice practice is marginal. For the other options, even though transforming to sustainable rice practice from both regions generally provides net benefits, the results present that the Northeast region seems to have higher net benefit from transforming to sustainable rice practice than the Central region. However, one dimension that expanding of sustainable rice practice in the Central region seems to provide higher benefit than the Northeast region is GHG reduction during cultivation. This is because more than 50 percent of rice areas of our study site in the Central region is in irrigated area. Therefore, the alternate wet and dry practice could be employed resulting in significant decrease in GHG emission during cultivation. In addition to the reduction of GHG during cultivation, another significant gain from expanding sustainable rice in the Central region is public health cost reduction from PM_{2.5}. This is because the current situation of rice field burning in the Central region is more serious than that in the Northeast region especially in the irrigated area where rice is grown twice a year. In this area, farmers usually burn rice field to prepare their land for the next crop resulting high concentration of rice field burning in relatively short period when compared to the Northeast region. Expansion of sustainable rice area, which does not allow rice field burning, would decrease air pollution especially PM_{2.5} resulting in better public health condition.

The other measurements that are not included to scenario analysis due to no appropriate financial proxy available or could not be quantitatively measured are insect biodiversity, trees on farms, and social capital. The result showed that the insect biodiversity index between these two practices within each region is not statistically significantly different, but the biodiversity index of the Northeast region seems to be better than that of the Central region. The sustainable rice practice is related to more quantity of trees and more diversification of trees on farms than conventional rice practice in both regions. For the social capital, communities and farmers adopting sustainable rice practice seem to have better social capital than conventional counterpart at least in term of trust, gender equality, prosocial behavior, and happiness especially meaning of lives.

In sum, our model predictions and scenario analysis clearly shed light that the expansion of sustainable rice area in both regions would bring higher net benefit to rice farmers and public. The clear visible private benefits to farmers are higher profit from growing rice due to better yield and lower cost of cultivation, and less risk of being sick from pesticide poisoning. Public receives better benefits from expansion of sustainable rice practice in forms of GHG emission reduction,

better health condition due to less air pollution, higher efficiency of water use and water availability.

Policy Discussion and Recommendations

Rice production is the main agricultural activity in Thailand as rice field covers more than 50 percent of country agricultural area. Furthermore, about 20 percent of the nation's households, or 4.30 from 21.58 million households, are rice farmers. The cumulative impacts of production practices at farm level are therefore significant not only at regional level but also at national and international levels.

Under business as usual (BAU) where there is no intervention to promote transformation from conventional rice practice to sustainable rice practice, over the period to 2050, the models developed in this study predict that the rice production under conventional rice practice would maintain at the current level. However, the current conventional rice practice would induce more GHG emission, inefficiency of water use, and impose significant risk to human health. By comparing the values of these losses to ecosystem services and human health with the equivalent values from the scenarios that promote sustainable rice production, a strong economic case can be made to support this shift to sustainable farming systems.

1. The sustainable rice practice generates positive externalities through public health improvement and environmental improvement. In addition, the sustainable rice practice would be able to deliver private economic benefit to farmers through rice yield improvement and cultivation cost reduction resulting in increasing of profit from growing rice. However, an increase in profit could not be realized in the early period of conversion. On the other hand, the costs of conversion such as soil fertility evaluation, land leveling, and nutrient management are immediate costs faced by farmers. Therefore, convincing farmers to adopt sustainable rice practice without any supports especially during transition period may not be enough to significantly increase adoption rate. Government should step in to ensure farmers that any costs and risks posed on farmers would be managed and mitigated until the private benefits from adopting sustainable rice practice could be realized by farmers.
2. One of the main tools in agriculture to support farmers is subsidy. The main subsidy policies in agriculture currently focus on mitigating financial hardship of farmers. However, it does not encourage farmers to adopt sustainable agricultural practice like

sustainable rice practice. We purpose that subsidy should be reoriented with condition on adopting sustainable agricultural practice such as sustainable rice practice.

3. Conversion to sustainable rice practice requires some management and access to necessary inputs such as soil nutrient evaluation, land leveling equipment, and fertilizers suitable for soil nutrient. Many farmers may not be able to efficiently access to these techniques and inputs. Even though, they would like to try the sustainable rice practice, without supports for these it is unlikely that the adoption of sustainable rice practice would be success. We purpose that the government should set up efficient systems that provide these kinds of supports to farmers.
4. The sustainable rice practice could provide highly potential net benefit from dimension of environmental and human health externality. However, most of these impacts are the public benefits that farmers have generated but could not receive the direct financial benefit, which is the high potential motivation to adopt friendly environmental practices.

In the fourth scenario, the benefit of health impact from reducing PM_{2.5} is tremendously high because of stubble burning prohibition in the sustainable rice practice. Rice fields in irrigated area with at least two crops of rice a year are the main area of rice field burning because farmers want to speed up the process of preparing the rice field for the next crop. Waiting for rice straw and stubble to naturally decompose is not the option for farmers. We purpose that the supports of technologies and innovations to handle with stubble decomposing would help farmers to reduce time and provide more practical ways to adopt no stubble burning.

5. The sustainable rice practice could reduce high GHG emission from soil carbon sequestration. Moreover, in the irrigation area, the alternate wet and dry technique (AWD) could be employed. From our results, this technique significantly reduces GHG emission, mainly from methane, from rice cultivation. However, these public benefits are invisible to farmers. The promotion of economic or market mechanism that could transfer this invisible benefit to financial benefit for farmers could play an important role. The voluntary carbon market could be one of the solutions, but for rice production, it is currently low possible to achieve financial feasibility for capture carbon credit due to the high cost of validation process. Thus, the low transaction cost and internationally acceptable method to capture carbon credit are highly necessary.

6. Widely transforming from conventional rice practice to sustainable rice practice would require significantly supports from the government especially during the early period of conversion. If the budget is limited, our study suggests that starting transformation from conventional rice practice to sustainable rice practice in the Northeast region would be more cost effectiveness than in the Central region as the net benefit gained from both private benefit and public benefit of transformation are clearly visible. In addition, according to Mungkung et al. (2022) the current rice cultivation practice in the Northeast region is significant closer to the sustainable rice practice than that in the Central region suggesting that the transformation in the Northeast region would be practically more possible and would require lower cost than that in the Central region.

TEEB AGRIFOOD THAILAND IMPACT

The transformation from conventional rice practice to sustainable rice practice would improve society's net benefit through rice productivity improvement, production and health cost reduction, GHGs reduction, and water consumption efficiency.

DELIVERY MECHANISMS

- Motivate policymakers to intensively systematic support toward sustainable rice practice.
- Promote extension programs to support farmers' knowledge on soil property evaluation relating with suitable and efficient input use.
- Provide efficient method reduces cost of carbon validation.

INPUTS

- Government supports on soil property self-analysis and other technics relating to productivity improvement, nationally. Building the business ecosystem of suitable and efficient input accessibility for rice productivity reinforcement.
- The government support to promote market linkage and public recognition of sustainable rice product in term of positive externality.
- Improve low transaction cost of carbon market for rice system.

PROBLEM

In Thailand, the conventional rice practice has resulted in GHG emission, health issue, biodiversity loss, rice productivity, and then heightened vulnerability of farmers' livelihoods due to the unsuitable use of chemical inputs. The mainly promoted rice practices intensively focus on economic or environmental aspect separately.

Root Causes: Conventional rice farming practices, which heavily rely on chemicals, have significant environmental and health consequences. In contrast, environmentally friendly rice cultivation practices may initially lead to lower rice productivity.

The impacts of climate change, low productivity, and market issues cause farmers' livelihood in **uncertain** situation.

The rice sector was mainly focusing on farmers' financial difficulties, but the rice practice considering environmental, economic, and social issue all together was slightly promoted.

OUTPUTS

- Improvement of farmers' knowledge and skills on making a decision to increase rice productivity based on sustainable rice practice.
- Both national and international consumers recognize the positive value for sustainable rice which easier and more accessible market channels both for farmer and public.
- Carbon credit from rice production is recognized, practicable and cost effective to support farmers' income.

OUTCOMES

- About 80% of conventional rice areas in the central and northeast of Thailand would be transformed into sustainable rice areas by 2050.
- Benefit from health cost reduction would increase by at least \$4 billion by 2050.
- Benefit of GHGs reduction would increase by at least \$3.6 million by 2050.
- The blue water efficiency for rice production would improve by about 0.76 and 1.44 kg. per cubic meter on average in the northeast and central region by 2050 respectively.
- The income of sustainable rice farmers would increase by about \$13 billion in 2050.

Risk to be mitigated: Policy uncertainty due to political changes, climate change impacts, weak linkage among government agencies, instability of global demand and supply of sustainable rice. Costly international or national certification for sustainable rice and

ASSUMES: All stakeholders agree with the proposal, and market preference for sustainable rice practice is certain.

References

- Ambarwulan, W., & Munibah, K. (2013). Landuse change during a decade as determined by landsat imagery of a rice production region and its implication to regional contribution to rice self sufficiency: case study of Karawang Regency, West Java, Indonesia.
- Arai, Hironori, et al. "Greenhouse gas emissions from rice straw burning and straw-mushroom cultivation in a triple rice cropping system in the Mekong Delta." *Soil science and plant nutrition* 61.4 (2015): 719-735.
- Arunrat, N.; Pumijumnong, N.; Sereenonchai, S.; Chareonwong, U.; Wang, C. 2021. Comparison of GHG emissions and farmers' profit of large-scale and individual farming in rice production across four regions of Thailand. *Journal of Cleaner Production*, <https://doi.org/10.1016/j.jclepro.2020.123945>.
- Atreya, K., Johnsen, F. H., & Sitaula, B. K. (2012). Health and environmental costs of pesticide use in vegetable farming in Nepal. *Environment, Development and Sustainability*, 14(4), 477-493.
- Ba, H. A., de Mey, Y., Thoron, S., & Demont, M. (2019). Inclusiveness of contract farming along the vertical coordination continuum: Evidence from the Vietnamese rice sector. *Land Use Policy*, 87, 104050.
- Babu, Y.J.; Li, C.; Frolking, S.; Nayak, D.R.; Adhya, T.K. 2006. Field Validation of DNDC Model for Methane and Nitrous Oxide Emissions from Rice-based Production Systems of India. *Nutr. Cycl. Agroecosyst.* 74, 157–174.
- Beisiegel, L. (2014). Consumer preferences regarding quality rice in Thailand (Doctoral dissertation, Master Thesis at the Faculty of Agriculture, University of Bonn, in cooperation with Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Bangkok. Thailand).
- Boithias, L.; Acuña, V.; Vergoñós, L.; Ziv, G.; Marcé, R.; Sabater, S. Assessment of the water supply: Demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. *Sci. Total Environ.* 2014.
- Bourguet, D., & Guillemaud, T. (2016). The hidden and external costs of pesticide use. *Sustainable Agriculture Reviews: Volume 19*, 35-120.

- Chapagain, A.K. and Hoekstra A.Y. 2010. The green, blue and grey water footprint of rice from both a production and consumption perspective. Value of Water Research Report Series No. 40. UNESCO-IHE Institute for Water Education, Delft, the Netherlands.
- Chapagain, A.K. and Hoekstra A.Y. 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. *Ecological Economics* 70: 749-758. <https://doi.org/10.1016/j.ecolecon.2010.11.012>.
- Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., Gautam, R., 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics* 60 (1), 186–203. <https://doi.org/10.1016/j.ecolecon.2005.11.027>.
- Cha-un, N.; Chidthaisong, A.; Towprayoon, S. 2015. Short-term and Long-term Soil Carbon Sequestration in Rice Field with Energy Crop Rotation. *J. Sustain. Energy Environ.* 6, 97–104.
- Cha-un, N.; Chidthaisong, A.; Towprayoon, S. 2017. Using the DNDC model to predict methane emissions from crop-rice rotation systems. *Res. J. Chem. Environ.* 21, 36–46
- Cha-un, N.; Chidthaisong, A.; Yagi, K.; Sudo, S.; Towprayoon, S. 2017. Greenhouse gas emissions, soil carbon sequestration and crop yields in a rain-fed rice field with crop rotation management. *Agric. Ecosyst. Environ.* 237, 109–120.
- Cha-un, N.; Chidthaisong, A.; Yagi, K.; Towprayoon, S. 2021. Simulating the Long-Term Effects of Fertilizer and Water Management on Grain Yield and Methane Emissions of Paddy Rice in Thailand. *Agriculture*, 11, 1144. <https://doi.org/10.3390/agriculture11111144>
- Chen, H.; Yu, C.; Li, C.; Xin, Q.; Huang, X.; Zhang, J.; Yue, Y.; Huang, G.; Li, X.; Wang, W. 2016. Modeling the impacts of water and fertilizer management on the ecosystem service of rice rotated cropping systems in China. *Agric. Ecosyst. Environ.* 219, 49–57.
- De Groot, R.S.; Wilson, M.A.; Boumans, R.M.J. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol. Econ.* 2002, 41, 393–408.
- Dwinanto, A. A. P., Munibah, K., & Sudadi, U. (2016). Model Perubahan dan Arahan Penggunaan Lahan untuk Mendukung Ketersediaan Beras di Kabupaten Brebes dan Kabupaten Cilacap. *Tataloka*, 18(3), 157-171.
- Emission of air pollutants from rice residue open burning in Thailand, 2018. *Atmosphere*, 9(11), 449.

- EPA. (2000). Handbook for non-cancer health effects valuation. Washington DC: EPA Science Policy Council, US Environmental Protection Agency.
- Food and Agriculture Organization of the United Nations (FAO). FAOSTAT Database. 2020. Available online: <https://www.fao.org/faostat/en/#data/QCL> (accessed on 26 December 2021)
- Freeman III, A. M., Herriges, J. A., & Kling, C. L. (2014). The measurement of environmental and resource values: theory and methods. Routledge.
- Freeman, A. M. (1993). The measurement of environmental and resource values. Theory and methods (No. 333.7 F855). Resources for the Future.
- Garivait, Savitri, Sébastien Bonnet, and Orachorn Kamnoed. "Air Pollutant Emissions from Paddy Residues Open Burning and their Potential for Bioenergy in the Greater Mekong Sub-Region (Cambodia, Lao PDR, Thailand and Vietnam)." GREATER MEKONG SUBREGION ACADEMIC AND RESEARCH NETWORK (2008): 169.
- Garming, H., & Waibel, H. (2009). Pesticides and farmer health in Nicaragua: a willingness-to-pay approach to evaluation. The European Journal of Health Economics, 10, 125-133.
- Gilhespy, S.L.; Anthony, S.; Cardenas, L.; Chadwick, D.; del Prado, A.; Li, C.; Misselbrook, T.; Rees, R.M.; Salas, W.; SanzCobena, A.; et al. 2014. First 20 years of DNDC (DeNitrification DeComposition): Model evolution. col. Model. 292, 51–62.
- Hoang, V. (2021). Impact of Contract Farming on Farmers' Income in the Food Value Chain: A Theoretical Analysis and Empirical Study in Vietnam. Agriculture, 11(8), 797.
- Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M. 2011. The water footprint assessment manual: setting the global standard [online]. Earth Scan, Washington, DC. Available at: [efaidnbmnnnibpcajpcgclclefindmkaj/https://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf](https://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf). Accessed date: August 14, 2022.
- Institute for the Study of Earth, Oceans, and Space, University of New Hampshire. 2017. The DNDC Model. Available online: <https://www.dndc.sr.unh.edu/> (accessed on 26 December 2021).
- Junpen, A., Pansuk, J., Kamnoet, O., Cheewaphongphan, P., & Garivait, S. (2018). Emission of air pollutants from rice residue open burning in Thailand, 2018. Atmosphere, 9(11), 449.

- Kristofersson, D. and Navrud, S. (2005). Validity Tests of Benefit Transfer: Are We Performing the Wrong Tests?, *Environmental and Resource Economics* 30, 279–286.
- Lampayan, M. Rubenito, Rejesus, M. Roderick, Singleton, R. Grant and Bouman, A.M Bas. 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research* (170): 95-108. <https://doi.org/10.1016/j.fcr.2014.10.013>.
- Lee, W. J., Cha, E. S., Park, J., Ko, Y., Kim, H. J., & Kim, J. (2012). Incidence of acute occupational pesticide poisoning among male farmers in South Korea. *American journal of industrial medicine*, 55(9), 799-807.
- Li, C.; Frolking, S.; Harriss, R. 1994. Modeling carbon biogeochemistry in agricultural soils. *Glob. Biogeochem. Cycles*. 8, 237–254.
- Maertens, M., & Velde, K. V. (2017). Contract-farming in staple food chains: The case of rice in Benin. *World Development*, 95, 73-87.
- Maes, J.; Liqueste, C.; Teller, A.; Erhard, M.; Luisa, M.; Barredo, J.I.; Grizzetti, B.; Cardoso, A.; Somma, F.; Petersenc, J.E.; et al. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosyst. Serv.* 2016, 17, 14–23.
- Mastrorilli, M., Rana, G., Verdiani, G., Tedeschi, G., Fumai, A., and Russo, G. 2018. Economic evaluation of hydrological ecosystem services in Mediterranean River Basins applied to a case study in Southern Italy. *Water*, 10, 241. <https://doi.org/10.3390/w10030241>
- Mastrorilli, M.; Gianfranco, R.; Guisepppe, V.; Guisepppe, T.; Fumai, A.; Giovanni, R. Economic Evaluation of Hydrological Ecosystem Services in Mediterranean River Basins Applied to a Case Study in Southern Italy. *Water*. 2018, 10, 241, 1-16.
- MEA (Millennium Ecosystem Assessment) project. *Ecosystems and Their Services. In Ecosystems and Human Well-Being: A Framework for Assessment*; Island Press: Washington, DC, USA, 2005.
- Meijer, K.S., Krogt, W.N.M., and Beek, E. 2012. A new approach to incorporating environmental flow requirements in water allocation modeling. *Water Resource Management*, 26: 1271–1286. <https://doi.org/10.1007/s11269-011-9958-z>.
- Mishra, A. K., Kumar, A., Joshi, P. K., D'Souza, A., & Tripathi, G. (2018). How can organic rice be a boon to smallholders? Evidence from contract farming in India. *Food Policy*, 75, 147-157.

- Mungkung, R., Gheewala, S., Silalertruksa, T. and Dangsi S. 2019. Water footprint inventory database of Thai rice farming for water policy decisions and water scarcity footprint label. *The International Journal of Life Cycle Assessment* 24: 2128-2139. <https://doi.org/10.1007/s11367-019-01648-0>.
- My, N. H., Demont, M., Van Loo, E. J., de Guia, A., Rutsaert, P., Tuan, T. H., & Verbeke, W. (2018). What is the value of sustainably-produced rice? Consumer evidence from experimental auctions in Vietnam. *Food Policy*, 79, 283-296.
- My, N. H., Van Loo, E. J., Rutsaert, P., Tuan, T. H., & Verbeke, W. (2018). Consumer valuation of quality rice attributes in a developing economy: Evidence from a choice experiment in Vietnam. *British Food Journal*.
- Naher, U.A.; Hossain, M.B.; Haque, M.M.; Maniruzzaman, M.; Choudhury, A.K.; Biswas, J.C. 2020. Effect of Long-Term Nutrient Management on Soil Organic Carbon Sequestration in Rice . . . Rice Fallow Rotation. *Curr. Sci.* 118, 587–592.
- Nunez, D.; Nahuelhual, L.; Oyarzun, C. Forests and water: the value of native temperate forests in supplying water for human consumption. *Ecol. Econ.* 2006, 58, 606–616.
- Okpiaifo, G., Durand-Morat, A., West, G. H., Nalley, L. L., Nayga Jr, R. M., & Wailes, E. J. (2020). Consumers' preferences for sustainable rice practices in Nigeria. *Global Food Security*, 24, 100345.
- ONEP. Second Biennial Update Report of Thailand; Office of Natural Resources and Environmental Policy and Planning (ONEP): Bangkok, Thailand, 2017; 108p.
- Patrawart, J., Sriurai, S., & Sangaroon, T. (2018). Promoting rice value addition through inclusive business model.
- Pimentel D. (2009) Environmental and economic costs of the application of pesticides primarily in the United States. In: Peshin R, Dhawan AK (eds) *Integrated pest management: innovation development process*. Springer, Dordrecht, 89–111
- Pimentel D., Burgess M (2014) Environmental and economic costs of the application of pesticides primarily in the United States. In: Pimentel D, Peshin R (eds) *Integrated pest management*. Springer, Dordrecht, 47–71
- Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, development and sustainability*, 7, 229-252.

- Quaye, W., Johnson-Kanda, I., Gayin, J., & Manful, J. T. (2010). Building the capacity of farmer based organisation for sustainable rice farming in Northern Ghana. *Journal of agricultural science*, 2(1), 93-106.
- Ren, Y., Peng, Y., Campos, B. C., & Li, H. (2021). The effect of contract farming on the environmentally sustainable production of rice in China. *Sustainable Production and Consumption*, 28, 1381-1395.
- Ruensuk, N., Rossopa, B., Channu, C. Paothong, K., Prayoosuk, N., Rakchum, P. and Malumpong, C. 2021. Improving water use efficiency and productivity in rice crops by applying alternate wetting and drying with pregerminated broadcasting in farmers' fields. *Agr. Nat. Resour.* 55 (2021) 119–130.
- Sangchom Siripanich (2013). The situation and health problems arising from the use of pesticide. *Weekly Epidemiological Surveillance Report*. 44: 689-92.
- Satyendra, Tripathi, R. N. Singh, and Sharma Shaishav. "Emissions from crop/biomass residue burning risk to atmospheric quality." *Int Res J Earth Sci* 1.1 (2013): 1-5.
- Shirato, Y. 2005. Testing the Suitability of the DNDC Model for Simulating Long-Term Soil Organic Carbon Dynamics in Japanese Paddy Soils. *Soil Sci. Plant Nutr.* 51, 183–192.
- Siriuma J., Wiwada K., Udomratana V., Phiman T., Supabhorn Y., Junjira M., and Ponadda P. 2017. Comparison of knowledge, attitudes, and behaviors of rice farmers and the amount of pesticide residue in the environment in Nakhon Si Thammarat Province. *Journal of Safety and Health* 10(37): 10-20.
- Sriphirom, P.; Chidthaisong, A.; Yagi, K.; Tripetchkul, S.; Towprayoon, S. Evaluation of biochar applications combined with alternate wetting and drying (AWD) water management in rice field as a methane mitigation option for farmers' adoption. *Soil Sci. Plant Nutr.* 2019, 66, 235–246.
- SRP. (2020). Sustainable Rice Platform Standard for Sustainable Rice Cultivation. Retrieved 16 Aug 2022, from <https://www.sustainablerice.org/wp-content/uploads/2021/10/103-SRP-Standard-Version-2.1.pdf>
- Tago, D., Andersson, H., & Treich, N. (2014). Pesticides and health: a review of evidence on health effects, valuation of risks, and benefit-cost analysis. *Preference measurement in health*.

- Towprayoon, S.; Smakgahn, K.; Poonkaew, S. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. *Chemosphere* 2005, 59, 1547–1556.
- Travisi, C. M., Nijkamp, P., & Vindigni, G. (2006). Pesticide risk valuation in empirical economics: a comparative approach. *Ecological Economics*, 56(4), 455-474.
- Varinruk, B. Thai Rice Production and Rice Research and Development on Climate Change. In *Proceedings of the Workshop on Strengthening APEC Cooperation on Food Security and Climate Change*, Asia-Pacific Economic Cooperation (APEC), Hanoi, Viet Nam, 19–21 April 2017.
- Venkatachalam, L. (2004). The contingent valuation method: A review. *Environmental Impact Assessment Review*, 24(1), 89–124.
- Wang, W., Jin, J., He, R., Gong, H., & Tian, Y. (2018). Farmers' willingness to pay for health risk reductions of pesticide use in China: A contingent valuation study. *International journal of environmental research and public health*, 15(4), 625.
- Wu, M., Li, Y., Xiao, J., Guo, X. and Cao, X. 2022. Blue, green, and grey water footprints assessment for paddy irrigation-drainage system. *Journal of Environmental Management* 302: 114116. <https://doi.org/10.1016/j.jenvman.2021.114116>.
- Yang, Y., Luo, L., Song, C., Yin, H., & Yang, J. (2018). Spatiotemporal Assessment of PM2.5-Related Economic Losses from Health Impacts during 2014–2016 in China. *International Journal of Environmental Research and Public Health*, 15(6), 1278. <https://doi.org/10.3390/ijerph15061278>
- Yin, H., Xu, L., & Cai, Y. (2015). Monetary valuation of PM10-related health risks in Beijing China: the necessity for PM10 pollution indemnity. *International journal of environmental research and public health*, 12(8), 9967-9987.

Appendix 1 Requirements of SRP Standard, Biodiversity, and GHG emissions

SRP Performance Indicators	Requirement No	SRP compliance minimum	Principle components	How this will be included in the study
Biodiversity	6 Land conversion and biodiversity	There has been no conversion of described areas after 2009.	Rice farming after 2009 has not been causing conversion within a (proposed) protected area, Key Biodiversity Areas™, Ramsar Sites (wetland), primary forest, secondary forest (native), or other natural ecosystems and land types such as prairie.	Not assessed. It is assumed that the area of rice production will not expand or contract. It is assumed that no land conversion from wild spaces to rice production has taken place in the relevant regions since 2009
			At the field level, farmer maintains and/ or enhances applicable site-specific biodiversity elements: • In-field habitat / refuge • Field margins • Non-cropped area • Plant species which host beneficial natural enemies • Trees (replanted if harvested)	Assessed
			Farming practices maintain and/or enhance ecosystem services.	Assessed
Biodiversity	7 Invasive Species	No invasive species are introduced intentionally by the farmer or group since 2009.	No invasive species (e.g., water hyacinth, golden apple snail) have been introduced intentionally by the farmer or group since 2009	Not assessed. It is assumed that no invasive species have been introduced intentionally in the study areas.
Biodiversity	8 Levelling	Land has been leveled (no machinery required, visual confirmation sufficient).	Rice cultivated on flat land or on terraces: If laser leveling is used, the land or terraces are leveled up to 1/1000 within-plot slope. If laser leveling is not used, visual observation confirms that the field does not have high and low spots when filled with water and crop stand is uniform in height (i.e., no undulating).	Not assessed. The equipment needed for this technique is not yet widely available in Thailand

SRP Performance Indicators	Requirement No	SRP compliance minimum	Principle components	How this will be included in the study
GHG	10 Water Management	Timely and appropriate crop establishment according to local climate. Direct seeding or effective puddling, and strong bunds	Rainfed systems - Measures are in place to enhance water-use efficiency including: 1. Timely and appropriate crop establishment according to local climate. 2. Direct seeding or effective puddling, and strong bunds 3. Use of varieties suitable for local climate (e.g., short or medium-duration varieties). 4. Provision of on-site rainwater harvesting and storage for supplementary irrigation.	Not assessed. It is assumed that all Thai rice farmers in rainfed systems comply with conditions 1-3. It is not known the extent to which condition 4 applies in Thailand.
		Timely crop establishment to avoid submergence of the crop during expected floods.	Irrigated Production System— Flood-Prone Measures are in place to enhance water-use efficiency including: 1. Timely crop establishment to avoid submergence of the crop during expected floods. 2. At least one dry-down event (i.e., mid-season drainage of 7 days drained period/ aeration), if possible. 3. Leveling with provision for minor drainage conditions. 4. Use of flood-tolerant varieties	Not Assessed
		Leveling and strong bunds. Alternate wetting and drying.	Irrigated Production System—Not Flood-Prone Measures are in place to enhance water-use efficiency including: 1. One dry tillage before flooding if soil is cracked. 2. Leveling and strong bunds. 3. Dry seeding, or transplanting following land soak, effective puddling, and tillage within a 1-week period. 4. Alternate wetting and drying. 5. Use of short or medium-duration varieties with similar yield potential as long duration varieties 6. Termination of irrigation at least 10-15 days before harvesting.	Application of AWD is assessed
Biodiversity	14 Drainage	Surface (sideways) drainage is delayed	Intentional surface (sideways) drainage after surface application of agrochemicals is sufficiently delayed to avoid	Assessed

SRP Performance Indicators	Requirement No	SRP compliance minimum	Principle components	How this will be included in the study
		after surface application of agrochemicals by at least 4 days for fertilizers and 14 days for pesticides, or according to the product label.	contamination from agrochemical runoff, or according to the product label. Agrochemical runoff can negatively impact biodiversity or surroundings and waterways	
Biodiversity / GHG	15 Nutrient management	2 of the efficient and site-specific nutrient management measures are followed	Nutrient Management (Inorganic And/Or Organic) Efficient and site-specific nutrient management is applied and documented. Measures for efficient nutrient management include: 1. Timing of fertilizer (inorganic and/or organic; N, P, and/or K) application is according to plant needs, locally adapted recommendations, and product label instructions (if available). 2. Amount of fertilizer (inorganic and/or organic; N, P, and/or K) applied is based on knowledge of soil fertility and expected yield, locally adapted recommendations, and product label instructions (if available). 3. Natural systems of soil fertility enhancement (e.g., crop rotation, intercropping, and/or non-invasive cover cropping) are used.	Assessed
GHG	16 Organic fertilizer choice	Farmer does not use organic material as fertilizer because one or more of the listed conditions cannot be met.	Organic material (e.g., animal manure, green manure, mulch, rice straw) is used as fertilizer if the conditions are favorable. Favorable conditions include: 1. It can be applied in non-flooded fields in composted or de-composted state. 2. There is sufficient time for its decomposition prior to flooding. 3. It is available locally (approximately within 50 km radius) and in sufficient quantity.	Assessed

SRP Performance Indicators	Requirement No	SRP compliance minimum	Principle components	How this will be included in the study
GHG	17 Inorganic fertilizer choice	Farmer uses inorganic fertilizers that are registered and come from a non-counterfeit source.	Inorganic fertilizers can be used only if they are registered and come from a non-counterfeit source.	Not assessed. It is assumed that all inorganic fertilizer used is non-counterfeit
Biodiversity	18 Integrated pest management	Preventative control methods are used, before considering curative methods. Pesticide used only if other methods not effective on their own, + if pest expected to cause significant damage or loss. Pesticide is selected as per national government recommendations, is registered for use in rice, is not on international lists*, and is not counterfeit Pesticide use is targeted to avoid non-application zones. Pesticide is applied according to product label, follows specified preharvest interval, and does not exceed dosage (for worker safety and food safety). For insects: + Broad spectrum insecticide is not used within the first 40 days after rice planted (unless in accordance	IPM combines preventative and curative pest control methods. • Preventative pest control methods help to manage conditions to avoid pest build-up and can include: resistant varieties, crop rotation, intercropping, sanitation, ecological engineering, and others. • Curative pest control methods help to treat pest build-up that has occurred and can include: mechanical control (e.g., hand weeding), biological control (e.g., biological control agents), and chemical control (e.g., synthetic pesticides). The SRP Standard seeks to encourage ongoing preventative pest control actions, and punctual curative pest control actions when preventative methods are not effective on their own. Pesticides are used only if and when action thresholds are exceeded and the severity of the pest is expected to cause significant damage or loss. Actions should be as targeted as possible to avoid unintended impacts. Measured actions can support cost-reduction for farmers.	Assessed

SRP Performance Indicators	Requirement No	SRP compliance minimum	Principle components	How this will be included in the study
		with local government extension expert advice)		
GHG	24 Rice stubble	Farmer doesn't burn rice.	Rice stubble is managed in a sustainable way to mitigate greenhouse gas emissions, minimize environmental impacts, and retain or improve soil quality. Rice straw is: 1. Not burned. 2. Allowed sufficient time (at least 3 weeks) for aerobic decomposition before wetting.	Assessed
GHG	25 rice straw	Farmer doesn't burn rice.	Rice straw is managed in a sustainable way to mitigate greenhouse gas emissions, minimize environmental impacts, and retain or improve soil quality. Rice straw is: 1. Not burned. 2. Allowed sufficient time (at least 2 weeks) for aerobic decomposition if rice straw is left on the field or plowed under. 3. Collected, used as livestock feed and animal manure is returned to the field. Or collected, composted, and returned to the field.	Assessed

Note: **bold font** refers to those included in the assessment

Appendix 2: Supplementary of biodiversity part

Table S1 The abundance of each Family, Genus, and function of insects sampled in the sampling sites.

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Carabidae	Ophionea	0	0	0	0	3
Lycosidae	Lycosa	0	0	0	0	1
Pipunculidae	Pipunculus	0	0	0	0	1
Acricidae	Hieroglyphus	0	0	2	0	0
Acrididae	Hieroglyphus	0	0	54	0	1
Acrididae	NA	0	0	6	0	8
Agrionidae	Agriocnemis	0	0	0	0	17
Agrionidae	Agriocnemis	0	0	0	0	58
Agrionidae	Ceriagrion	0	0	0	0	2
Agromyzidae	Liriomyza	0	0	20	0	0
Agromyzidae	Agromyza	0	0	2	0	0
Agromyzidae	Agromyza	0	0	8	0	0
Agromyzidae	Chromatomyia	0	0	5	0	0
Agromyzidae	Liriomyza	0	0	33	0	0
Agromyzidae	Liriomyza	0	0	1	0	0
Agromyzidae	Liriomyza	0	0	2	0	0
Alydidae	Diplacodes	0	0	7	0	0
Alydidae	Leptecorisa	0	0	1	0	0
Alydidae	Leptecorisa	0	0	76	0	4
Anthocoridae	Orius	0	0	0	0	1
Anthocoridae	Orius	0	0	0	0	1
Anthomyiidae	NA	0	0	0	0	0
Aphididae	Aphididae	0	0	1	0	0
Aphididae	Aphis	0	0	20	0	0
Aphididae	NA	0	0	3	0	0

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Aphrophoridae	Neophilaenus	0	0	27	0	0
Aphrophoridae	Philaenus	0	0	1	0	0
Apidae	Apis	0	0	0	1	0
Araneidae	Agriope	0	0	0	0	2
Araneidae	Araneus	0	0	0	0	1
Araneidae	Argiope	0	0	0	0	2
Araneidae	Argiope	0	0	0	0	3
Araneidae	Atypena	0	0	0	0	9
Araneidae	NA	0	0	0	0	3
Araneidae	Neoscona	0	0	0	0	2
Araneidae	Tetragnatha	0	0	0	0	17
Asilidae	NA	0	0	0	0	5
Bethylidae	Goniozus	0	7	0	0	1
Bethylidae	Goniozus	sp.	1	0	0	0
Blaberidae	Pycnoscelus	1	0	0	0	0
Braconidae	Aleiodes	0	0	0	0	1
Braconidae	Apanteles	0	1	0	0	0
Braconidae	Bracon	0	63	0	0	1
Braconidae	Cardiochiles	0	3	0	0	0
Braconidae	Cotesia	0	20	0	0	0
Braconidae	Diachasmimorpha	0	1	0	0	0
Braconidae	Doryctobracon	0	1	0	0	0
Braconidae	Macrocentrus	0	7	0	0	0
Braconidae	NA	0	3	0	0	0
Braconidae	Opius	0	4	0	0	0
Braconidae	Rogadinae	0	1	0	0	0
Braconidae	Snellenius	0	9	0	0	0

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Braconidae	Snellenius	sp	0	0	0	1
Braconidae	Tropobracon	0	15	0	0	0
Braconidae	Xanthopimpla	0	6	0	0	0
Calliphoridae	Calliphora	0	0	0	0	0
Calliphoridae	Chrysomya	0	0	2	0	0
Carabidae	Ophionea	0	0	1	0	30
Cecidomyiidae	Orselia	0	0	16	0	0
Cecidomyiidae	Orseoli	0	0	1	0	0
Cecidomyiidae	Orseolia	0	0	105	0	0
Cecidomyiidae	Orseolio	0	0	1	0	0
Cecidomyiidae	Oseolia	0	0	1	0	0
Celyphidae	NA	0	0	0	0	0
Ceratopogonidae	NA	0	0	0	0	0
Cercopidae	NA	0	0	5	0	0
Cercopidae	Ophionea	0	0	0	0	1
Ceropidae	NA	0	0	4	0	0
Chalcidae	Brachymeria	0	12	0	0	1
Chalcididae	Brachymeria	0	0	0	0	1
Chalicidae	Brachymeria	0	2	0	0	0
Chalicidae	Chalcidae	0	2	0	0	0
Cheiracanthiidae	Cheiracanthium	0	0	0	0	7
Chironomidae	Chilomus	0	0	1	0	1
Chironomidae	Chironomus	0	0	92	0	90
Chironomidae	NA	0	0	5	0	1
Chironomidae	Chironomus	0	0	4	0	3
Chironomus	Chironomus	sp.	0	1	0	0
Chloropidae	Anatrichus	0	0	0	0	0
Chloropidae	Chlorops	0	0	0	0	0

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Chloropidae	NA	0	0	0	0	1
Chrysomelidae	Aphthona	0	0	1	0	0
Chrysomelidae	Aulacophora	0	0	1	0	0
Chrysomelidae	Aulacophora	0	0	1	0	0
Chrysomelidae	Chaetocnema	0	0	4	0	0
Chrysomelidae	Chrysochus	0	0	1	0	0
Chrysomelidae	Chrysolina	0	0	7	0	1
Chrysomelidae	Dicladispa	0	0	24	0	1
Chrysomelidae	Donacia	0	0	1	0	0
Chrysomelidae	Monolepta	0	0	2	0	0
Chrysomelidae	NA	0	0	4	0	0
Chrysomelidae	Neocrepidodera	0	0	1	0	0
Chrysomelidae	Pachybrachis	0	0	1	0	0
Chrysomelidae	Phyllotreta	0	0	1	0	0
Chrysomelidae	Aulacophora	0	0	2	0	0
Chrysomelidae	Chaetocnema	0	0	5	0	0
Chrysomelidae	Phyllotreta	0	0	1	0	0
Chrysomelidae	Dicladispa	0	0	1	0	0
Cicadellidae	Balclutha	0	0	9	0	0
Cicadellidae	Cicadella	0	0	3	0	0
Cicadellidae	Cofana	0	0	1	0	0
Cicadellidae	Edwardsiama	0	0	3	0	0
Cicadellidae	Edwardsiana	0	0	29	0	0
Cicadellidae	Empoasca	0	0	3	0	0
Cicadellidae	Maestas	0	0	11	0	0
Cicadellidae	Maestos	0	0	7	0	0
Cicadellidae	NA	0	0	46	0	0
Cicadellidae	Naphotettix	0	0	2	0	0

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Cicadellidae	nephotettix	0	0	1	0	0
Cicadellidae	Nephotettix	0	0	463	0	0
Cicadellidae	Nephottix	0	0	7	0	0
Cicadellidae	Nilaparvata	0	0	2	0	0
Cicadellidae	Nilaparvate	0	0	1	0	0
Cicadellidae	Prourtista	0	0	1	0	0
Cicadellidae	Recilia	0	0	13	0	0
Cicadellidae	Sogatella	0	0	13	0	0
Clubionidae	Clubiona	0	0	0	0	32
Coccinellidae	Chironomus	0	0	0	0	1
Coccinellidae	Coccinelli	0	0	0	0	1
Coccinellidae	Micraspis	0	0	0	0	47
Coccinellidae	Micraspis	0	0	0	0	131
Coccinellidae	NA	0	0	1	0	0
Coccinellidae	Micraspin	0	0	0	0	6
Coccinellidae	micraspis	0	0	0	0	1
Coccinellidae	Micraspis	0	0	0	0	64
Coccinellidae	Micraspis	0	0	0	0	3
Coccinellidae	NA	0	0	1	0	7
Cocnagrionidae	Agriocnemis	0	0	0	0	1
Coenagrionidae	Agriocnemis	0	0	0	0	2
Coenagrionidae	Agriocnemis	0	0	1	0	65
Coenagrionidae	Agriocnemis	0	0	0	0	48
Coenagrionidae	Ceragrion	0	0	0	0	3
Coenagrionidae	Diplacodes	0	0	0	0	1
Coenagrionidae	Ischnura	0	0	0	0	1
Coenagrionidae	Pseudagrion	0	0	0	0	2
Coenagrionidae	Pseudagrion	0	0	0	0	2

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Coreidae	Chariesterus	0	0	6	0	1
Coreidae	NA	0	0	0	0	0
Culicidae	Anopheles	0	0	2	0	0
Culicidae	NA	0	0	0	0	0
Curculionidae	Hydromidius	0	0	4	0	0
Curculionidae	Euwallacea	0	0	2	0	0
Curculionidae	Hydromidius	0	0	48	0	4
Curculionidae	Hydronomidius	0	0	106	0	0
Curculionidae	Hypomeces	0	0	6	0	0
Curculionidae	NA	0	0	1	0	0
Cydidae	NA	0	0	2	0	0
Cynipoidea		0	1	0	0	0
Delphacidae	NA	0	0	2	0	0
Delphacidae	Naphotettix	0	0	2	0	0
Delphacidae	Nilaparvara	0	0	33	0	0
Delphacidae	Nilaparvata	0	0	136	0	0
Delphacidae	Nilaparvata.	0	0	1	0	0
Delphacidae	Nilaparvate	0	0	47	0	0
Delphacidae	Proutista	0	0	1	0	0
Delphacidae	Sogatella	0	0	2	0	0
Delphacidae	Tagosodes	0	0	10	0	0
Derbidae	Proutista	0	0	4	0	0
Derbidae	Proutista	0	0	12	0	0
Dernidae	Proutista	0	0	4	0	0
Dictyopharidae	Proutista	0	0	2	0	0
Dictyopharidae.	Proutista	0	0	1	0	0
Dolichopodidae	Condylostylus	0	0	0	0	10
Dolichopodidae	Dolichopodidae	0	0	1	0	3

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Dolichopodidae	Dolichopus	2	0	4	0	13
Dolichopodidae	Sympycnus	0	0	0	0	1
Dolichopodidae	NA	0	0	1	0	0
Drosophilidae	Drosophila	0	0	4	0	0
Drosophilidae	Lordiphosa	0	0	0	0	0
Drosophilidae	NA	0	0	0	1	0
Drosophilidae	Platygaster	0	0	0	0	2
Drosophilidae.	Drosophila	0	0	4	0	0
Dryinidae	Echthrodelp	0	1	0	0	0
Dryinidae	Echthrodelp	0	5	0	0	0
Dryinidae	Pseudogonatopus	0	2	0	0	0
Ehpydridae	Hydrellia	0	0	30	0	0
Ehpydridae	Ochthera	0	0	0	0	1
Elasmidae	Elasmus	0	57	0	0	0
Elateridae	Melanotus	0	0	1	0	0
Elateridae	Melanotus	0	0	4	0	0
Empididae	Drapetis	0	0	0	0	36
Empididae	NA	0	0	0	0	1
Encyrtidae	Copidosomopsis	0	4	0	0	0
Ephydridae	Hrdrellia	0	0	0	0	1
Ephydridae	Hydrellia	0	0	114	0	0
Ephydridae	Hydrellia	0	0	13	0	0
Ephydridae	NA	0	0	4	0	0
Ephydridae	Ochthera	0	0	0	0	2
Eulophidae	Aprostocetus	0	7	0	0	0
Eulophidae	Aprostocetus	sp.	1	0	0	0
Eulophidae	Pediobius	0	1	0	0	0
Eulophidae	Tetrastichus	0	20	1	0	0

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Eupelmidae	Eupelmidae	0	4	0	0	0
Eupelmidae	Neanastatus	0	11	0	0	0
Eupelmidae	Neophilaenus	0	3	0	0	0
Euphaeidae	NA	0	0	1	0	0
Eutichuridae	Cheiracanthium	0	0	0	0	4
Flatidae	Flatidae	0	0	1	0	0
Flatidae	NA	0	0	1	0	0
Formicidae	Carebara	0	0	0	0	1
Formicidae	Lasius	0	0	0	0	13
Formicidae	NA	0	0	1	0	47
Formicidae	Oecophylla	0	0	0	0	2
Formicidae	Solenopsis	0	0	0	0	2
Gomphidae	Orthetrum	0	0	0	0	1
Gryllidae		0	0	1	0	0
Gryllidae	NA	0	0	17	0	0
Gryllidae	Orthoptera	0	0	0	0	2
Grylloidea	NA	0	0	4	0	0
Hesperiidae	NA	0	0	0	0	0
Hydrodidae	Hydrophilus	0	0	0	0	0
Ichneumonidae	Goryphus	0	3	0	0	0
Ichneumonidae	Hyposoter	0	14	0	0	1
Ichneumonidae	Isotima	0	1	0	0	0
Ichneumonidae	Paraphylax	0	78	0	0	0
Ichneumonidae	Temelicha	0	1	0	0	0
Ichneumonidae	Temelucha	0	15	0	0	0
Ichneumonidae	Xanthopimpla	0	42	0	0	0
Libellulidae	Diplacodes	0	0	0	0	11
Libellulidae	Macrodiplax	0	0	0	0	2

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Libellulidae	NA	0	0	0	0	26
Libellulidae	Nephotettix	0	0	0	0	1
Libellulidae	Neurothemis	0	0	1	0	50
Libellulidae	Orthetrum	0	0	0	0	2
Libellulidae.	Neurothemis	0	0	0	0	10
Linyphiidae	Atypena	0	0	0	0	16
Linyphiidae	Callitrichia	0	0	0	0	2
Linyphiidae	NA	0	0	0	0	1
Lycosidae	Lycoca	0	0	0	0	22
Lycosidae	Lycosa	0	0	0	0	38
Lycosidae	NA	0	0	0	0	2
Lysocidae	Lycosa	0	0	0	0	1
Mantidae	Hierodula	0	0	1	0	0
Mantidae	NA	0	0	0	0	2
Mantidae	Tenodera	0	0	0	0	1
Mantispidae	NA	0	0	0	0	1
Membracidae	NA	0	0	1	0	0
Membracidae	NA	0	0	2	0	0
Miridae	Cyrtorhinus	0	0	3	0	27
Miridae	Ophionea	0	0	0	0	2
Miridae	Tytthus	0	0	1	0	29
Miridae.	Cyrtorhinus	0	0	0	0	16
Muscidae	Atherigona	0	0	2	0	0
Muscidae	Hydrellia	0	0	19	0	0
Muscidae	Hydrellia	Sp.	0	1	0	0
Muscidae	Hydrellia	Spp	0	1	0	0
Muscidae	NA	0	0	0	0	0
Mymaridae	Anagrus	0	7	0	0	0

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
NA	.	0	0	1	0	0
NA	Cicadella	0	0	1	0	0
NA	NA	1	1	20	0	9
NA	Tagosodes	0	0	1	0	0
Nabidae	Nabis	0	0	1	0	0
Noctuidae	Spodoptera	0	0	3	0	0
Noctuidae	Trichoplusia	0	0	1	0	0
Oxyopidae	Oxyopes	0	0	0	0	56
Oxyopidae	Oxyopes	0	0	0	0	3
Pentatomida	Tessaratomia	0	0	1	0	0
Pentatomidae	Scotinophara	0	0	6	0	0
Pentatomidae	Tetroda	0	0	23	0	3
Pentatomidae	NA	0	0	1	0	0
Phoridae	Megaselia	0	0	0	0	2
Pieridae	Eurema	0	0	1	0	0
Pieridae	NA	0	0	0	1	0
Pipunculidae	Pipunculus	0	4	17	0	12
Plataspidae	Coptosoma	0	0	7	0	0
Platygastridae	Chromoteleia	0	4	0	0	16
Platygastridae	Chromotetleia	0	0	0	0	5
Platygastridae	Platygaster	0	90	0	0	29
Platystomatidae	Poecilotrappera	0	0	0	0	11
Psilidae	Psila	0	0	0	0	0
Pteromalidae	Obtusiclava	0	17	0	0	0
Pteromalidae	Trichomalopsis	0	3	0	0	0
Pyralidae	Chilo	0	0	4	0	0
Pyralidae	Cnaphalocrocis	0	0	2	0	0
Pyralidae	NA	0	0	38	0	1

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Pyralidae	Scirpophaga	0	0	5	0	0
Pyrrhocoridae	Antilochus	0	0	0	0	1
Rutelidae	Adoretus	compressus	0	1	0	0
Salticidae	NA	0	0	1	0	46
Scarabaeidae	Dyscinetus	0	0	1	0	0
Scelionidae	Psix	0	6	0	0	0
Scelionidae	Telenomus	0	5	0	0	0
Staphylinoidea	NA	0	0	0	0	1
Syrphidae	Eupeodes	0	0	0	2	0
Syrphidae	NA	0	0	0	1	0
Tachinidae	Argyrophylax	0	0	0	0	1
Tachinidae	NA	0	3	0	0	0
Tephritidae	Bactrocera	0	0	1	0	0
Tephritidae	NA	0	0	1	0	0
Tephritidae	Tephritis	0	0	4	0	0
Tetragnathidae	Conocephalus	0	0	1	0	0
Tetragnathidae	NA	0	0	1	0	0
Tetragnathidae	Tetragnatha	0	0	1	0	195
Tetragnathidae	Tetragnatha	Sp.	0	0	0	1
Tetrigidae	Criotettix	0	0	2	0	0
Tettigoniidae	Conocephalus	0	0	2	0	0
Tettigoniidae	Conocephalus	0	0	57	0	16
Tettigoniidae	NA	0	0	2	0	0
Tettigoniidae	Neoconcocephalus	0	0	2	0	0
Tettigoniidae	Neoconocephalus	0	0	5	0	0
Theridiidae	Argriope	0	0	0	0	3

Family	Genus	Decomposer	Parasite	Pest	Pollinator	Predator
Theridiidae	Argyrodes	0	0	0	0	2
Thomisidae	NA	0	0	0	0	7
Thomisidae	Thomisus	0	0	0	0	14
Thripidae	NA	0	0	2	0	2
Thripidae	Stenchaetothrips	0	0	6	0	0
Tipulidae		1	0	0	0	0
Tipulidae	Dolichopodidae	0	0	0	0	1
Tipulidae	NA	33	0	7	0	3
Tipulidae	Tipula	2	0	0	0	0
Torymidae	Podagrion	0	1	0	0	0
Trichogrammatidae	Oligosita	0	12	0	0	0
Ulidiidae	NA	0	0	1	0	0
Alidae	Ypthima	0	0	0	1	0

Appendix 3: Table 6.1. List of plant species and number of individuals recorded on the sampled rice paddies.

No.	Scientific Names	Family	Status	No. recorded	Density (trees/ha)
1	<i>Leucaena leucocephala</i> (Lam.) de Wit	LEGUMINOSAE	Cultivated	281	1.49
2	<i>Acacia auriculiformis</i> A. Cunn. ex Benth.	LEGUMINOSAE	Cultivated	75	0.40
3	<i>Acacia mangium</i> willd.	LEGUMINOSAE	Cultivated	14	0.07
4	<i>Mitragyna speciosa</i> (Roxb.) Korth.	RUBIACEAE	Cultivated	12	0.06
5	<i>Musa sapientum</i> L.	MUSACEAE	Cultivated	505	2.68
6	<i>Theobroma cacao</i> L.	STERCULIACEAE	Cultivated	1	0.01
7	<i>Artocarpus heterophyllus</i> Lam.	MORACEAE	Cultivated	1	0.01
8	<i>Senna siamea</i> (Lam.) H.S. Irwin & Barneby	FABACEAE	Cultivated	53	0.28
9	<i>Cassia fistula</i> L.	FABACEAE	Cultivated	15	0.08
10	<i>Sesbania grandiflora</i> (L.) Pers.	FABACEAE	Cultivated	51	0.27
11	<i>Bauhinia purpurea</i> L.	FABACEAE	Cultivated	2	0.01
12	<i>Dalbergia oliveri</i> Gamble	PAPILIONACEAE	Cultivated	1	0.01
13	<i>Hopea odorata</i> Roxb.	DIPTEROCARPACEAE	Cultivated	10	0.05
14	<i>Borassus flabellifer</i> L.	ARECACEAE	Cultivated	50	0.27

No.	Scientific Names	Family	Status	No. recorded	Density (trees/ha)
15	<i>Alstonia scholaris</i> (L.) R.Br.	APOCYNACEAE	Cultivated	1	0.01
16	<i>Durio zibethinus</i> L.	BOMBACACEAE	Cultivated	25	0.13
17	<i>Annona squamosa</i> L.	ANNONACEAE	Cultivated	44	0.23
18	<i>Pterocarpus indicus</i> Willd.	LEGUMINOSAE	Cultivated	162	0.86
19	<i>Elaeis guineensis</i> L.	ARECACEAE	Cultivated	24	0.13
20	<i>Millingtonia hortensis</i> L.f.	BIGNONIACEAE	Cultivated	2	0.01
21	<i>Melientha sauvais</i> Pierre	OPILIACEAE	Cultivated	2	0.01
22	<i>Bambusa arundinacea</i> Willd.	GRAMINEAE	Cultivated	62	0.33
23	<i>Psidium guajava</i> L.	MYRTACEAE	Cultivated	43	0.23
24	<i>Dalbergia cochinchinensis</i> Pierre	LEGUMINOSAE	Cultivated	177	0.94
25	<i>Ziziphus mauritiana</i> Lam.	RHAMNACEAE	Cultivated	4	0.02
26	<i>Oroxylum indicum</i> (L.) Kurz	BIGNONIACEAE	Cultivated	2	0.01
27	<i>Citrus hystrix</i> DC.	RUTACEAE	Cultivated	3	0.02
28	<i>Feronia limonia</i> (L.) Swingle	RUTACEAE	Cultivated	1	0.01
29	<i>Pithecellobium dulce</i> (Roxb.) Benth.	LEGUMINOSAE	Cultivated	56	0.30
30	<i>Tamarindus indica</i> L.	LEGUMINOSAE	Cultivated	43	0.23
31	<i>Tamarindus indica</i> L.	LEGUMINOSAE	Cultivated	2	0.01
32	<i>Citrus aurantifolia</i> (Christm.) Swingle	RUTACEAE	Cultivated	1	0.01
33	<i>Cocos nucifera</i> L. var. <i>Nucifera</i>	PALMAE	Cultivated	248	1.32
34	<i>Anacardium occidentale</i> L.	ANACARDIACEAE	Cultivated	18	0.10
35	<i>Phyllanthus acidus</i> (Linn.) Skeels	MYRSINACEAE	Cultivated	1	0.01
36	<i>Moringa oleifera</i> Lam.	MORINGACEAE	Cultivated	5	0.03
37	<i>Swietenia mahogany</i> (L.) Jacq.	MELIACEAE	Cultivated	16	0.09
38	<i>Dipterocarpus alatus</i> Roxb. ex G.Don	DIPTEROCARPACEAE	Cultivated	434	2.31
39	<i>Dipterocarpus costatus</i> C.F.Gaertn.	DIPTEROCARPACEAE	Cultivated	0	0.00
40	<i>Hevea brasiliensis</i> Mull-Arg.	EUPHORBIACEAE	Cultivated	83	0.44
41	<i>Eucalyptus globulus</i> Labill.	MYRTACEAE	Cultivated	588	3.13
42	<i>Thunbergia laurifolia</i> Lindl.	ACANTHACEAE	Cultivated	1	0.01
43	<i>Pandanus odorifer</i> (Forssk.) Kuntze	PANDANACEAE	Cultivated	10	0.05
44	<i>Dimocarpus longan</i>	SAPINDACEAE	Cultivated	2	0.01
45	<i>Litchi chinensis</i>	SAPINDACEAE	Cultivated	8	0.04
46	<i>Melia azedarach</i> L.	MELIACEAE	Cultivated	1	0.01
47	<i>Citrus maxima</i> (Burm.f.) Merr.	RUBIACEAE	Cultivated	5	0.03
48	<i>Azadirachta indica</i> A. Juss. var. <i>siamensis</i> Valetton	MELIACEAE	Cultivated	302	1.61
49	<i>Tectona grandis</i> L. f.	LAMIACEAE	Cultivated	124	0.66
50	<i>Areca catechu</i> L.	ARECACEAE	Cultivated	1	0.01
51	<i>Calamus viminalis</i> Willd.	ARECACEAE	Cultivated	4	0.02
52	<i>Peltophorum dasyrachis</i> (Miq.) Kurz	CAESALPINIACEAE	Cultivated	4	0.02
53	<i>Lagerstroemia speciosa</i> Pers.	LYTHRACEAE	Cultivated	1	0.01
54	<i>Phoenix dactylifera</i> L.	ARECACEAE	Cultivated	30	0.16
Sum # of cultivated trees				3,611	19.19
1	<i>Careya sphaerica</i> Roxb.	LECYTHIDACEAE	Native	1	0.01

No.	Scientific Names	Family	Status	No. recorded	Density (trees/ha)
2	<i>Anthocephalus chinensis</i> (Lam.) A. Rich ex Walp.	RUBIACEAE	Native	41	0.22
3	<i>Irvingia malayana</i> Oliv. ex A.W.Benn.	IRVINGIACEAE	Native	5	0.03
4	<i>Fagraea fragrans</i> Roxb.	LOGANIACEAE	Native	2	0.01
5	<i>Crateva adansonii</i> subsp. <i>trifoliata</i> (Roxb.) Jacobs	CAPPARACEAE	Native	5	0.03
6	<i>Streblus asper</i> Lour.	MORACEAE	Native	28	0.15
7	<i>Dolichandrone serrulata</i> (Wall. ex DC.) Seem.	BIGNONIACEAE	Native	34	0.18
8	<i>Bombax ceiba</i> L.	MALVACEAE	Native	21	0.11
9	<i>Samanea saman</i> (Jacq.) Merr.	MIMOSACEAE	Native	11	0.06
10	<i>Albizia lebbekoides</i> (DC.) Benth.	FABACEAE	Native	8	0.04
11	<i>Barringtonia coccinea</i> Kostel	LECYTHIDACEAE	Native	7	0.04
12	<i>Dalbergia lanceolaria</i> subsp. <i>paniculata</i> (Roxb.) Thoth.	FABACEAE	Native	3	0.02
13	<i>Xylia xylocarpa</i> (Roxb.) Taub.	FABACEAE	Native	20	0.11
14	<i>Diospyros rhodocalyx</i> Kurz	EBENACEAE	Native	30	0.16
15	<i>Muntingia calabura</i> L.	MUNTINGIACEAE	Native	17	0.09
16	<i>Schleichera oleosa</i> (Lour.) Merr.	SAPINDACEAE	Native	6	0.03
17	<i>Lagerstroemia floribunda</i> Jack	LYTHRACEAE	Native	3	0.02
18	<i>Cratoxylum formosum</i> (Jack) Dyer	GUTTIFERAE	Native	21	0.11
19	<i>Shorea obtusa</i> Wall. ex Blume	DIPTEROCARPACEAE	Native	1	0.01
20	<i>Butea monosperma</i> (Lam.) Taub	LEGUMINOSAE	Native	6	0.03
21	<i>Ficus Benjamina</i> L.	MORACEAE	Native	2	0.01
22	<i>Buchanania siamensis</i> Miq.	ANACARDIACEAE	Native	16	0.09
23	<i>Hibiscus macrophyllus</i> Roxb. ex Hornem.	MALVACEAE	Native	1	0.01
24	<i>Albizia lebbek</i> (L.) Benth.	FABACEAE	Native	23	0.12
25	<i>Ficus religiosa</i> L.	MORACEAE	Native	12	0.06
26	<i>Diospyros mollis</i> Griff.	EBENACEAE	Native	3	0.02
27	<i>Sindora siamensis</i> Miq.	LEGUMINOSAE	Native	3	0.02
28	<i>Azelia xylocarpa</i> (Kurz) Craib	LEGUMINOSAE	Native	60	0.32
29	<i>Ficus racemosa</i> L.	MORACEAE	Native	2	0.01
30	<i>Mangifera indica</i> L.	ANACARDIACEAE	Native	128	0.68
31	<i>Antidesma puncticulatum</i> Miq.	PHYLLANTHACEAE	Native	6	0.03
32	<i>Lepisanthes rubiginosa</i> (Roxb.) Leenh.	SAPINDACEAE	Native	1	0.01
33	<i>Morinda elliptica</i> (Hook.f.) Ridl.	RUBIACEAE	Native	2	0.01
34	<i>Dipterocarpus intricatus</i> Dyer	DIPTEROCARPACEAE	Native	9	0.05
35	<i>Pentaptera tomentosa</i> Roxb. ex DC.	COMBRETACEAE	Native	5	0.03
36	<i>Shorea siamensis</i> Miq.	DIPTEROCARPACEAE	Native	2	0.01
37	<i>Terminalia chebula</i> Retz. var. <i>Chebula</i>	COMBRETACEAE	Native	1	0.01
38	<i>Combretum quadrangulare</i> Kurz.	COMBRETACEAE	Native	47	0.25
39	<i>Sterculia foetida</i> L.	STERCULIACEAE	Native	1	0.01
40	<i>Phyllanthus taxodiifolius</i> Beille	EUPHORBIACEAE	Native	0	0.00

No.	Scientific Names	Family	Status	No. recorded	Density (trees/ha)
41	<i>Bauhinia variegata</i> L.	FABACEAE	Native	11	0.06
42	<i>Syzygium cumini</i> (L.) Skeels	MYRTACEAE	Native	68	0.36
43	Unknown species		Native	3	0.02
Sum # of native trees				676	3.59
Sum No. of all tree species				4,287	22.78

Appendix 4 The greenhouse gases (GHG) emissions, soil organic carbon stocks (SOC), and rice yield from seven rice field management practices under different climate model, RCP 4.5 and 8.5, in the Northeast and Central of Thailand

1) Climate data

The climate data from 2001-2020 are obtain from the observation stations of Thai Meteorological Department (TMD) and the climate data for the future simulation (2021-2050) obtained from the Regional Climate Model Version 4.3.7, CNRM-CM5 Model, Resolution 25 x 25 km, assuming the emissions scenario on the Representative Concentration Pathways (RCP) 4.5 and 8.5 which refer to different climate scenarios of the Intergovernmental Panel on Climate Change (IPCC) (Ramkhamhaeng University Center of Regional Climate Change and Renewable Energy: RU-CORE, 2020). RCP 4.5 is described by IPCC as a moderate scenario with intermediate greenhouse gas emissions while RCP 8.5 is a scenario with very high greenhouse gas emissions. Mean temperature and total precipitation over 2021-2050 of the studied sites obtained from the model RCP 4.5 and 8.5 were presented in Figures 4.4 and 4.5. Mean temperatures under RCP 4.5 are between 24 – 25 °C in the lower northeast region, 23 – 25 °C in the upper northeast region and 25 – 26 °C in the central region. Whereas, the mean temperatures under RCP 8.5 slightly increase, which are between 24 – 25 °C in the lower northeast and the upper northeast regions and 25 – 27 °C in the central region. Annual precipitations under RCP 4.5 are within the ranges of 1700 – 2900 mm in the lower northeast region, 1400 – 2500 mm in the upper northeast region, and 1700 – 3100 mm in the central region. While, annual precipitations under RCP 8.5 have narrower ranges

of 1800 – 2600 mm in the lower northeast region, 1600 – 2400 mm in the upper northeast region, and 1900 – 2800 mm in the central region.

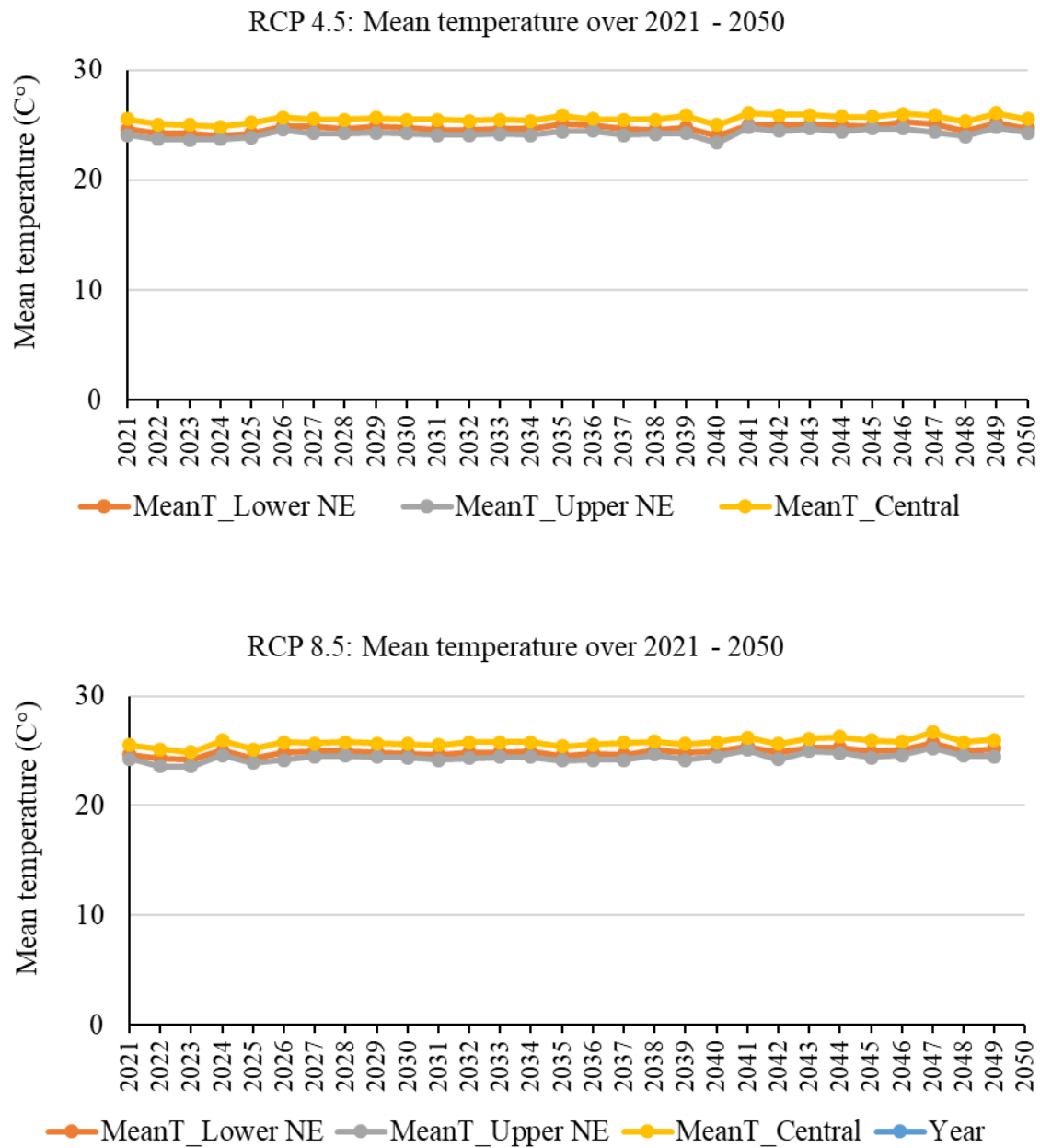


Figure 4.4 Mean daily temperature over 2021-2050 of the studied sites

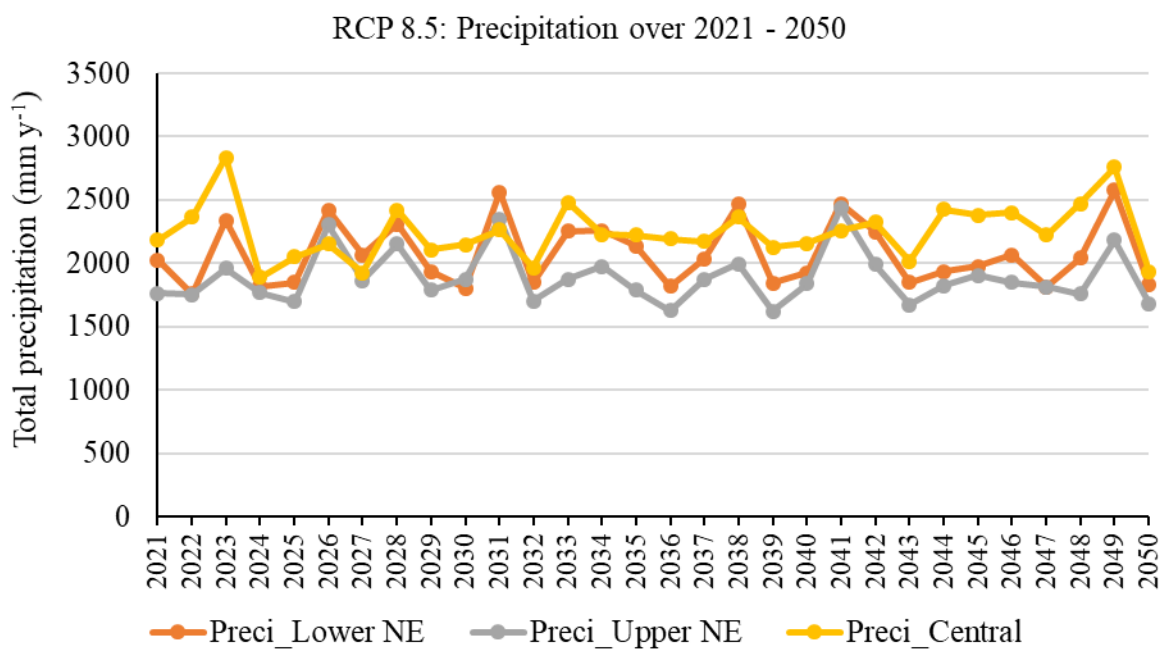
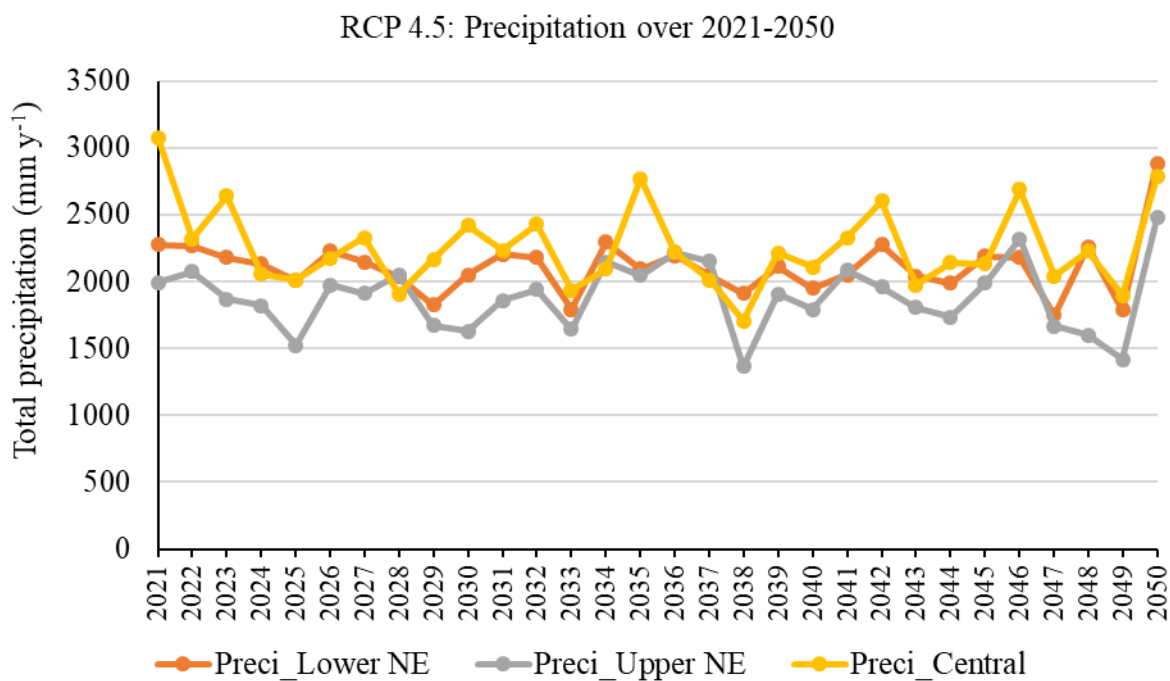


Figure 4.5 Total precipitation over 2021-2050 of the studied sites

2) *Long-term GHG emission estimations under different rice field management practices and climate models*

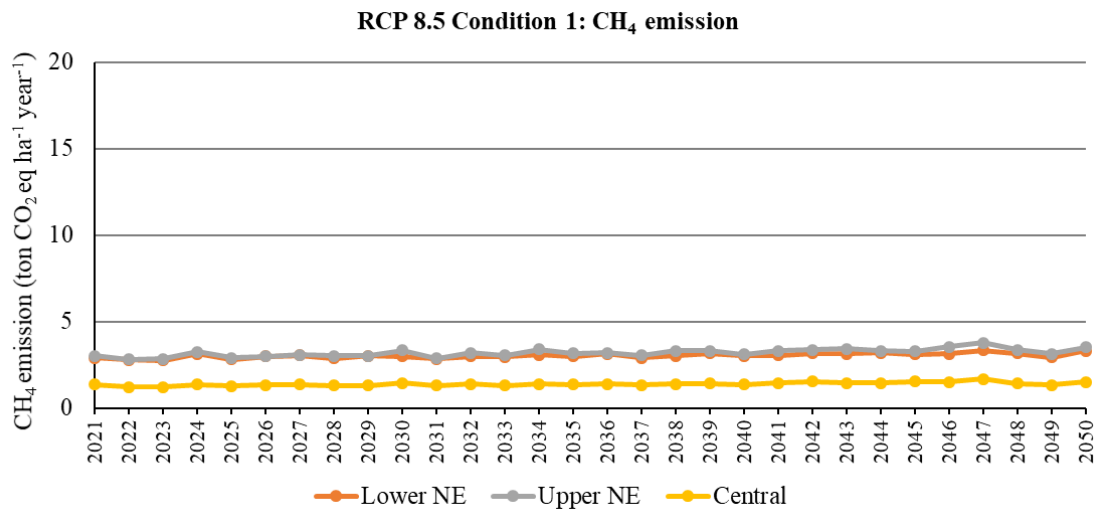
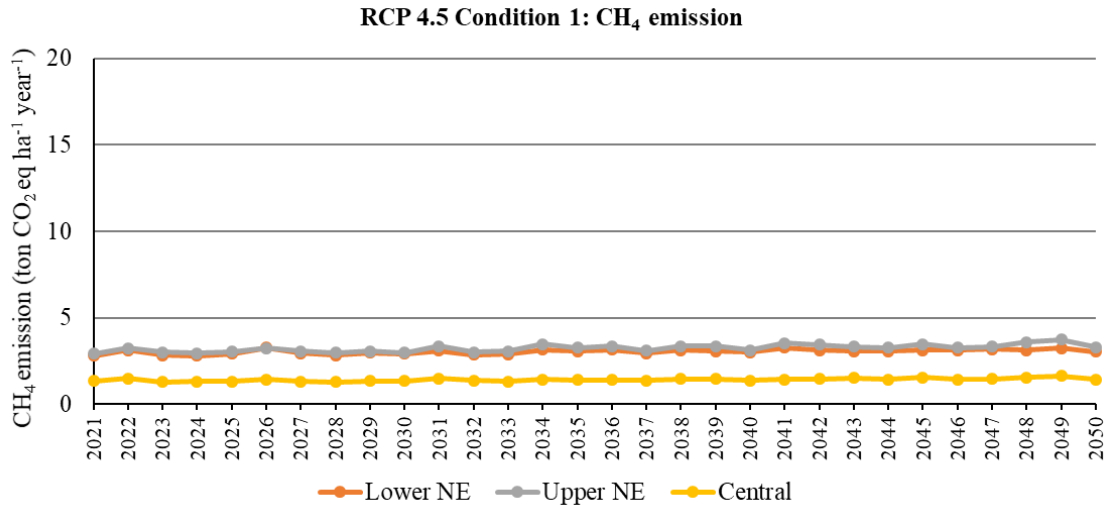
The greenhouse gases (GHG) emissions from seven rice field management practices under different climate model, RCP 4.5 and 8.5, in the Northeast and Central of Thailand were compared. The seven managements include 1) a conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding (C1), 2) a conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding (C2), 3) a suitable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation (C3), 4) a suitable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation (C4), 5) a suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation (C5), 6) a suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding (C6), and 7) a suitable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding (C7).

The main sources of GHG emissions in the study are focused from rice field throughout the entire year. Additionally, this section also estimates the soil carbon stock (SOC), which determines the capacity for GHG removal, as well as the crop yield generated by the rice field. In order to calculate GHG emissions, specifically methane (CH₄) and nitrous oxide (N₂O), emitted by the rice field, the units were converted to CO₂ equivalent using Global Warming Potential (GWP) values from the IPCC Fifth Assessment Report (AR5). The GWP value for methane (CH₄) is 28, while for nitrous oxide (N₂O) it is 265.

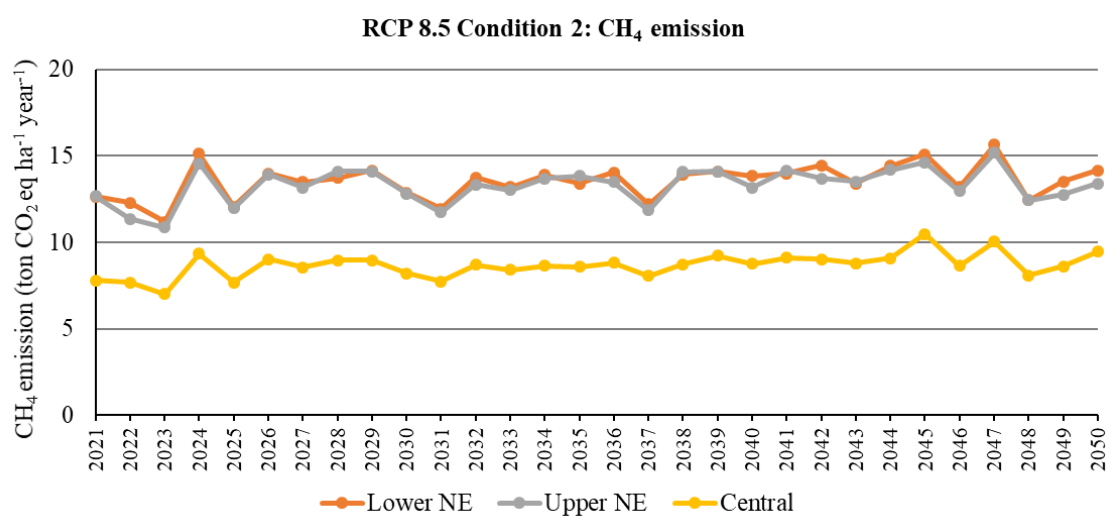
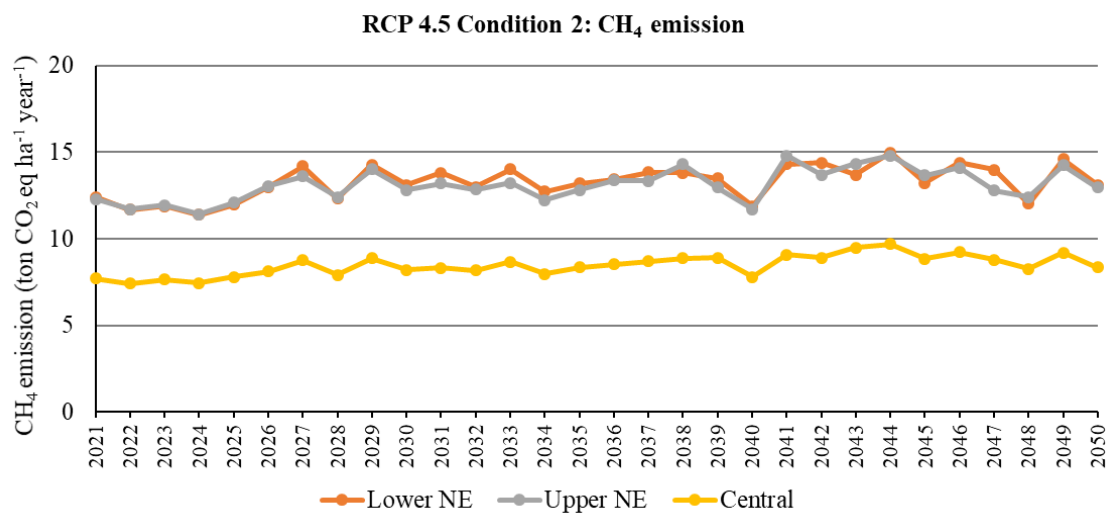
3) CH₄ emissions from the rice fields under different rice field management practices and climate models

Annual CH₄ emissions from conventional and suitable rice practice over 2021-2050 under different managements and different climate scenarios are shown in Figure 4.7. Comparing between annual CH₄ emissions under RCP 4.5 and 8.5 in the same condition, the study shows that despite differences in the climate scenarios of RCP 4.5 and 8.5, the annual CH₄ emissions under both scenarios are similar in terms of range and patterns. Whereas, the different management practices can lead to varying patterns and ranges of annual CH₄ emissions.

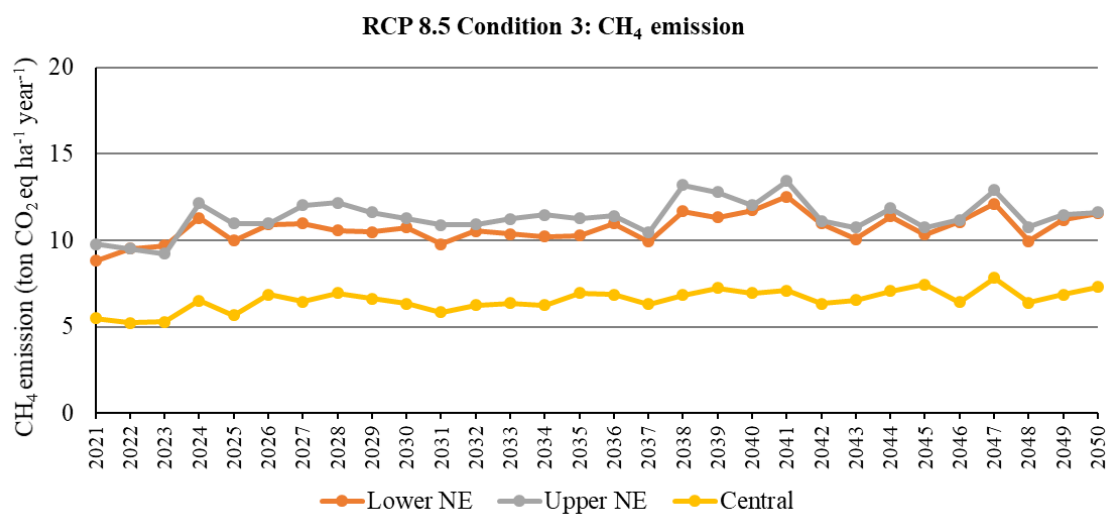
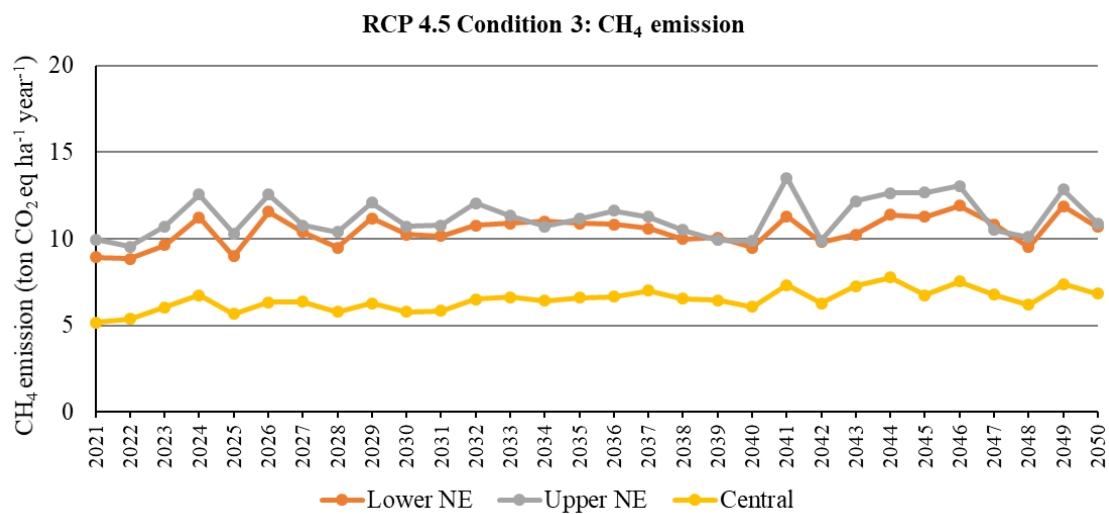
- a) A conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



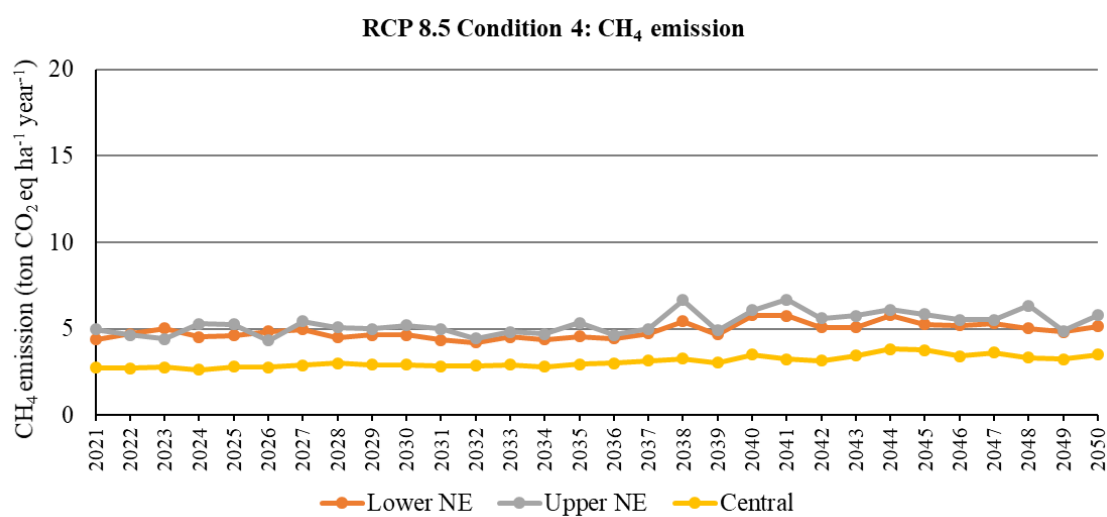
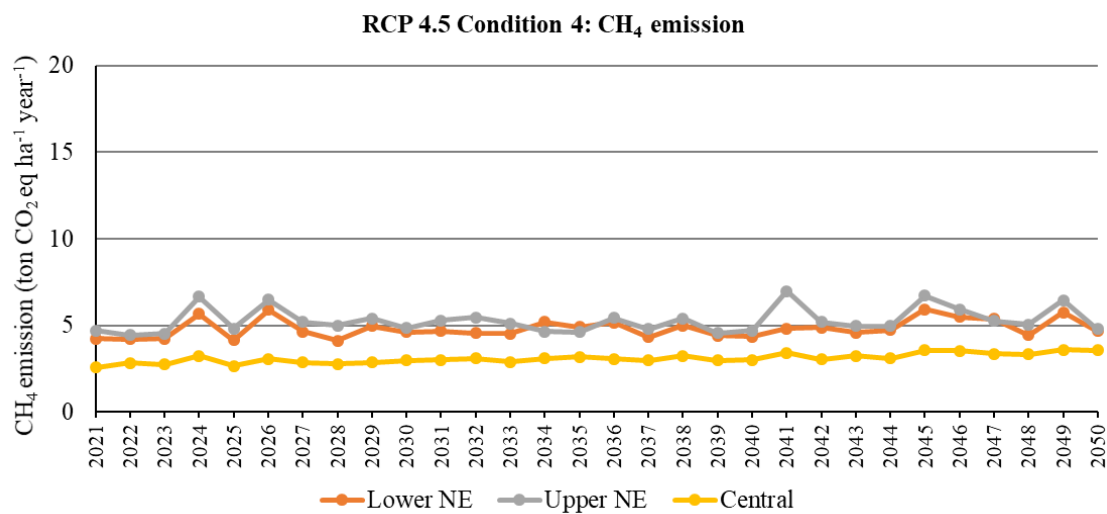
- b) A conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



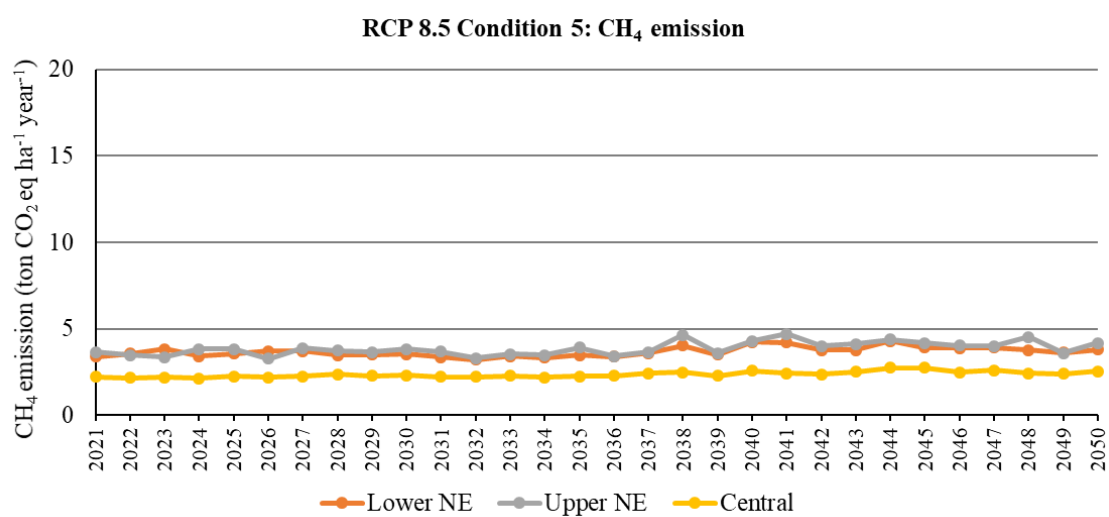
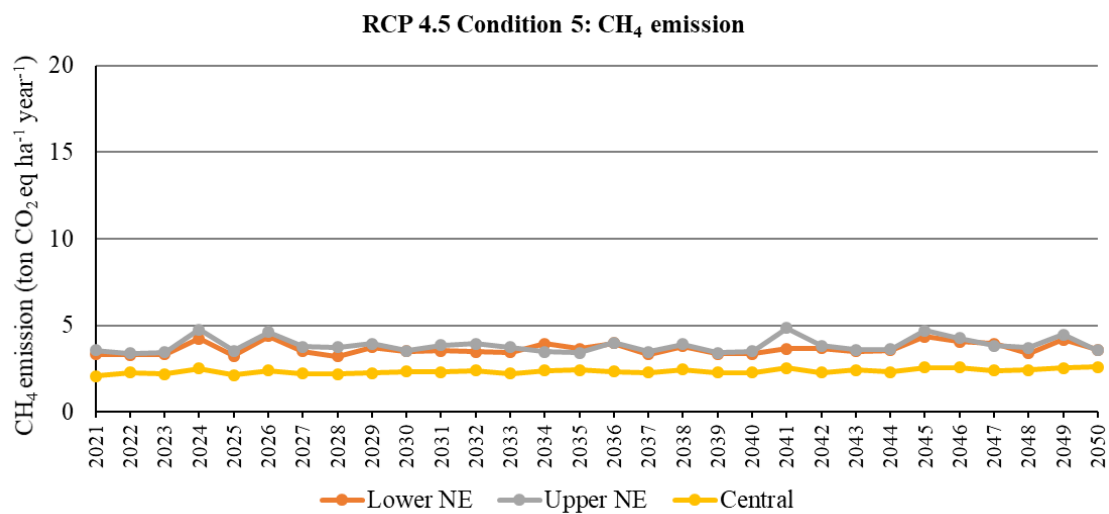
- c) A suitable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



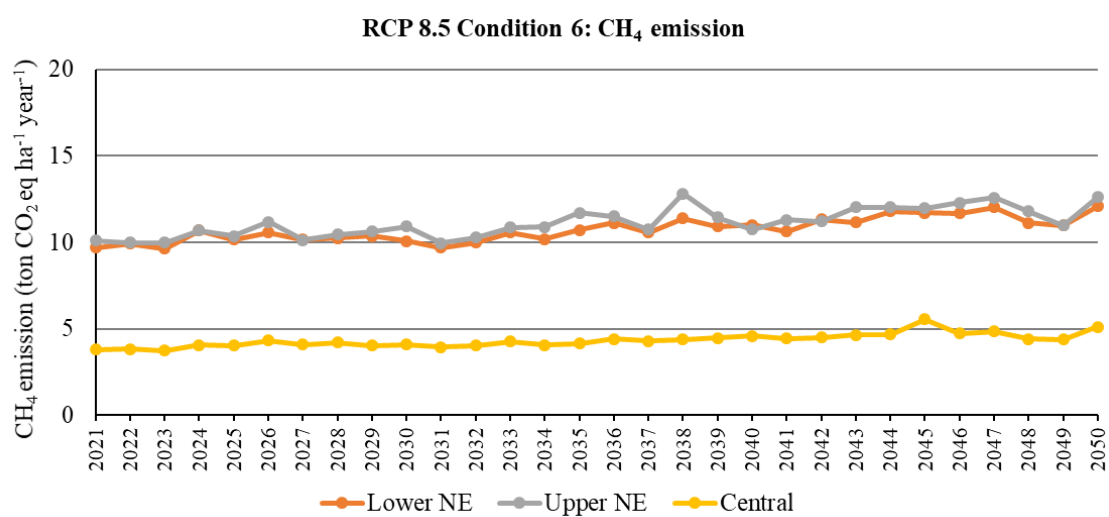
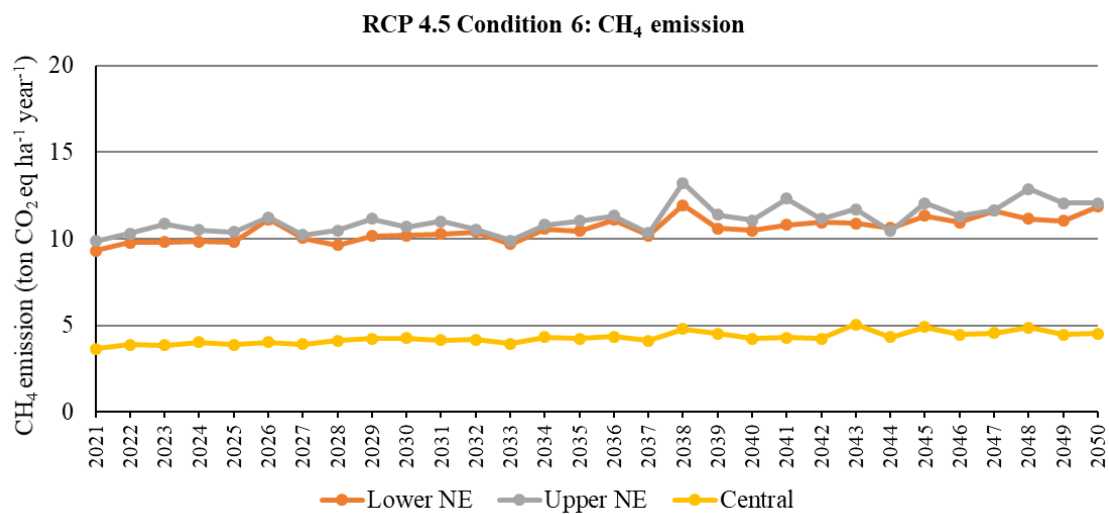
- d) A suitable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- e) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- f) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding



- g) A suitable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding

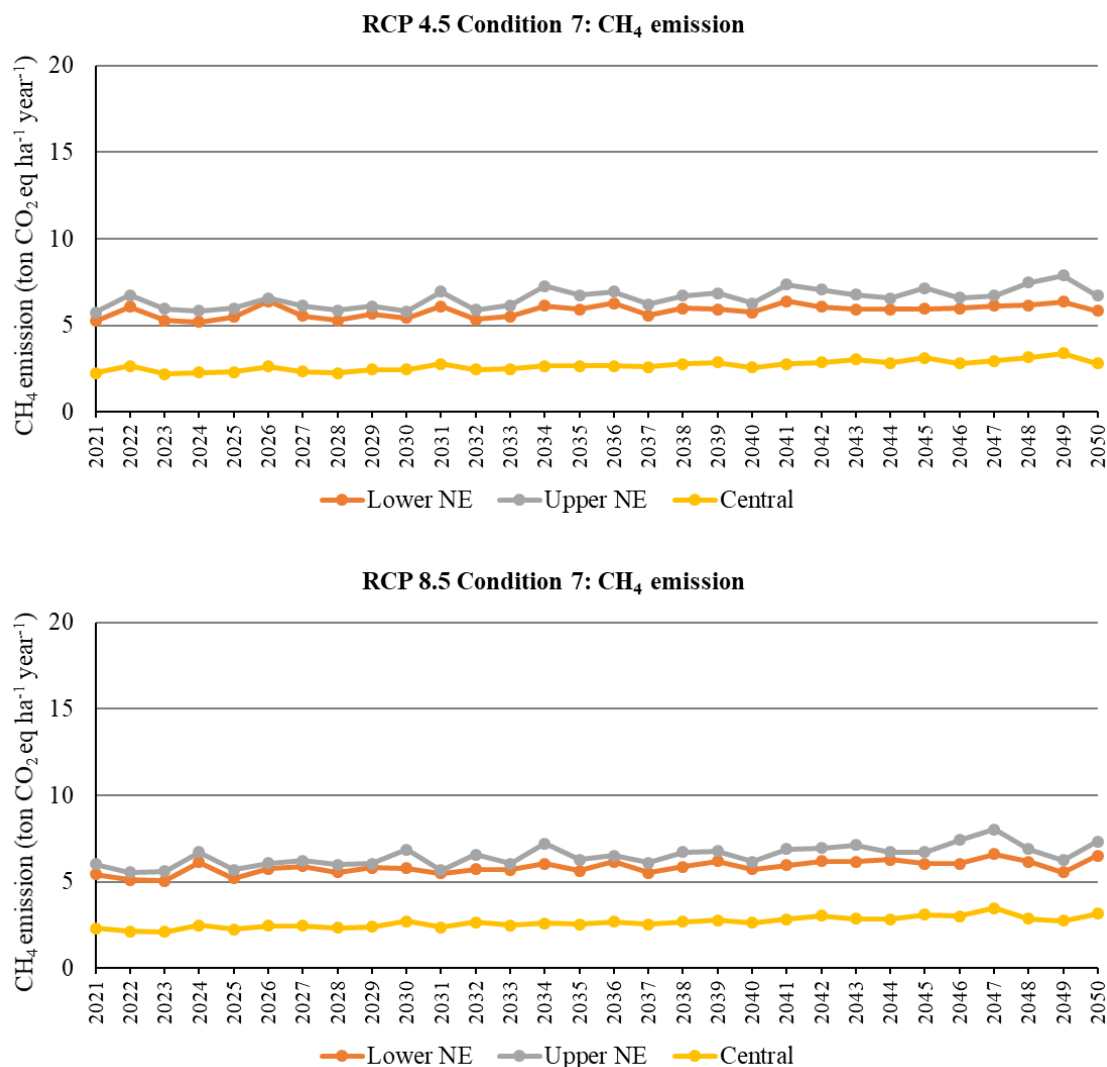
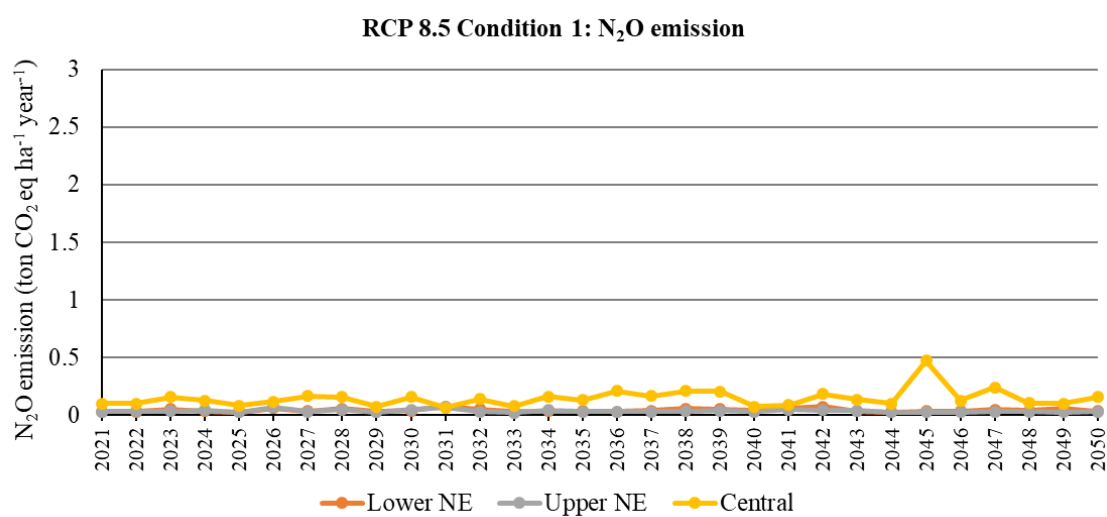
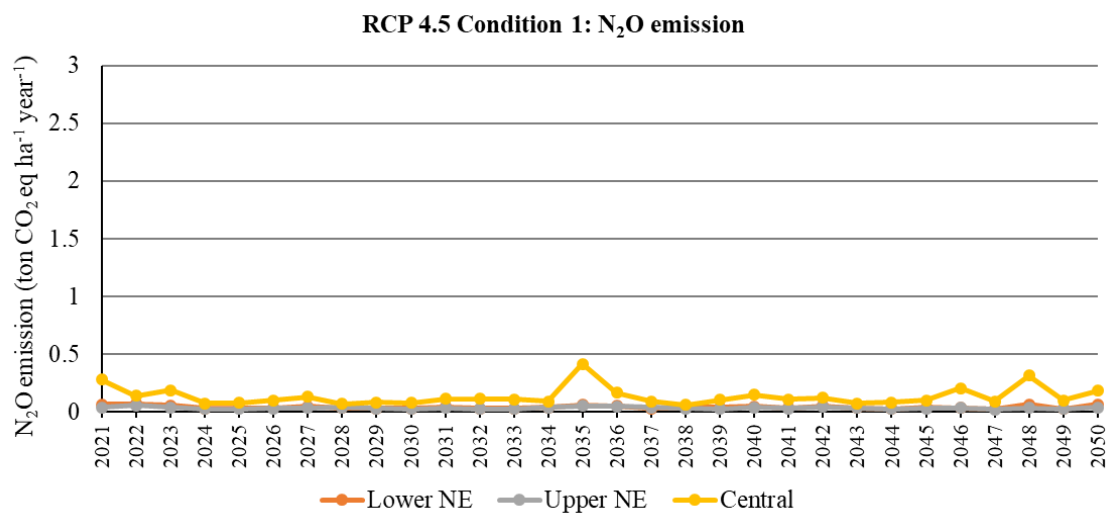


Figure 4.7 Annual CH₄ emissions from different rice practices over 2021-2050

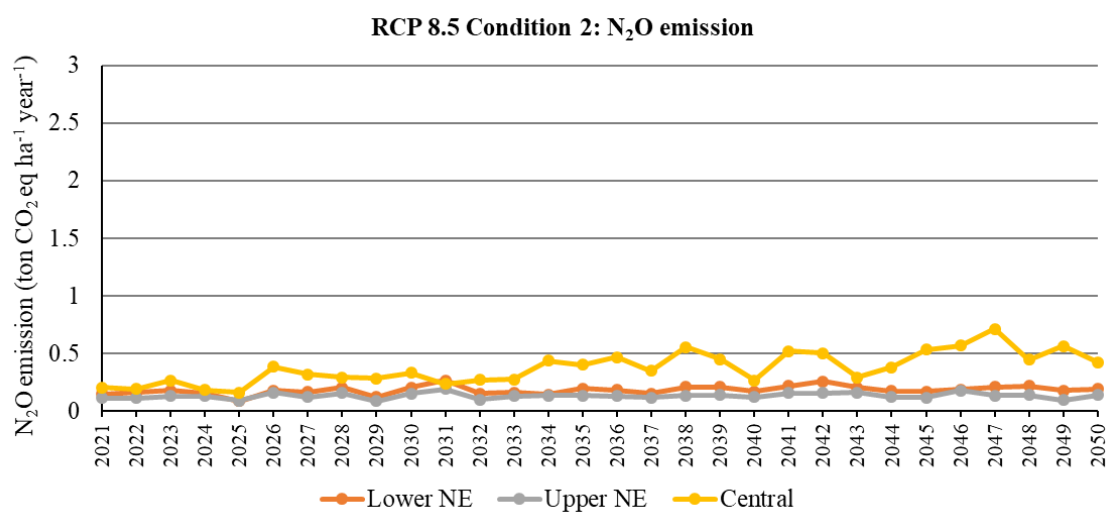
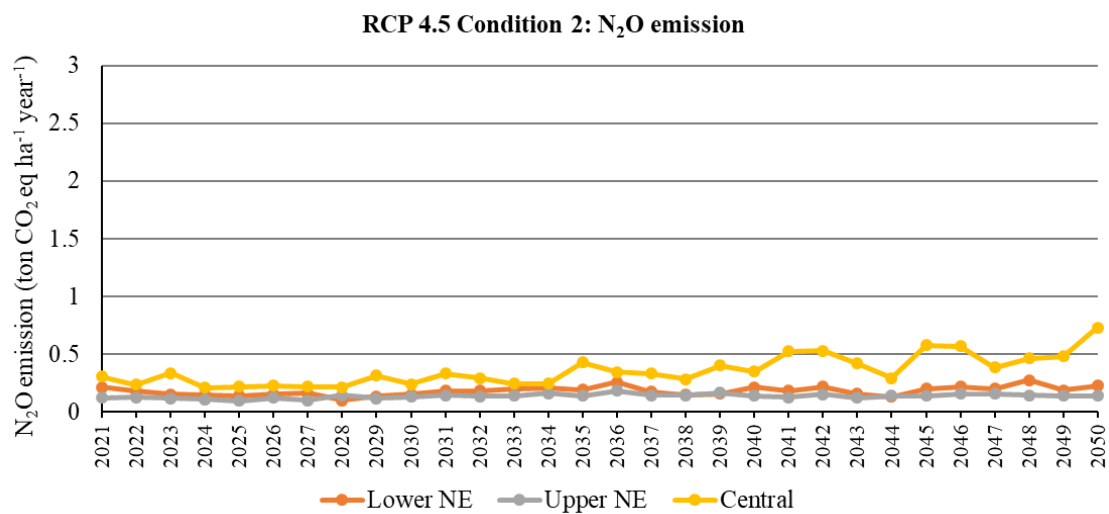
4) N₂O emissions from the rice fields under different rice field management practices and climate models

Annual N₂O emissions from conventional and suitable rice practice over 2021-2050 under different managements and different climate scenarios are shown in Figure 4.9. Despite variations in the climate scenarios of RCP 4.5 and 8.5, a study comparing annual N₂O emissions under the same conditions revealed similar emission patterns and values for both scenarios.

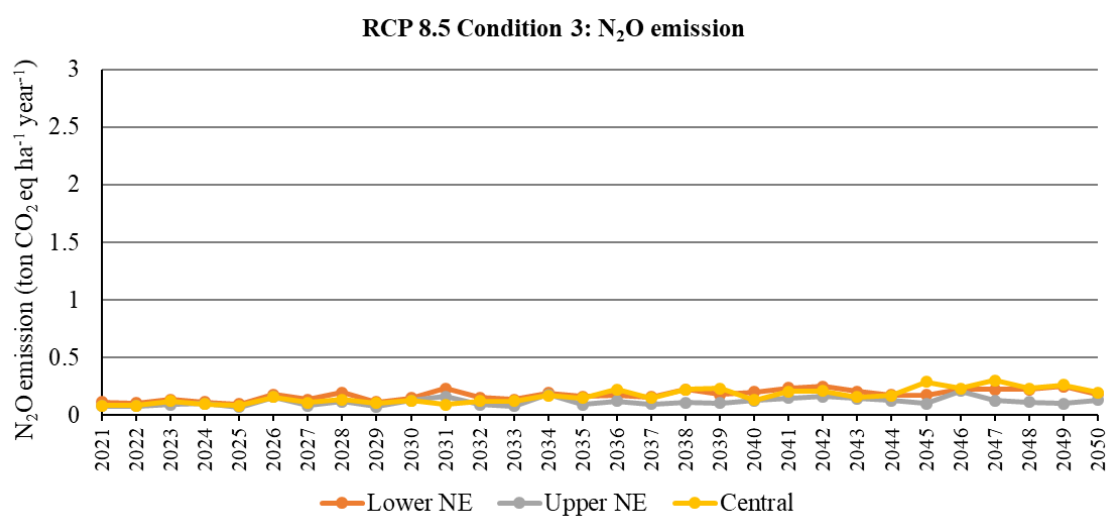
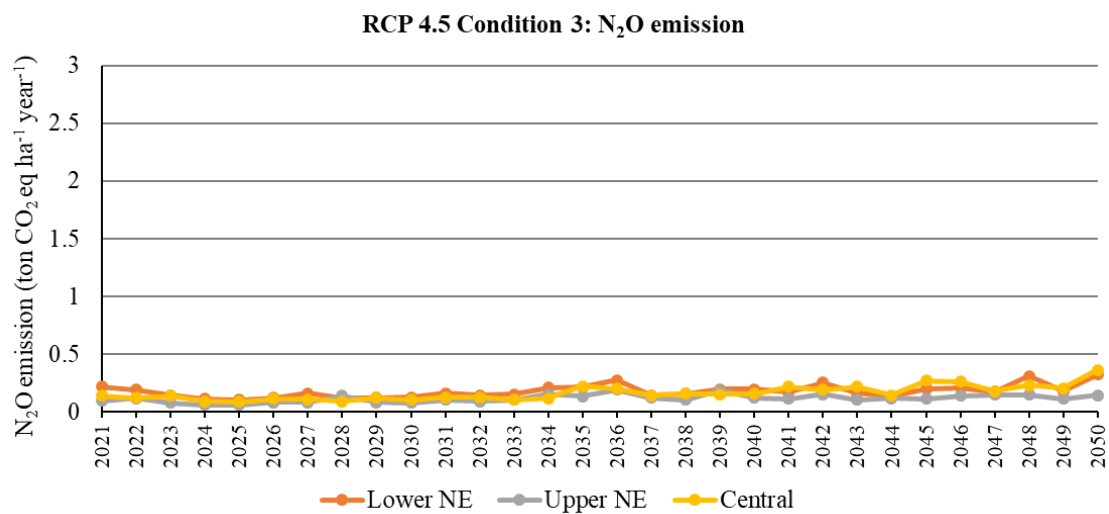
- a) A conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



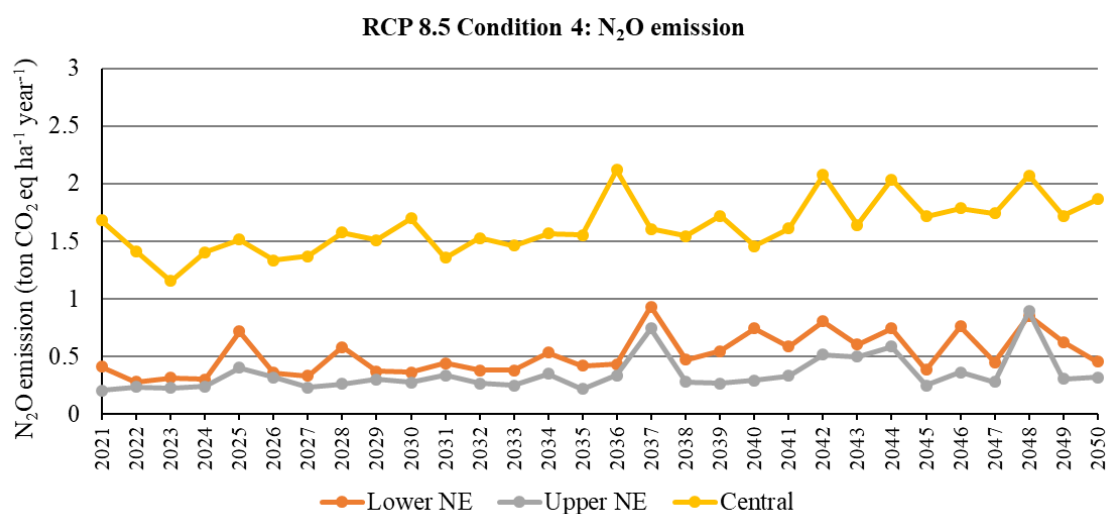
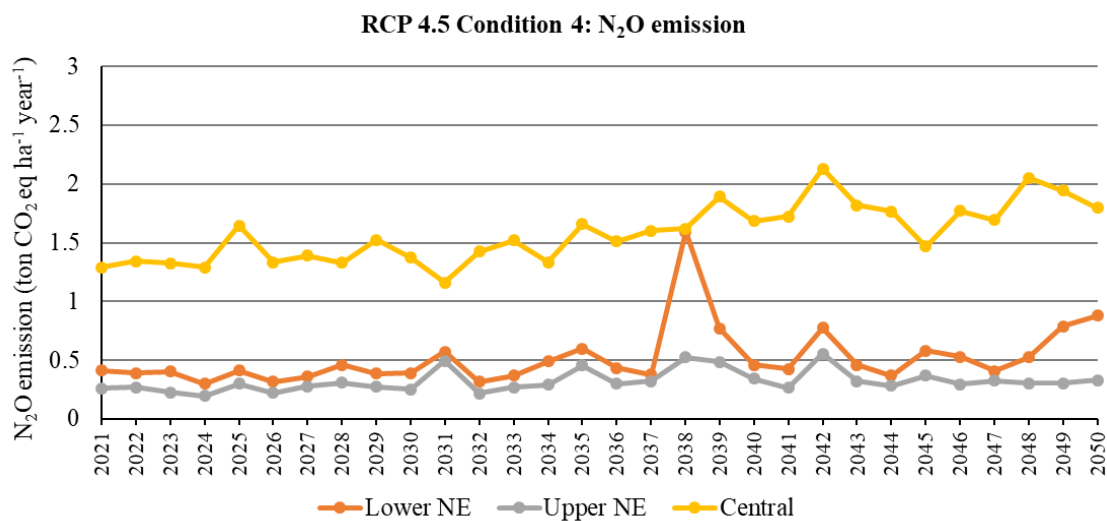
- b) A conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



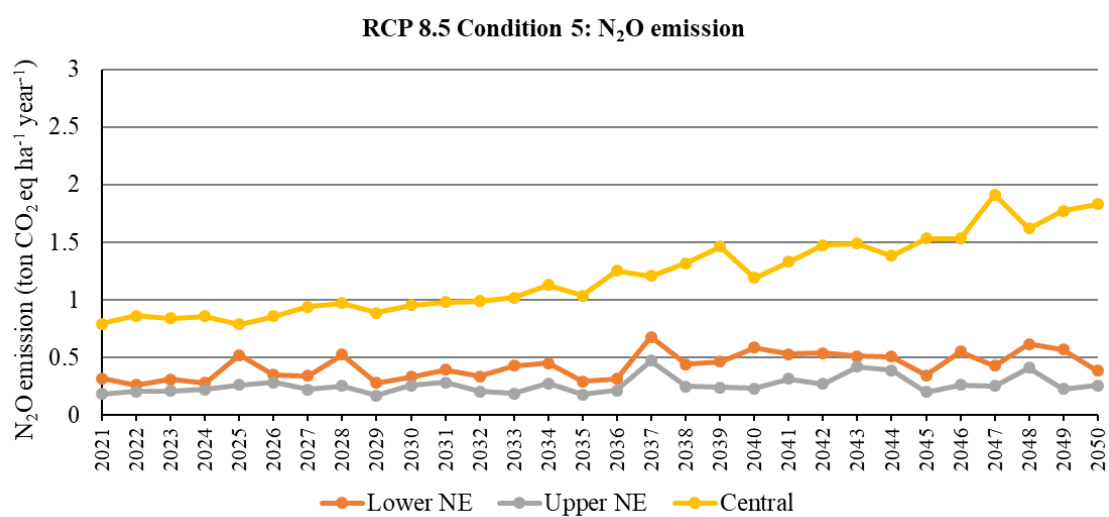
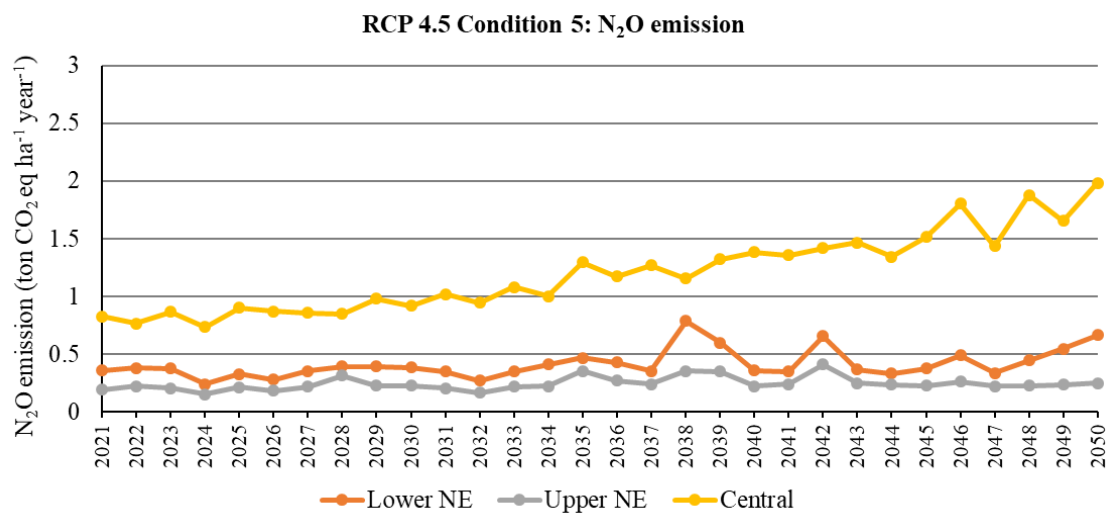
- c) A suitable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



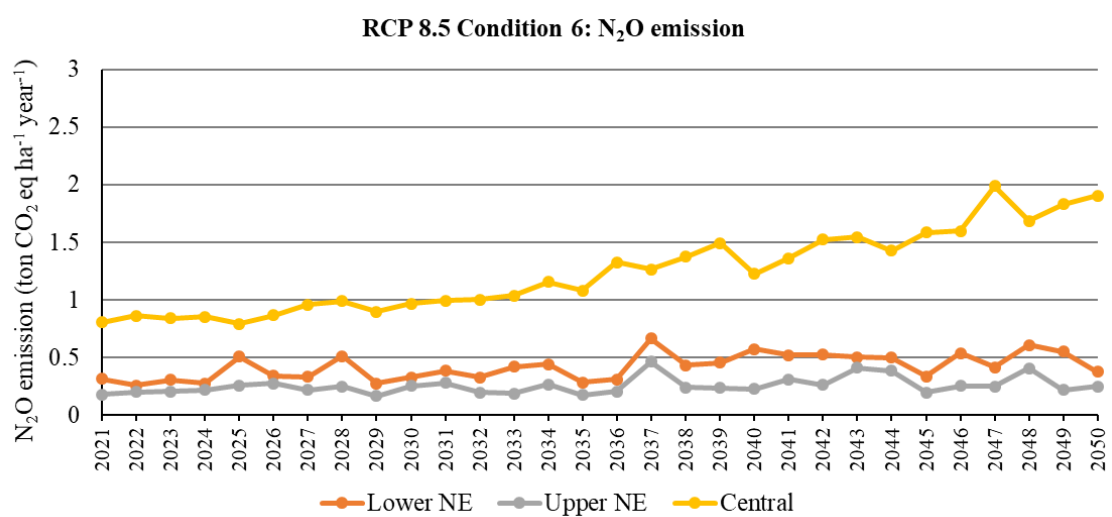
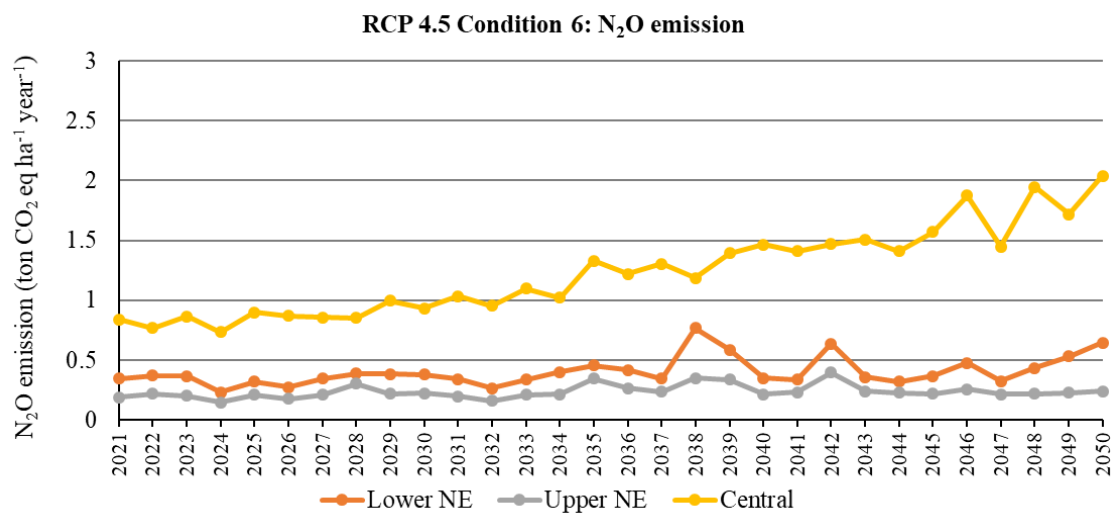
- d) A suitable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- e) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- f) A suitable rice practice with single rice cultivation, crop rotation with mung bean, unburnt crop residue, recommended fertilizer application, and continuous flooding



- g) A suitable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding

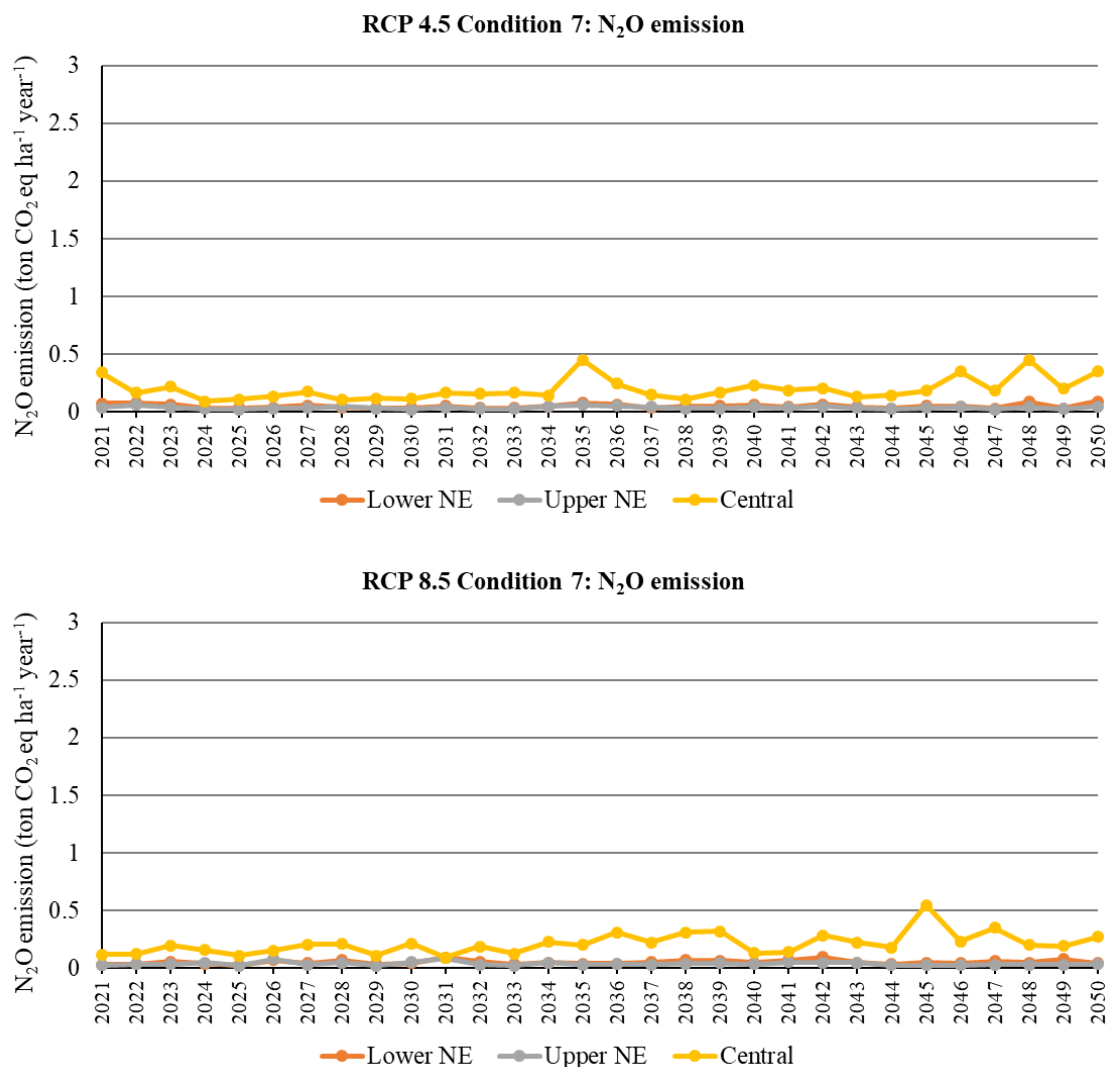
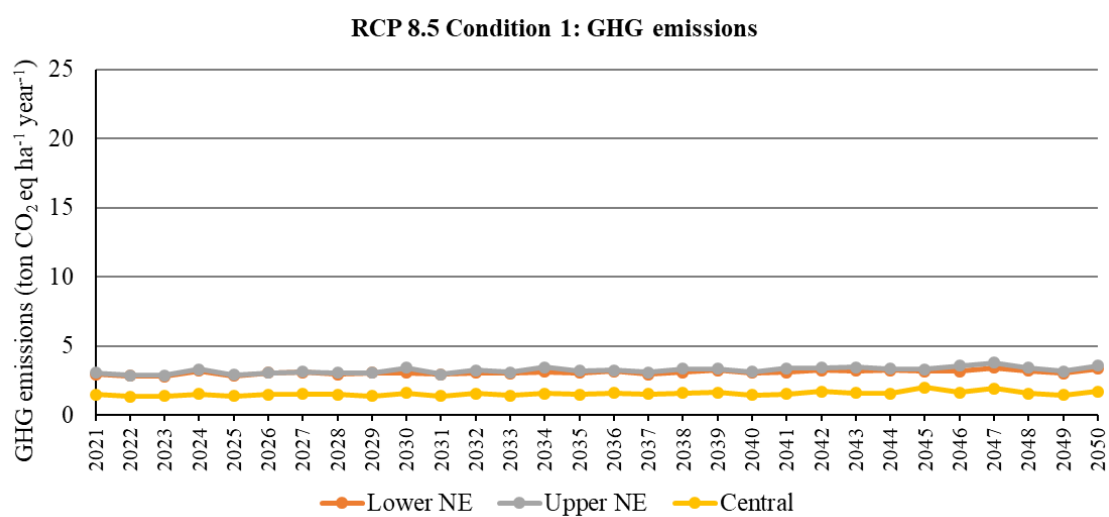
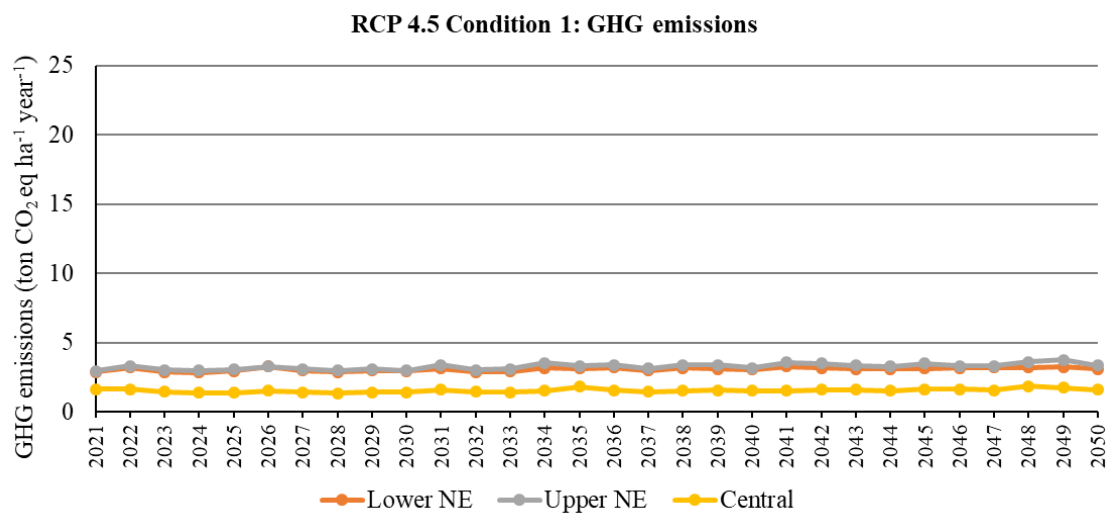


Figure 4.9 Annual N₂O emissions from different rice practices over 2021-2050

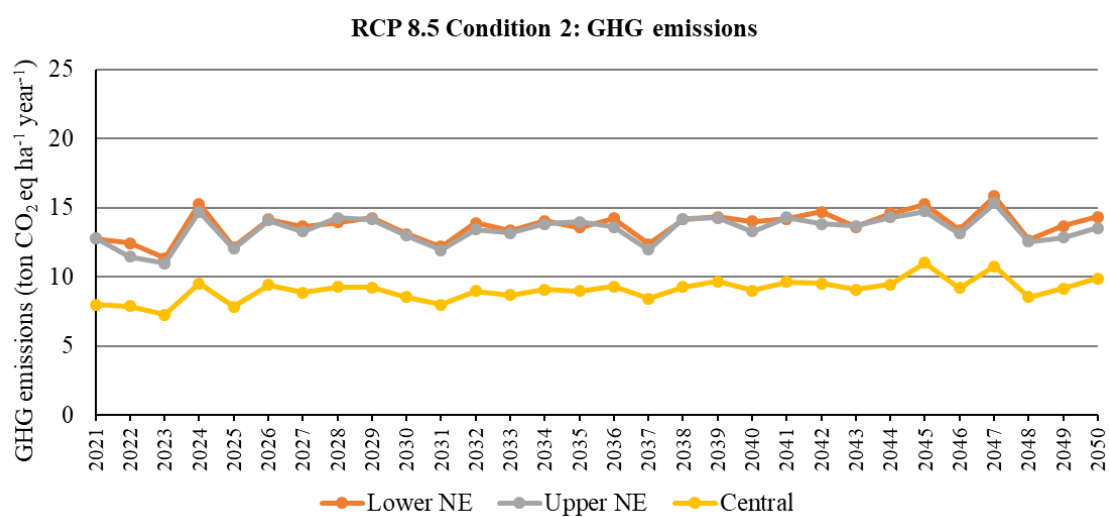
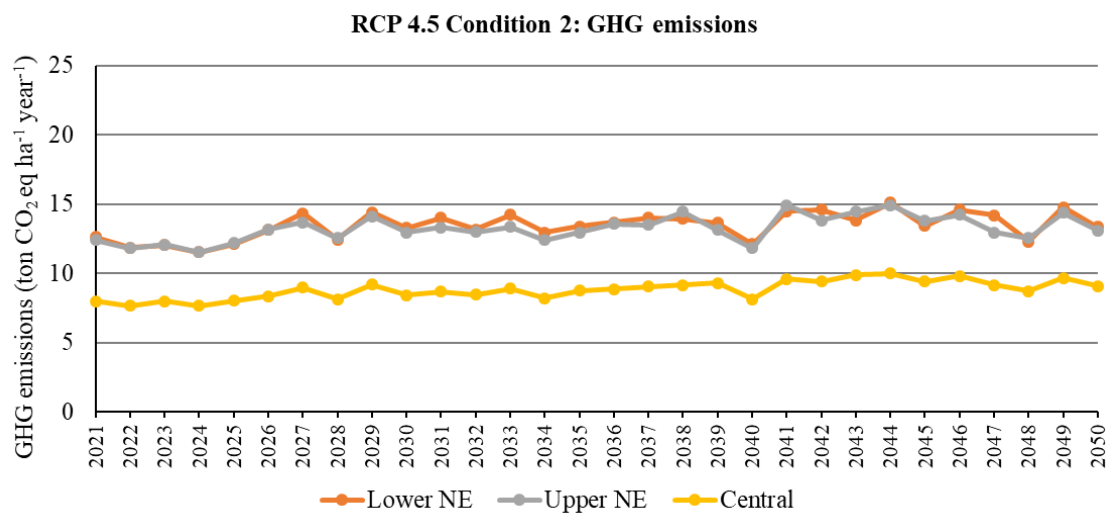
5) Total GHG emissions (CH₄ and N₂O emissions) from the rice fields under different rice field management practices and climate models

The study combines projected methane (CH₄) and nitrous oxide (N₂O) emissions to determine the total greenhouse gas (GHG) emissions. Since methane emissions are the primary contributors in rice fields, the overall GHG trend depicted in Figure 4.10 closely aligns with the projected CH₄ emission trend shown in Figure 4.7.

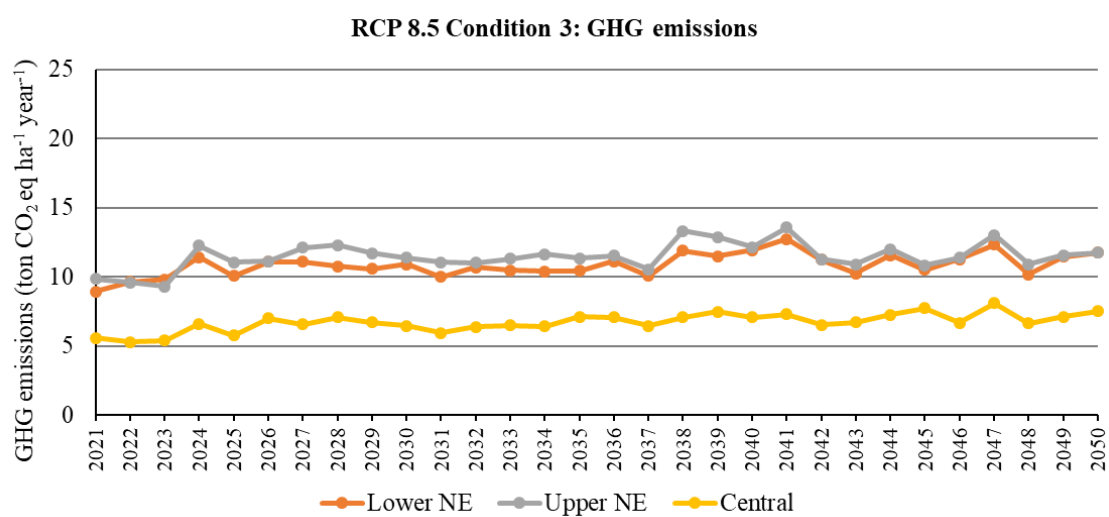
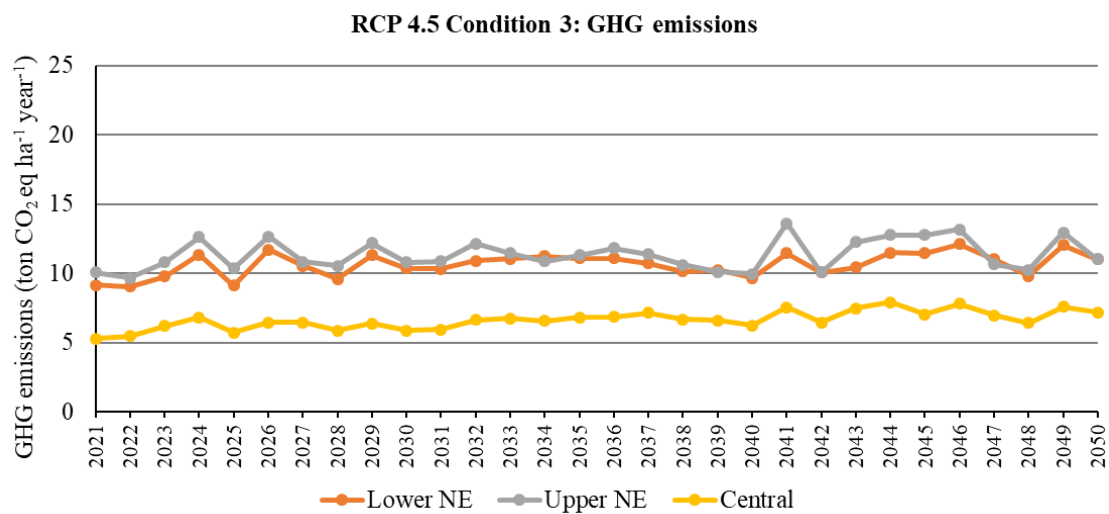
- a) A conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



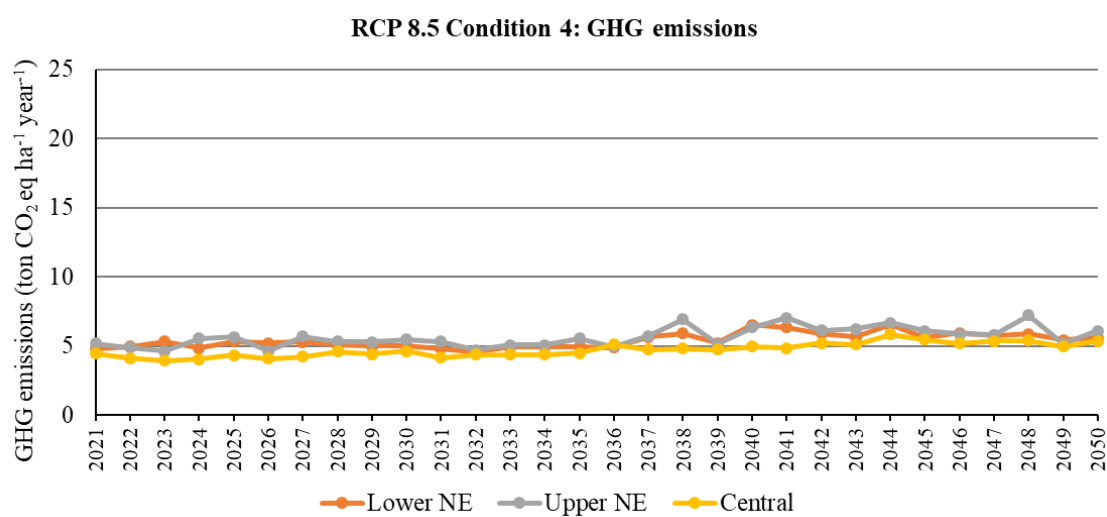
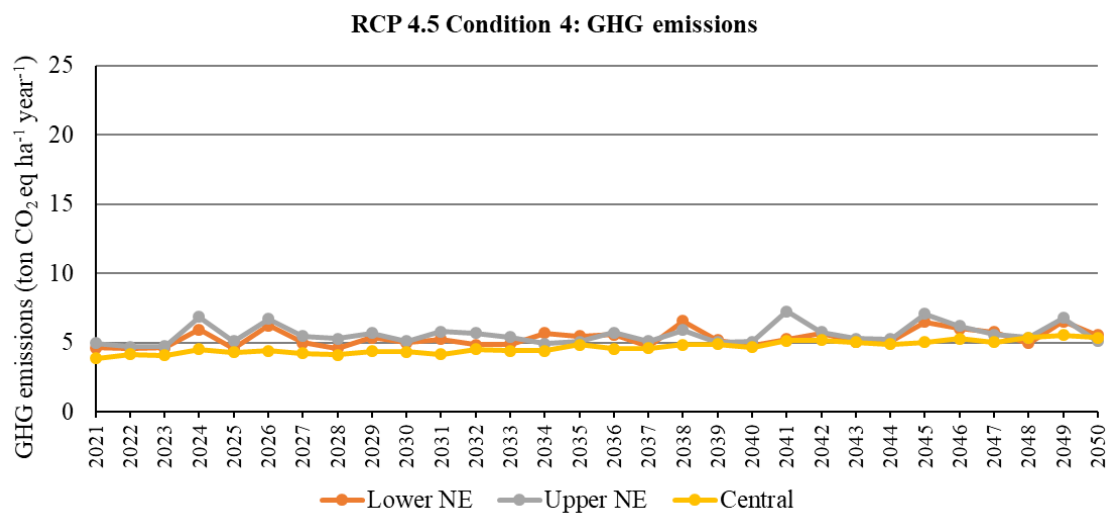
- b) A conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



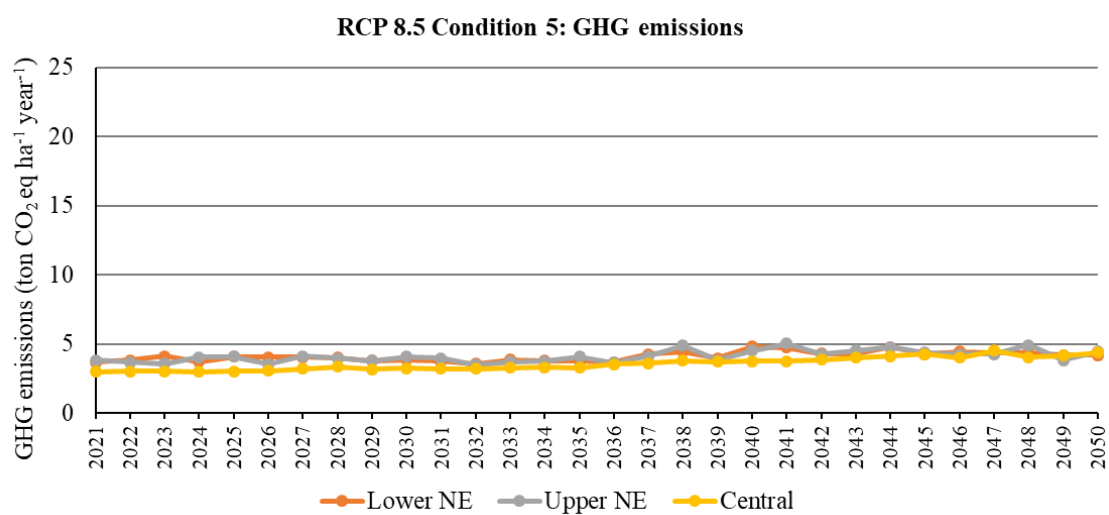
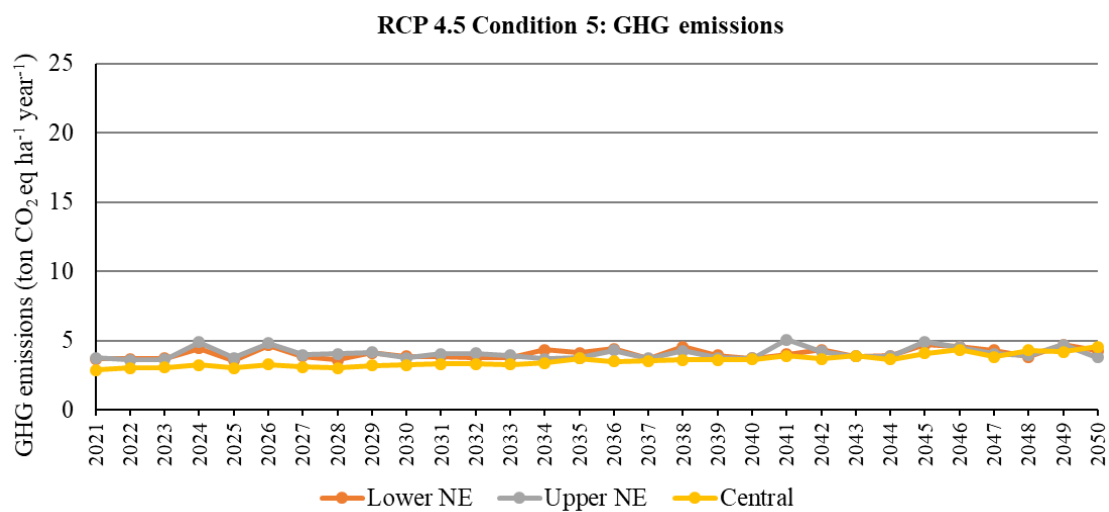
- c) A suitable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



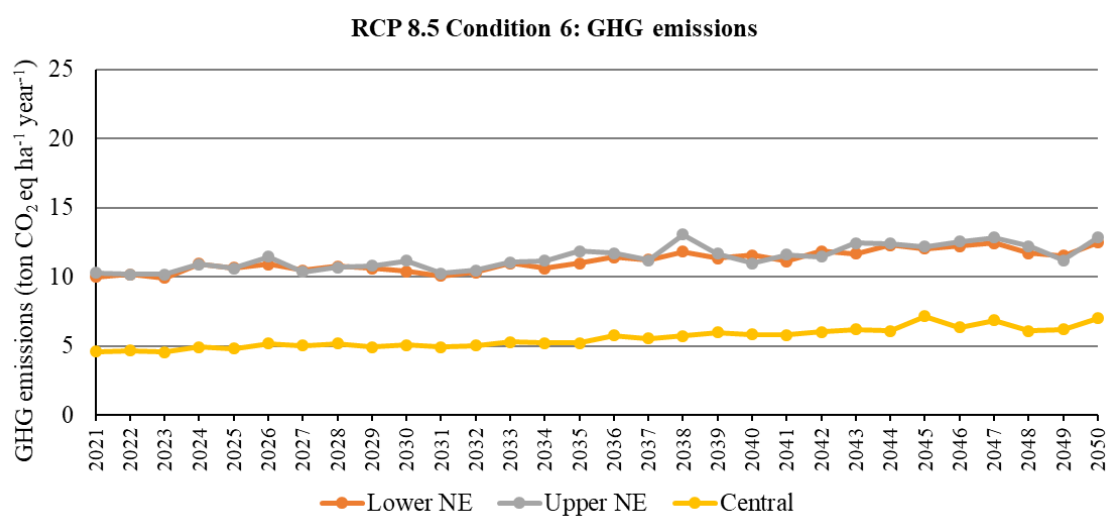
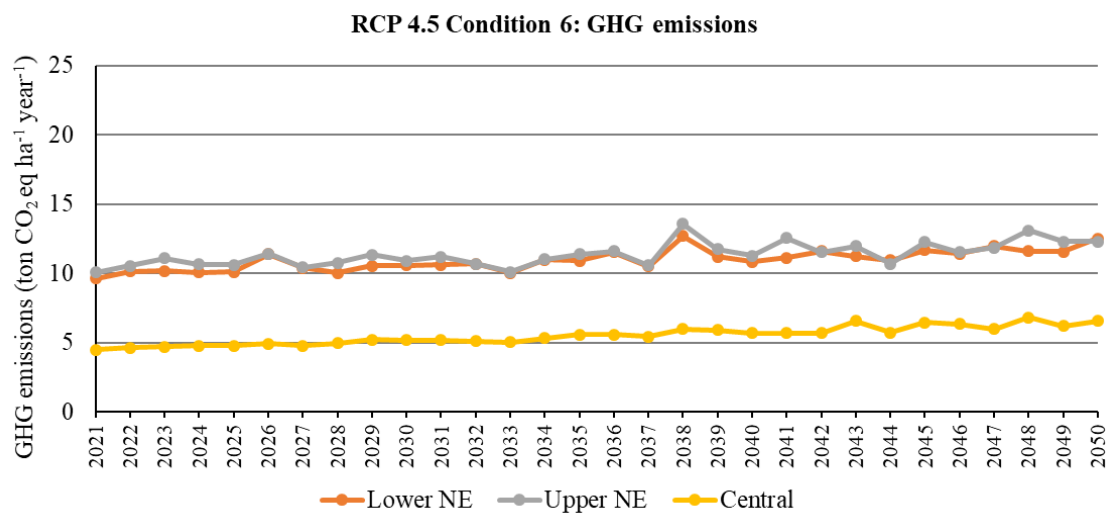
- d) A suitable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- e) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- f) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding



- g) A suitable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding

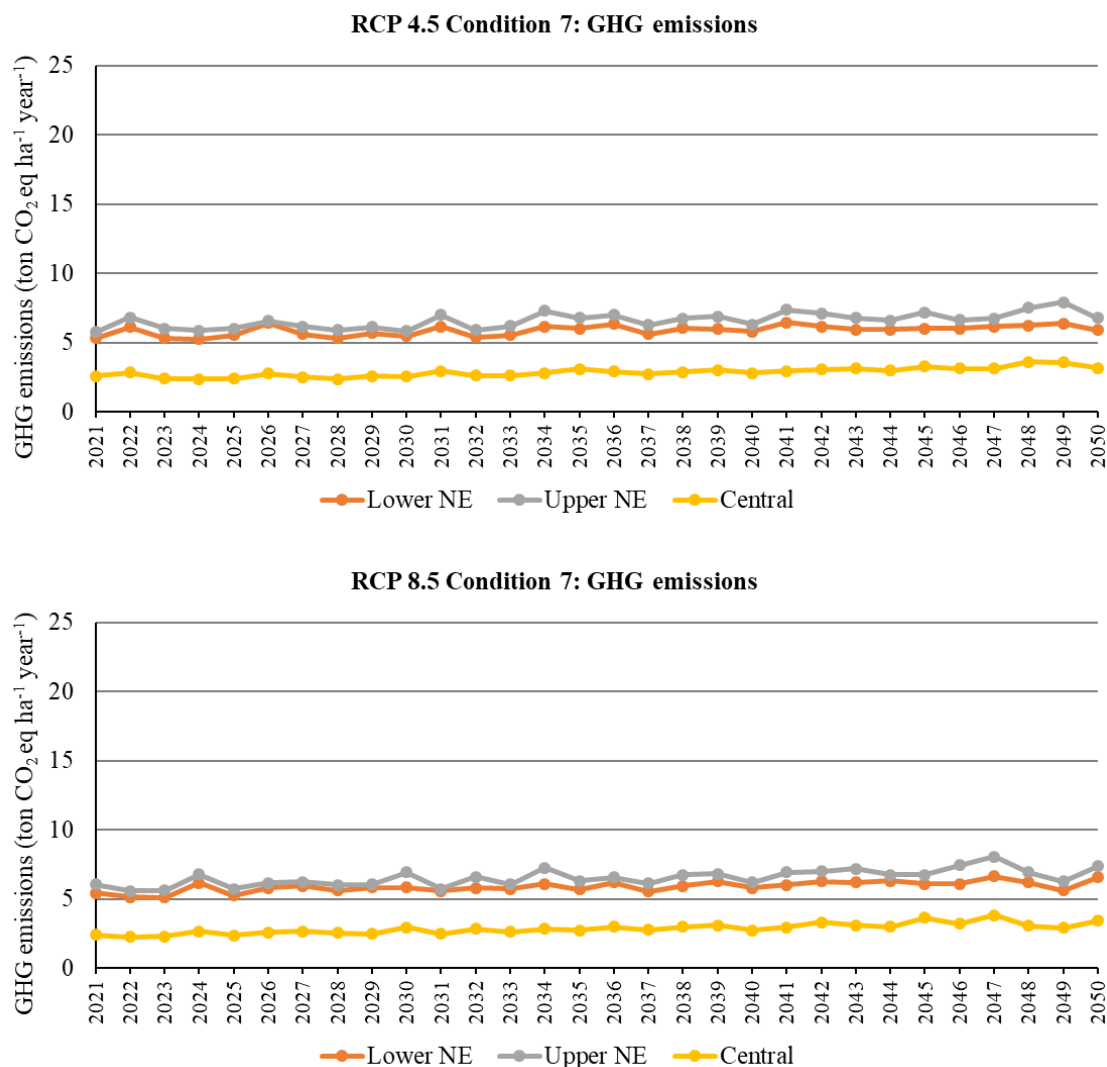
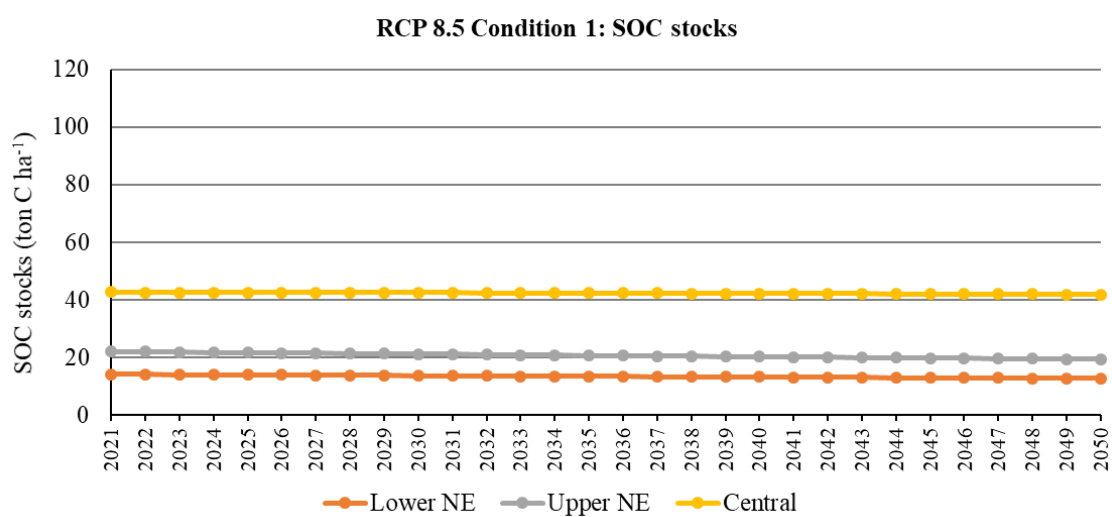
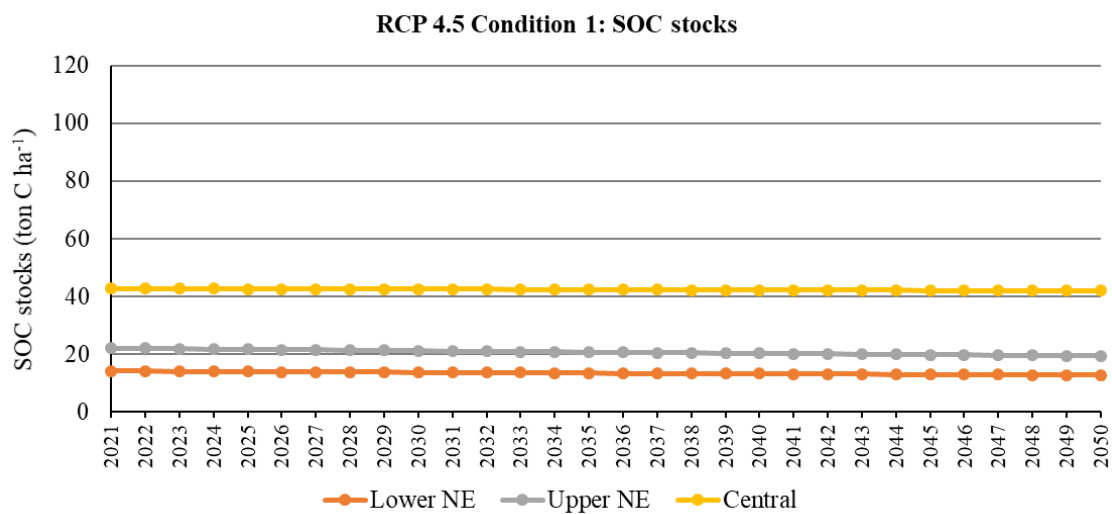


Figure 4.10 Annual total GHG emissions from different rice practices over 2021-2050

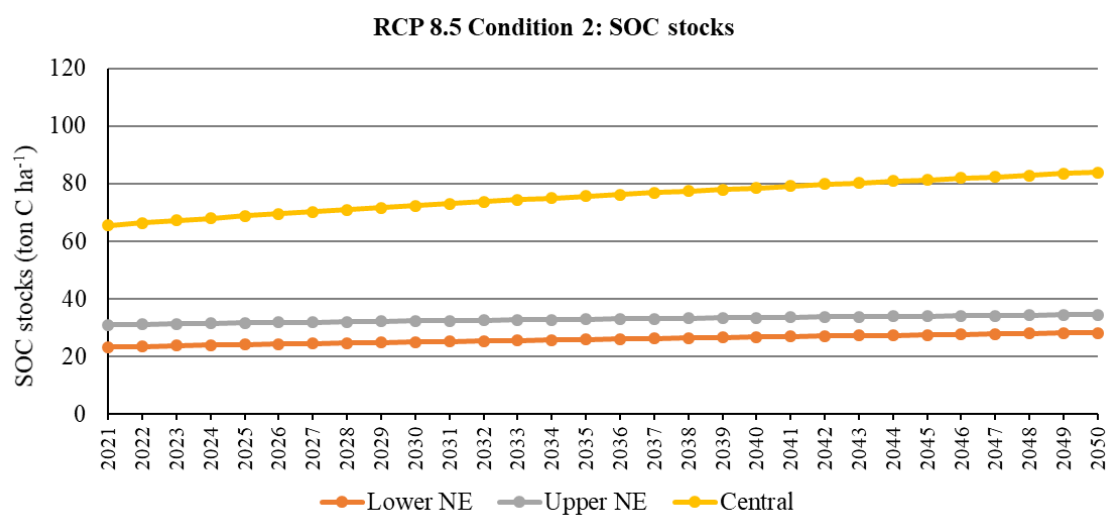
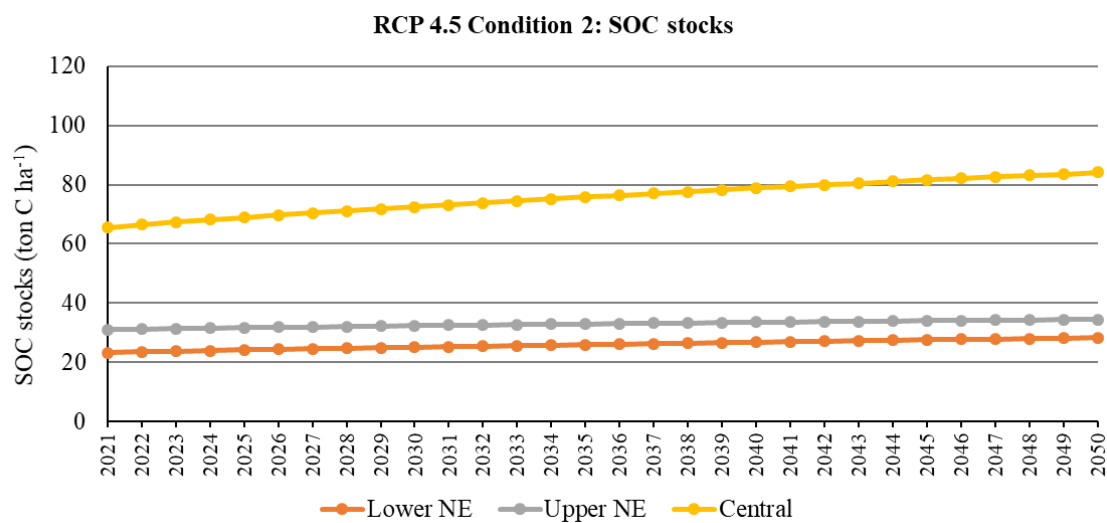
6) Long-term SOC stocks estimations under different rice field management practices and climate models

The soil organic carbon (SOC) stocks in the topsoil layer (0-30 cm depth) for all seven conditions, considering various climate scenarios, during the period from 2021 to 2050 are shown in Figure 4.11. The study indicates that under the same condition, annual SOC stocks under RCP 4.5 and 8.5 have similar ranges and patterns, despite differences in their climate scenarios.

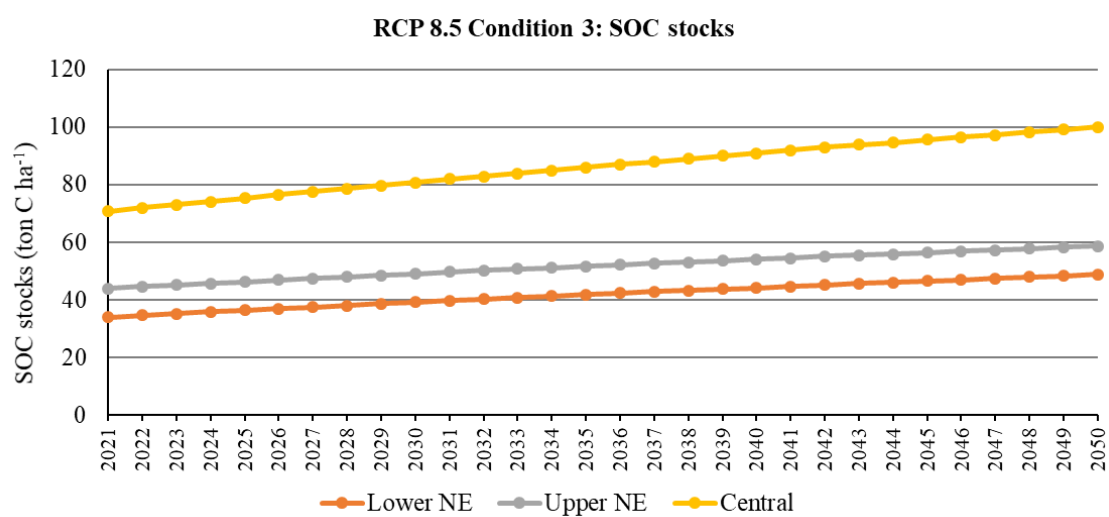
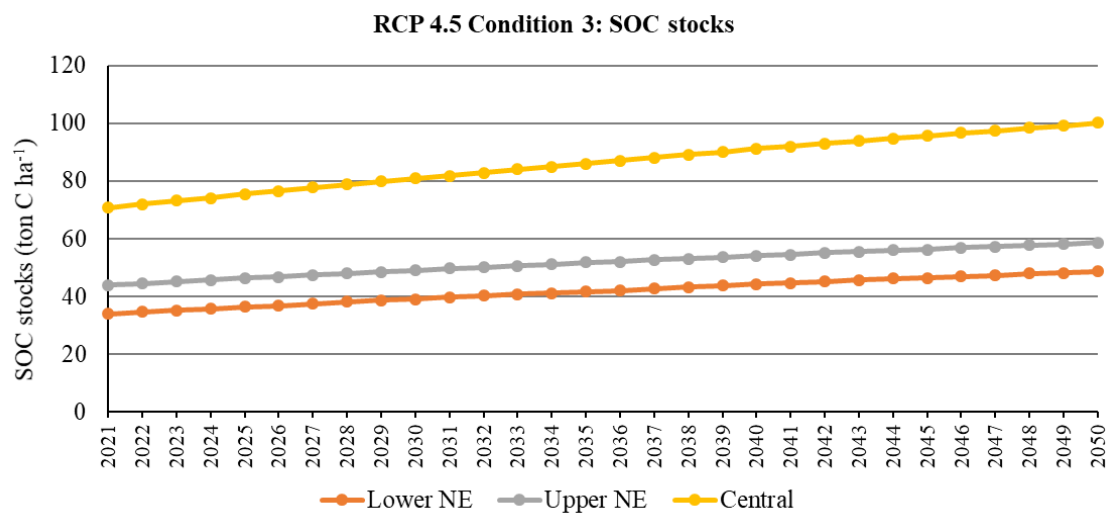
- a) A conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



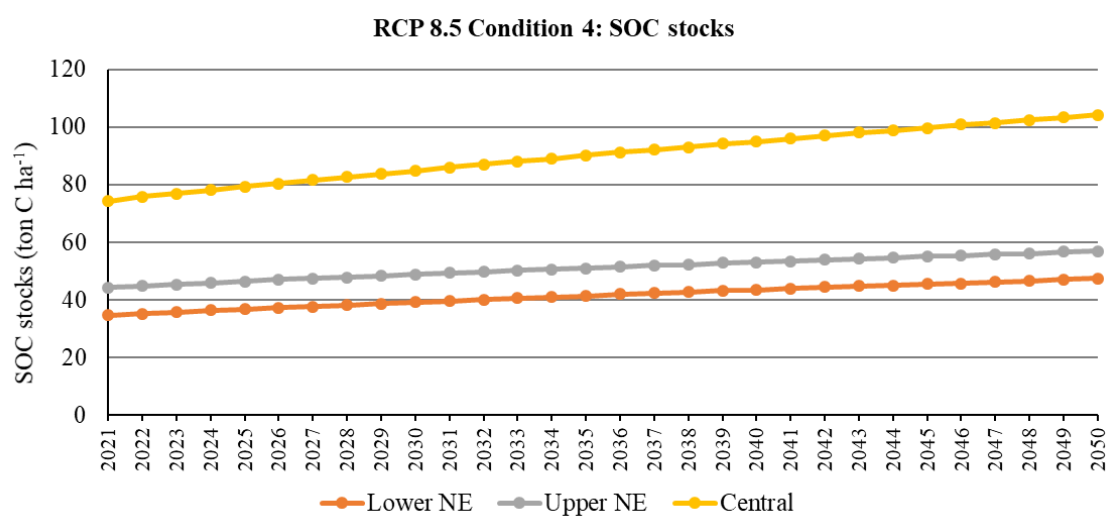
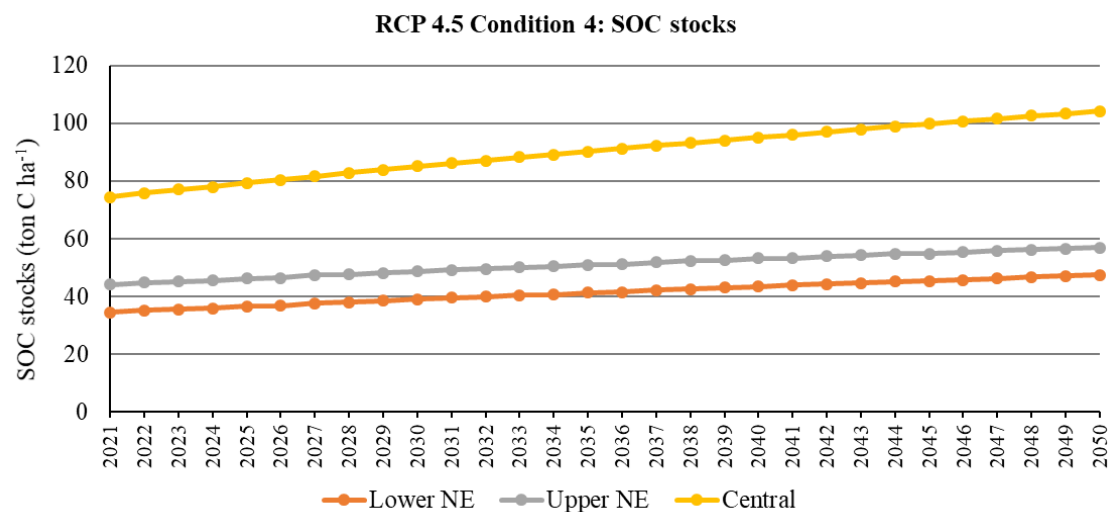
- b) A conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



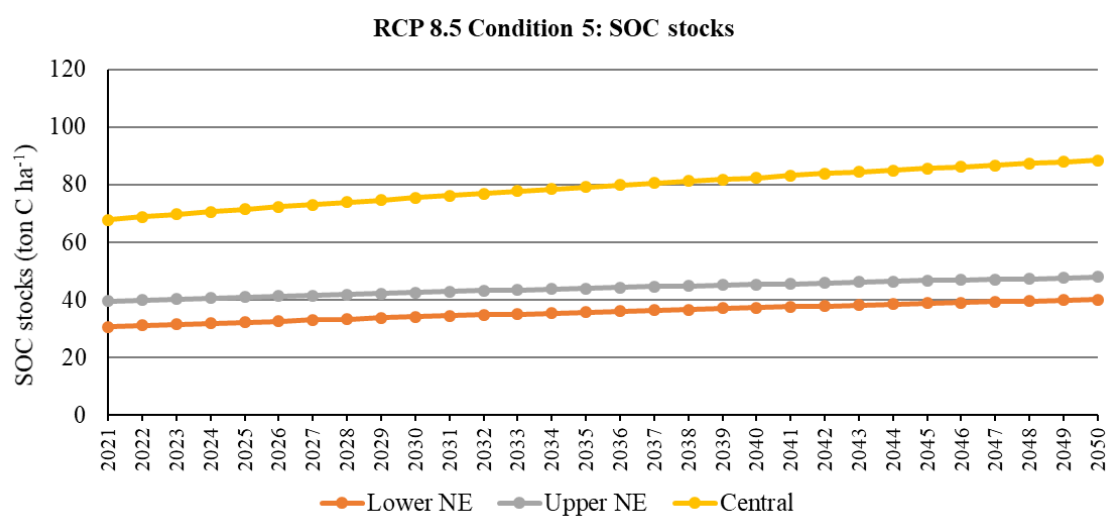
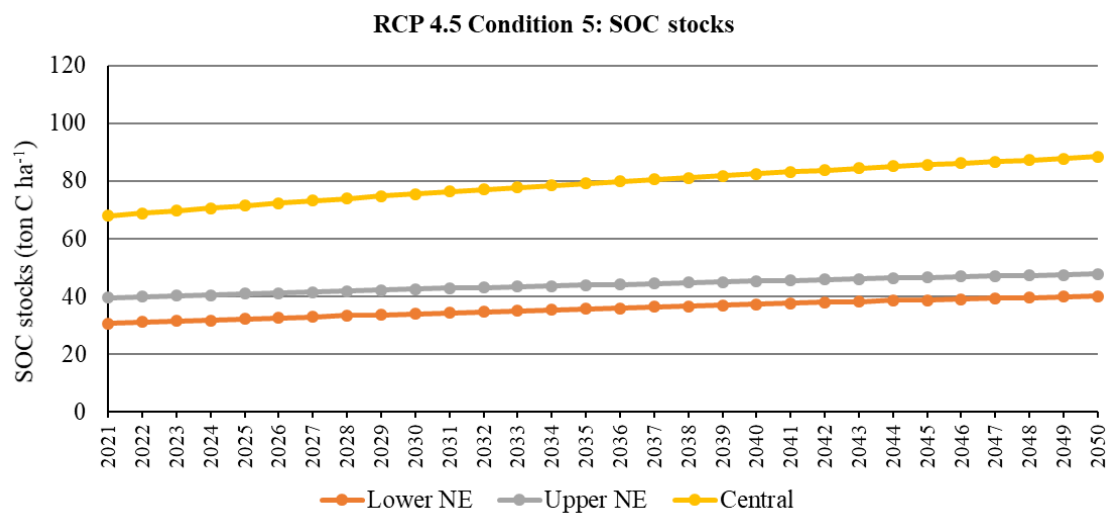
- c) A suitable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



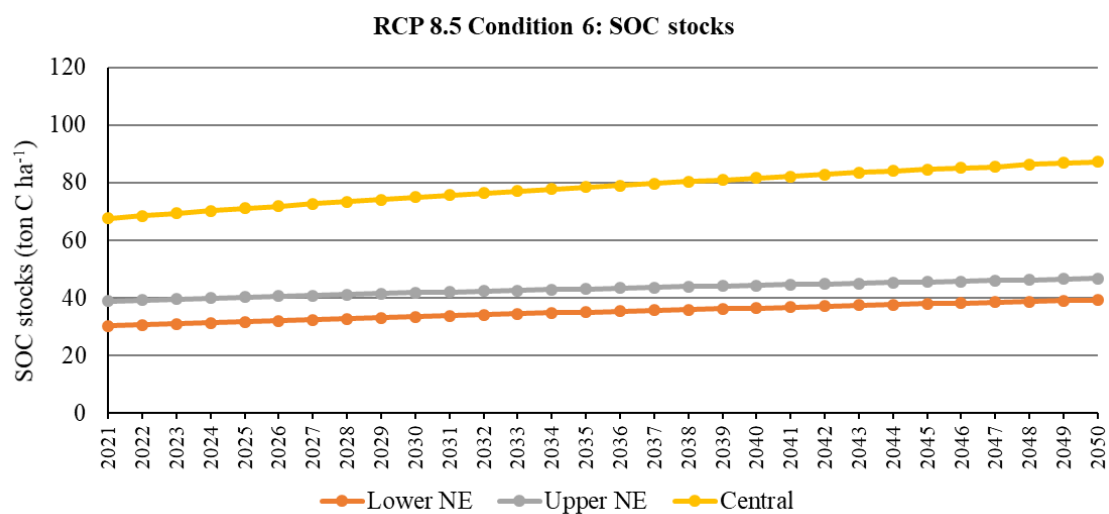
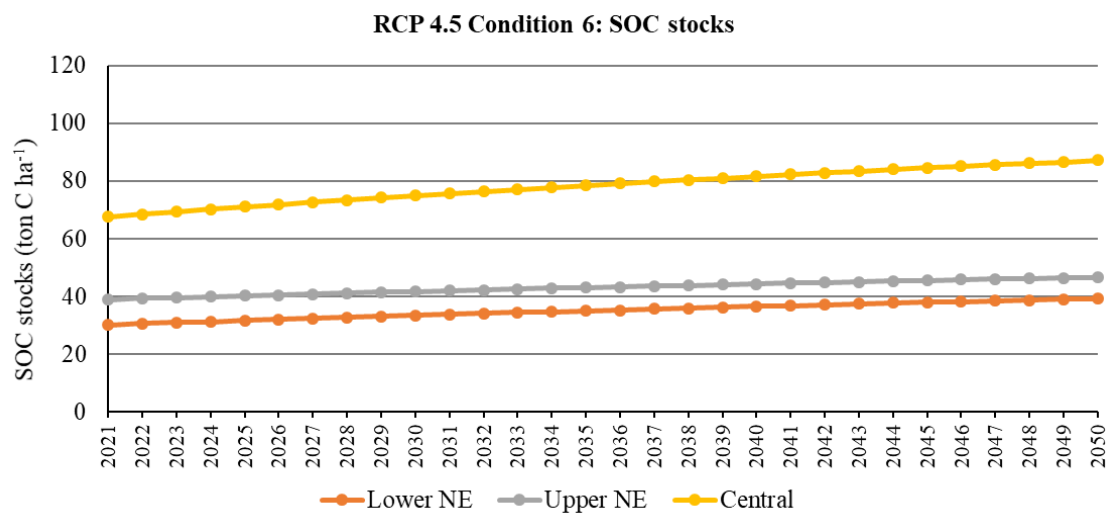
- d) A suitable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- e) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- f) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding



- g) A suitable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding

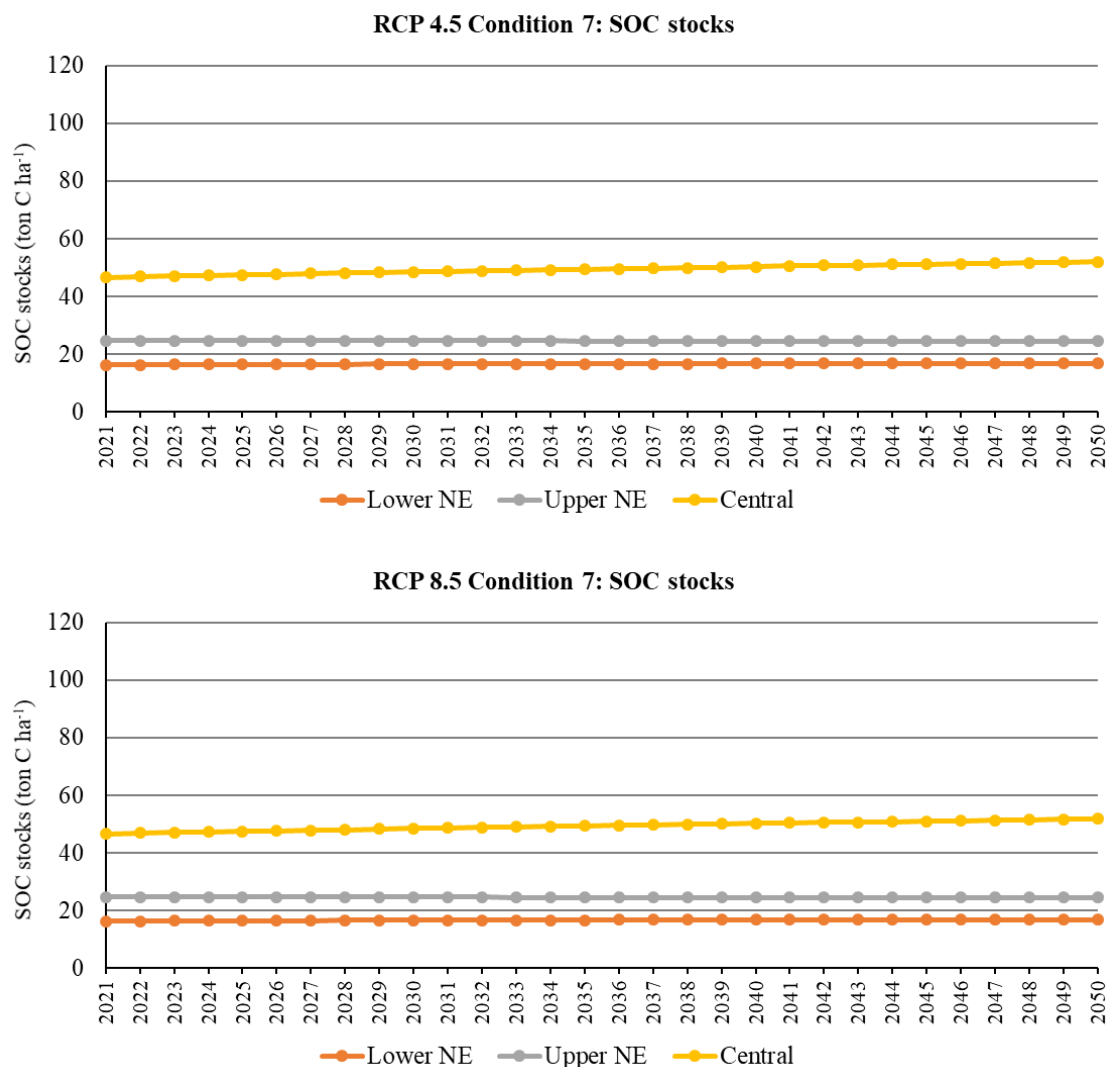
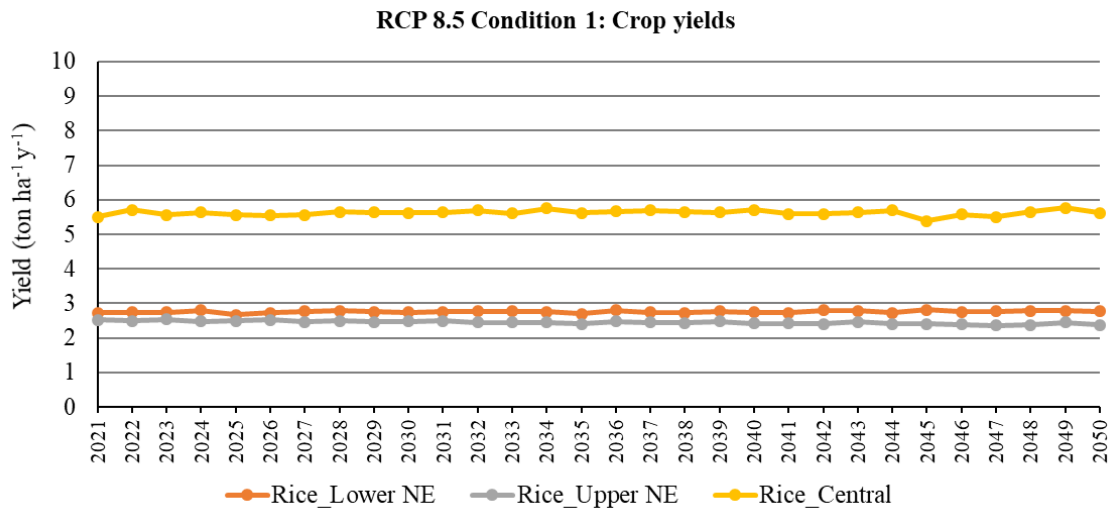
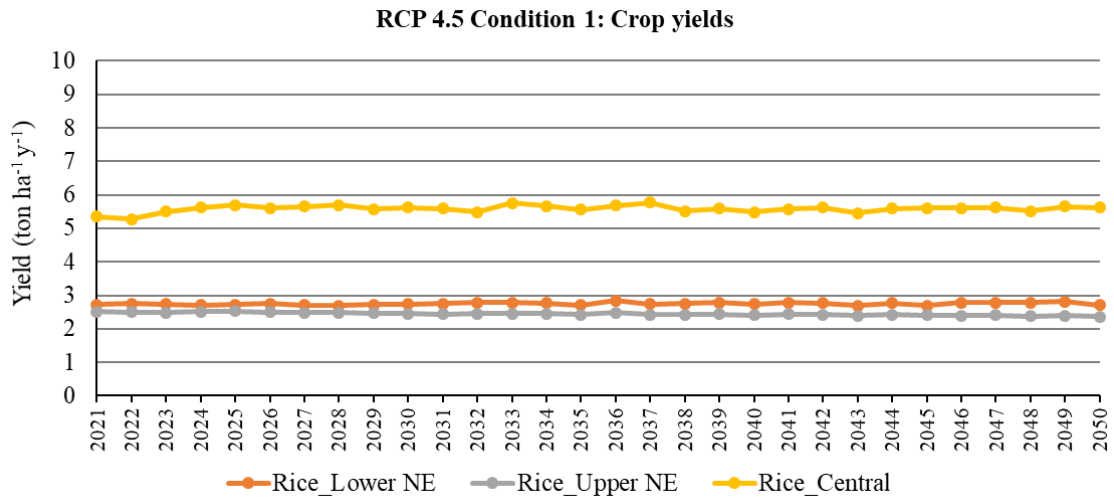


Figure 4.11 SOC stocks of topsoil (0-30 cm in depth) from different rice practices over 2021-2050

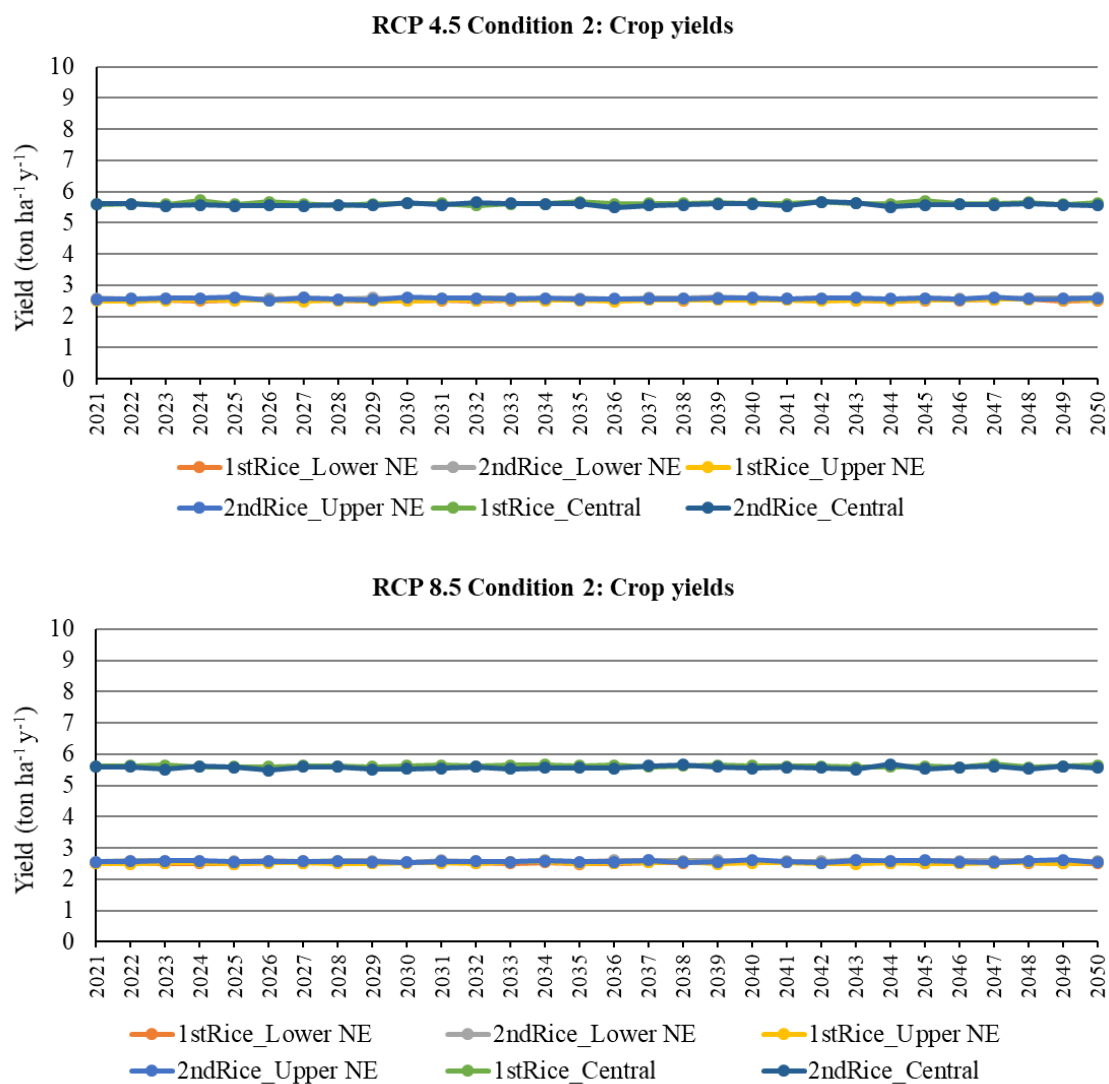
7) *Rice, maize, and mung bean yields estimations under different field management practices and different climate scenarios*

The annual yields from different rice practices under various climate scenarios from 2021 to 2050 are shown in Figure 4.12. The study reveals that, despite variations in their climate scenarios, annual crop yields under both RCP 4.5 and 8.5 exhibit similar ranges and patterns when applied to the same conditions.

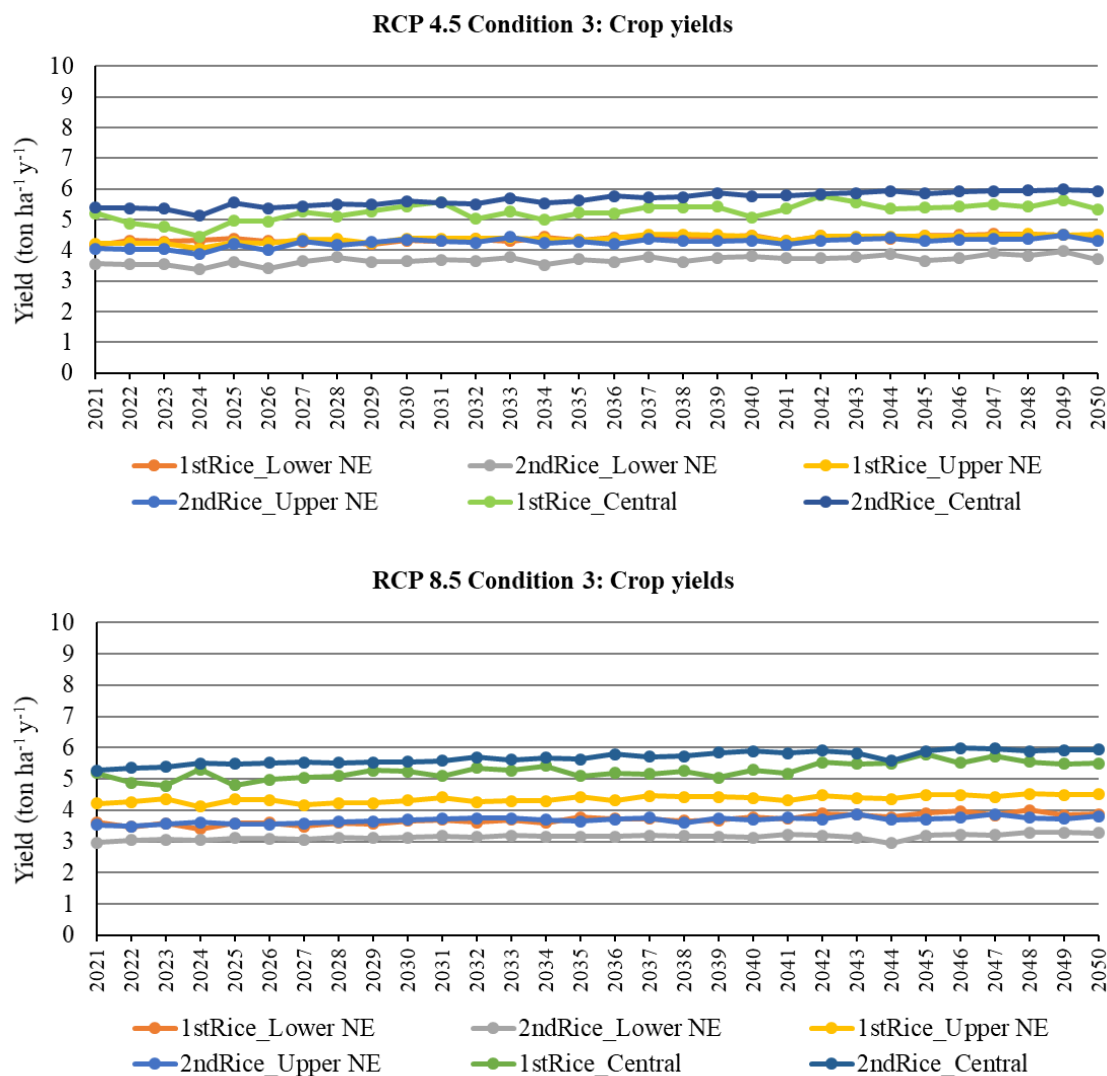
- a) A conventional practice with single rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



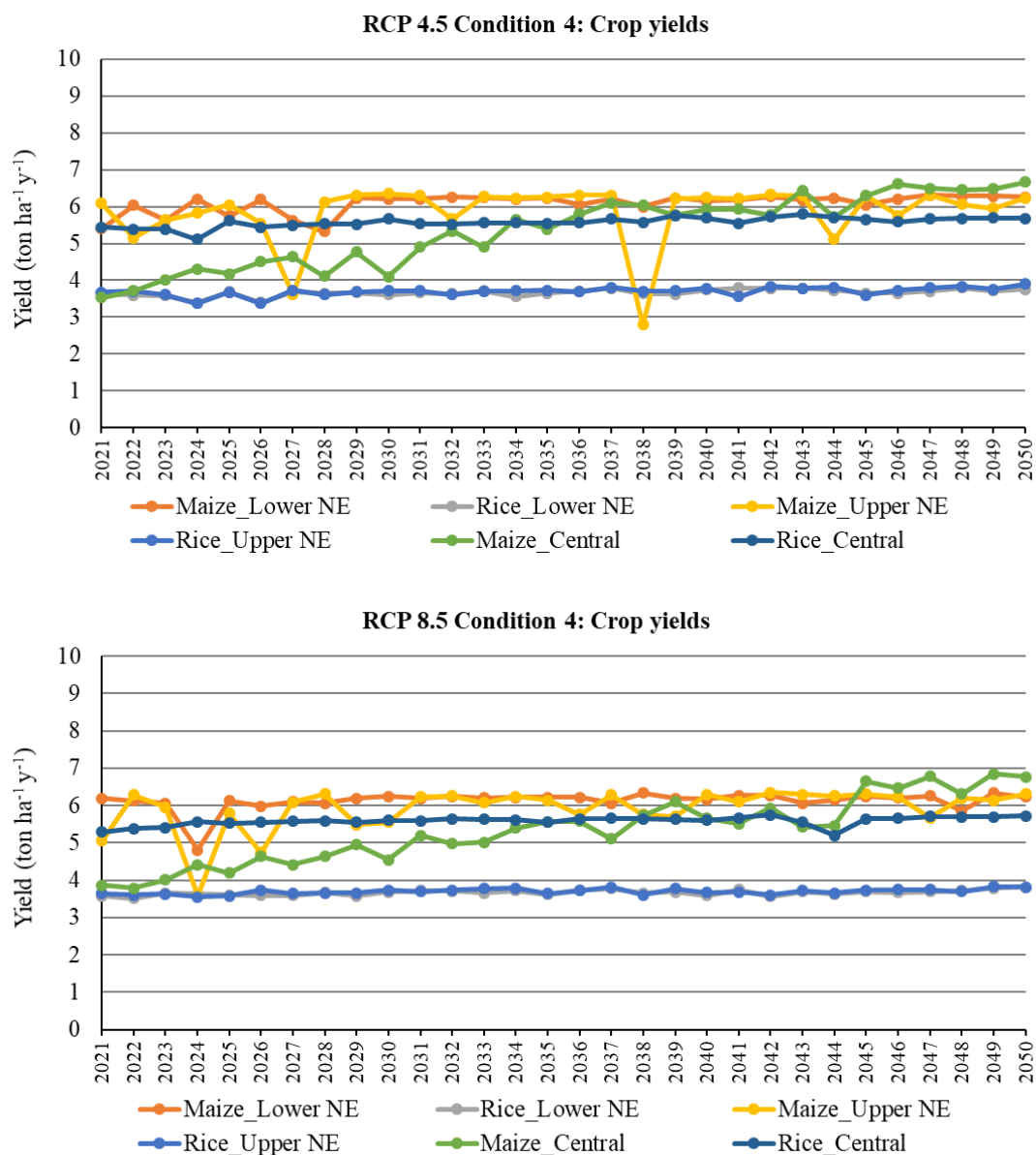
- b) A conventional practice with double rice cultivation, burnt crop residue, chemical fertilizer application, and continuous flooding



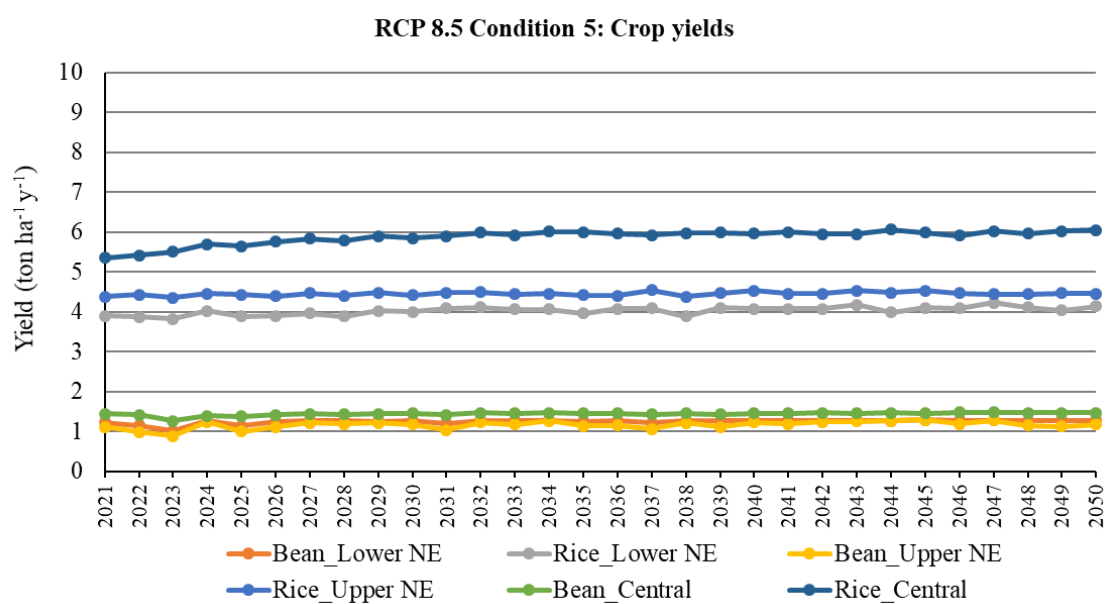
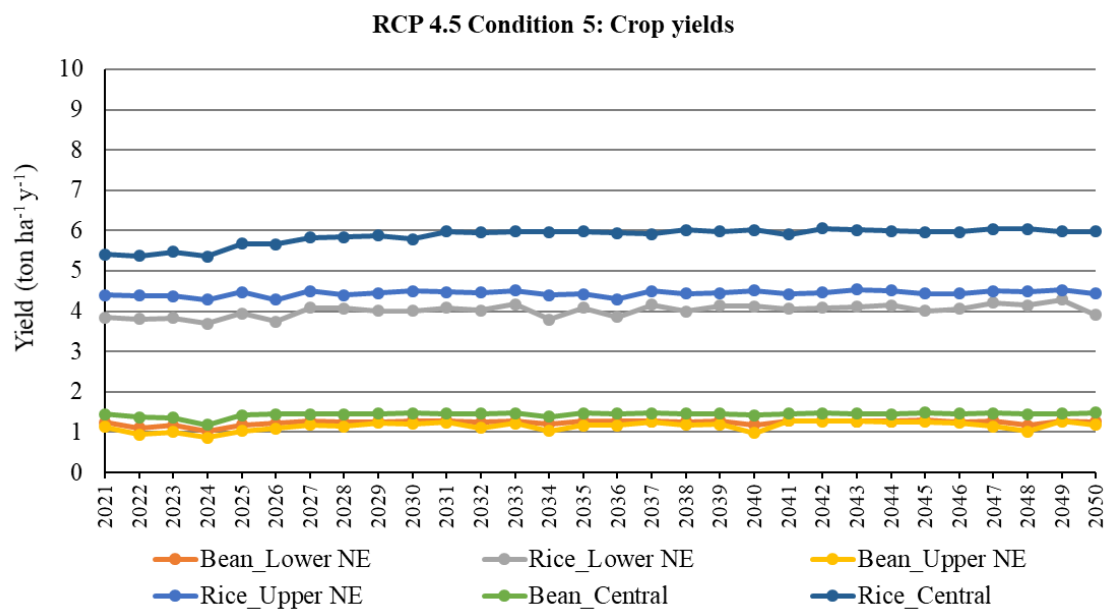
- c) A suitable rice practice with double rice cultivation, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



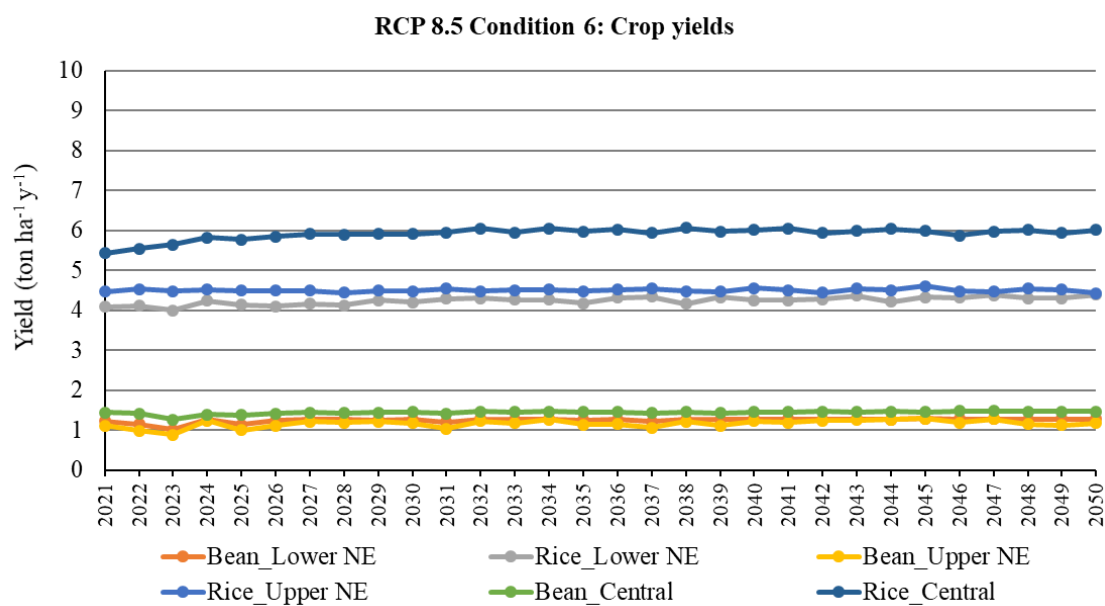
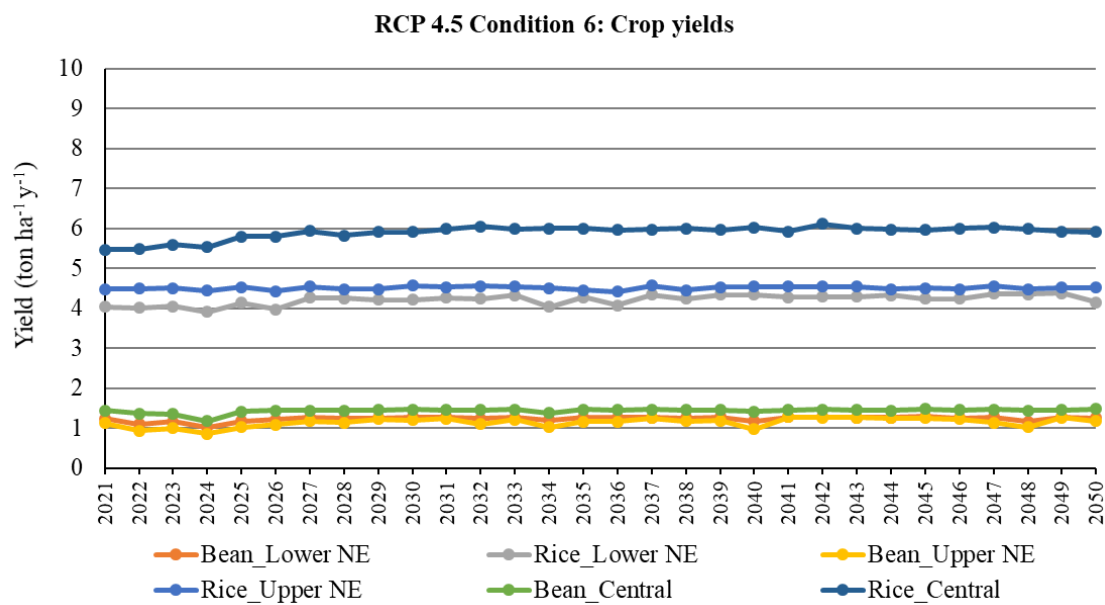
- d) A suitable rice practice with single rice cultivation, crop rotation with maize, un-burnt crop residue, recommended fertilizer application, and alternate wet and dry irrigation



- e) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer applicati, z alternate wet and dry irrigation



- f) A suitable rice practice with single rice cultivation, crop rotation with mung bean, un-burnt crop residue, recommended fertilizer application, and continuous flooding



- g) A suitable rice practice with single rice cultivation, un-burnt crop residue, recommended fertilizer application, and continuous flooding

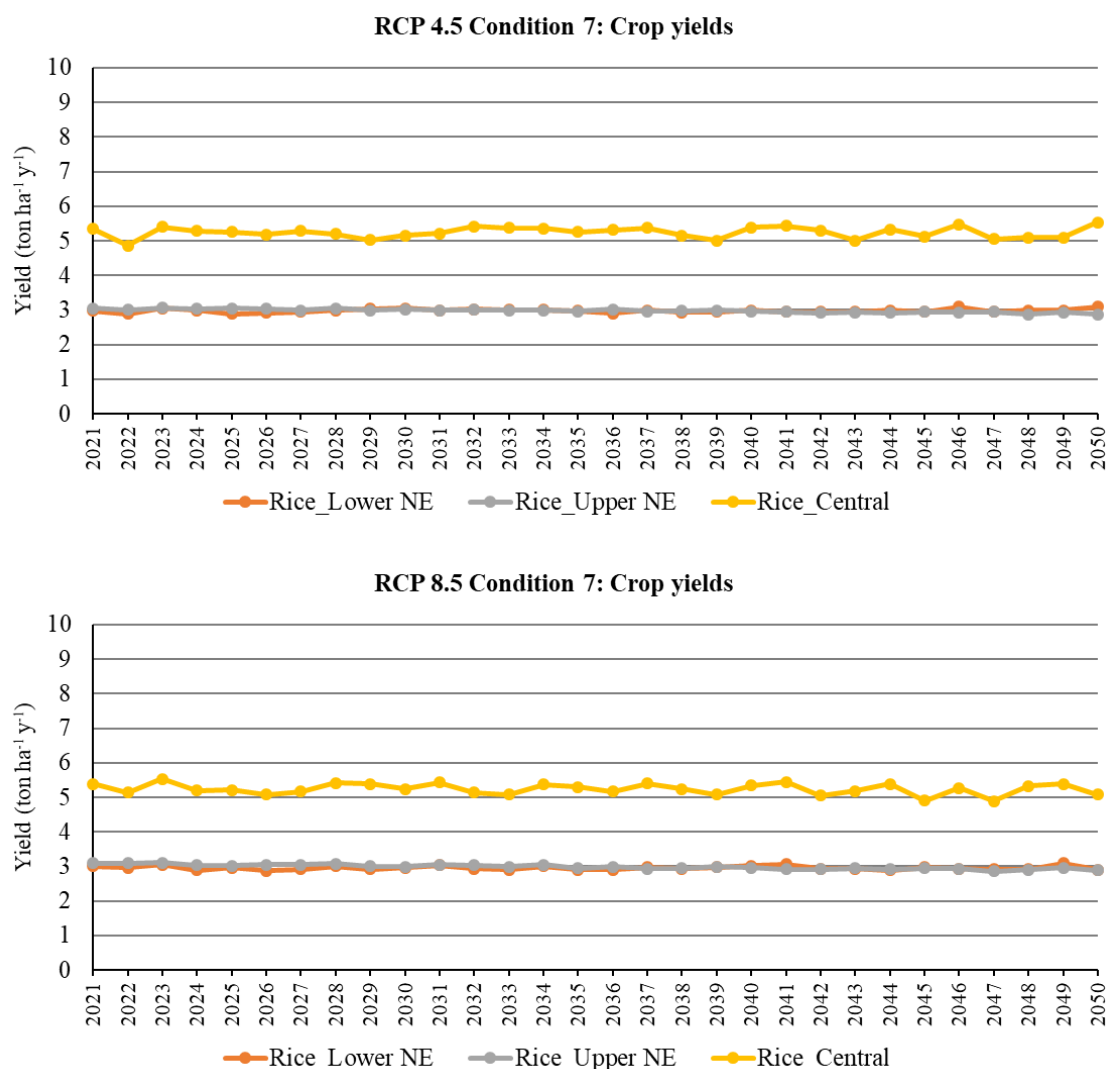


Figure 4.12 Crop yields from seven practices over 2021-2050

8) Greenhouse gas emissions, soil carbon stock, and rice grain yields from cultivation based on scenario analysis under different climate scenarios

Seven managements (C1 to C7), as previously described in this report, have been proposed for assessment under both RCP 4.5 and 8.5. Results from these assessments are summarized for the years 2025, 2030, 2035, 2040, 2045, and 2050 (Table 4.10 – 4.12).

Based on the model projections (Table 4.10), the results reveal that greenhouse gas (GHG) emissions between RCP 4.5 and 8.5 are comparable. However, starting from 2030, the GHG emissions from six scenarios under RCP 8.5 show a slight increase compared to those under RCP 4.5. This is true for most scenarios, except for scenario C7, which represents a sustainable rice

practice involving single rice cultivation, unburned crop residue, recommended fertilizer application, and continuous flooding. Notably, scenario C7 demonstrates a variation in emission trends when comparing RCP 4.5 and 8.5.

Table 4.10 Accumulated CH₄, N₂O, and total emissions in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050 under RCP 4.5 and 8.5

g) Situation involving C1, C2, C3, and C6 under RCP 4.5 and 8.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.77	0.28	25.05	25.34	0.30	25.65	26.78	0.37	27.15	28.82	0.45	29.28
2030	154.10	1.84	155.94	158.68	2.05	160.73	170.04	2.57	172.61	186.53	3.32	189.85
2035	287.34	3.77	291.11	300.65	4.38	305.04	333.68	5.90	339.58	382.90	8.11	391.02
2040	424.51	5.96	430.47	451.65	7.40	459.05	520.64	10.98	531.62	623.67	16.07	639.74
2045	568.92	8.00	576.92	614.73	10.34	625.06	732.25	16.19	748.43	907.73	24.40	932.13
2050	714.50	10.41	724.91	785.92	14.19	800.11	967.66	23.33	990.99	1225.76	35.20	1260.96

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.27	0.32	9.59	9.27	0.33	9.60	9.25	0.35	9.60	9.18	0.38	9.57
2030	58.78	2.12	60.90	58.75	2.19	60.94	58.49	2.35	60.85	57.92	2.58	60.49
2035	108.26	4.65	112.91	108.16	4.85	113.01	107.55	5.31	112.86	106.48	6.01	112.49
2040	159.13	7.23	166.36	158.95	7.71	166.66	157.76	8.83	166.59	157.27	10.98	168.26
2045	213.63	10.47	224.10	213.19	11.32	224.51	211.25	13.40	224.65	213.97	18.29	232.26
2050	266.07	14.51	280.57	265.54	15.92	281.45	263.84	19.71	283.54	270.51	27.67	298.18

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total

2025	24.26	0.25	24.51	24.88	0.29	25.17	26.42	0.40	26.82	28.62	0.55	29.16
2030	155.30	2.18	157.48	159.91	2.40	162.31	171.35	2.93	174.28	187.95	3.70	191.64
2035	287.52	4.17	291.69	300.82	4.79	305.60	333.84	6.28	340.12	383.11	8.47	391.58
2040	425.28	6.34	431.62	452.76	7.78	460.54	522.66	11.35	534.02	627.06	16.41	643.48
2045	570.25	8.72	578.96	617.32	11.20	628.52	737.98	17.40	755.39	917.84	26.10	943.94
2050			729.00			806.24			1002.17	1241.6		1278.9
	717.94	11.06		791.26	14.98		977.59	24.58		5	37.30	5

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.14	0.26	9.40	9.15	0.27	9.42	9.14	0.29	9.43	9.09	0.32	9.42
2030	60.69	2.64	63.33	60.70	2.70	63.40	60.56	2.84	63.40	60.16	3.02	63.18
2035	110.57	5.02	115.59	110.45	5.20	115.66	109.80	5.62	115.42	108.65	6.25	114.91
2040	162.23	8.22	170.46	162.11	8.66	170.77	161.10	9.64	170.75	160.92	11.56	172.48
2045	217.25	11.77	229.01	216.72	12.54	229.26	214.60	14.42	229.02	217.58	18.92	236.51
2050	270.77	15.74	286.51	270.02	17.08	287.10	267.83	20.66	288.49	274.71	28.27	302.97

h) Situation involving C1, C2, C3, and C7 under RCP 4.5 and 8.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.11	0.24	24.34	24.32	0.24	24.56	24.84	0.24	25.08	25.56	0.24	25.80
2030	149.64	1.56	151.19	151.31	1.56	152.87	155.29	1.57	156.85	160.99	1.58	162.57
2035	277.96	3.15	281.11	282.93	3.16	286.09	294.89	3.20	298.09	312.76	3.24	316.00
2040	408.33	4.78	413.11	418.20	4.82	423.02	442.60	4.91	447.50	479.23	5.02	484.25
2045	544.68	6.25	550.93	561.31	6.32	567.63	603.12	6.46	609.58	666.68	6.64	673.33
2050	680.54	7.93	688.46	706.19	8.05	714.24	770.45	8.30	778.75	864.43	8.59	873.02

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
------	---	--	--	--	--	--	--	--	--	--	--	--

	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.21	0.29	9.50	9.19	0.29	9.48	9.11	0.28	9.39	8.96	0.27	9.23
2030	58.39	1.93	60.32	58.16	1.92	60.08	57.44	1.87	59.31	56.20	1.78	57.98
2035	107.48	4.25	111.72	106.87	4.18	111.05	105.02	4.00	109.02	102.07	3.71	105.78
2040	157.84	6.49	164.32	156.61	6.35	162.96	152.89	5.95	158.85	148.00	5.42	153.42
2045	211.76	9.26	221.02	209.61	8.96	218.58	203.40	8.15	211.55	197.90	7.30	205.21
2050	263.57	12.71	276.28	260.55	12.21	272.76	252.31	10.93	263.23	247.40	9.95	257.35

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	23.51	0.18	23.69	23.71	0.18	23.89	24.19	0.18	24.38	24.87	0.19	24.66
2030	150.84	1.87	152.72	152.57	1.88	154.45	156.68	1.89	158.57	162.63	1.90	161.20
2035	278.02	3.54	281.56	282.92	3.56	286.47	294.65	3.59	298.24	312.12	3.63	306.06
2040	408.77	5.15	413.92	418.61	5.19	423.80	442.92	5.27	448.19	479.45	5.37	464.66
2045	545.15	6.87	552.02	561.87	6.95	568.82	603.74	7.11	610.85	667.20	7.32	641.86
2050	682.87	8.44	691.31	708.76	8.57	717.32	773.48	8.84	782.31	867.62	9.16	829.76

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.07	0.24	9.31	9.05	0.24	9.29	8.98	0.23	9.21	8.84	0.23	9.07
2030	60.30	2.47	62.76	60.12	2.44	62.56	59.53	2.38	61.90	58.50	2.26	60.76
2035	109.78	4.62	114.40	109.17	4.54	113.71	107.30	4.32	111.61	104.30	3.97	108.26
2040	160.92	7.50	168.42	159.74	7.34	167.08	156.16	6.86	163.02	151.47	6.20	157.68
2045	215.28	10.62	225.90	212.95	10.31	223.26	206.27	9.46	215.73	200.47	8.53	209.00
2050	268.14	13.98	282.12	264.75	13.45	278.20	255.61	12.05	267.66	250.18	10.90	261.09

i) Situation involving C1, C2, C4, and C6 under RCP 4.5 and 8.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
------	---	--	--	--	--	--	--	--	--	--	--	--

	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.70	0.28	24.98	25.27	0.31	25.58	26.65	0.37	27.03	28.58	0.47	29.05
2030	153.63	1.86	155.49	158.12	2.08	160.20	168.92	2.62	171.55	184.39	3.42	187.80
2035	286.38	3.81	290.18	299.24	4.45	303.69	330.32	6.06	336.39	375.98	8.45	384.43
2040	423.03	6.05	429.07	449.12	7.56	456.68	513.95	11.44	525.39	609.47	17.02	626.49
2045	566.80	8.12	574.92	610.59	10.60	621.19	720.63	16.92	737.55	883.03	25.90	908.94
2050	711.69	10.57	722.26	779.73	14.58	794.31	949.54	24.46	974.00	1188.85	37.38	1226.23

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.16	0.38	9.54	9.11	0.42	9.52	8.91	0.53	9.44	8.57	0.70	9.27
2030	58.06	2.42	60.48	57.54	2.70	60.24	55.93	3.45	59.37	53.13	4.62	57.75
2035	106.68	5.28	111.97	104.96	6.13	111.09	99.91	8.36	108.27	91.87	11.83	103.70
2040	156.39	8.37	164.75	152.75	10.29	163.04	142.18	15.31	157.50	128.10	23.08	151.18
2045	209.37	12.23	221.59	202.71	15.65	218.36	184.17	24.61	208.78	166.07	38.11	204.17
2050	260.15	17.03	277.18	250.17	22.50	272.67	223.80	36.88	260.68	204.57	55.81	260.37

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.19	0.26	24.45	24.80	0.30	25.10	26.28	0.41	26.69	28.35	0.58	28.93
2030	154.80	2.20	157.00	159.32	2.42	161.74	170.16	2.98	173.14	185.65	3.81	189.46
2035	286.52	4.21	290.74	299.39	4.85	304.24	330.46	6.43	336.89	376.17	8.77	384.93
2040	423.71	6.42	430.13	450.08	7.93	458.02	515.58	11.76	527.34	612.00	17.25	629.25
2045	568.07	8.84	576.91	613.10	11.46	624.56	726.17	18.14	744.31	892.86	27.61	920.47
2050	715.05	11.22	726.28	784.89	15.38	800.27	959.03	25.74	984.78	1204.07	39.59	1243.66

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		

	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.04	0.31	9.35	8.99	0.35	9.34	8.82	0.45	9.27	8.51	0.62	9.12
2030	59.87	2.96	62.83	59.32	3.25	62.57	57.60	4.02	61.62	54.64	5.22	59.87
2035	108.85	5.69	114.54	106.98	6.56	113.54	101.53	8.86	110.39	92.86	12.45	105.31
2040	159.29	9.39	168.68	155.50	11.30	166.80	144.51	16.28	160.79	129.88	24.00	153.88
2045	212.93	13.58	226.51	206.22	17.00	223.22	187.58	25.94	213.52	169.70	39.28	208.98
2050	264.76	18.32	283.08	254.52	23.79	278.30	227.55	38.14	265.69	208.46	56.89	265.35

j) Situation involving C1, C2, C4, and C7 under RCP 4.5 and 8.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.038	0.243	24.280	24.25	0.24	24.49	24.71	0.25	24.96	25.32	0.25	25.58
2030	149.161	1.576	150.737	150.76	1.58	152.34	154.17	1.62	155.79	158.84	1.68	160.52
2035	276.991	3.190	280.182	281.52	3.23	284.75	291.54	3.36	294.90	305.84	3.58	309.42
2040	406.850	4.866	411.717	415.67	4.99	420.65	435.91	5.37	441.27	465.03	5.97	471.00
2045	542.562	6.373	548.934	557.18	6.58	563.76	591.50	7.20	598.70	641.98	8.15	650.13
2050	677.732	8.084	685.816	700.00	8.44	708.44	752.33	9.43	761.77	827.52	10.77	838.29

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.11	0.35	9.45	9.02	0.37	9.40	8.77	0.46	9.23	8.34	0.59	8.93
2030	57.66	2.24	59.90	56.96	2.43	59.38	54.87	2.96	57.83	51.41	3.82	55.23
2035	105.90	4.88	110.78	103.66	5.46	109.13	97.39	7.04	104.43	87.46	9.53	96.99
2040	155.09	7.62	162.71	150.41	8.92	159.34	137.31	12.44	149.75	118.83	17.52	136.35
2045	207.49	11.03	218.52	199.13	13.30	212.43	176.33	19.36	195.68	150.00	27.12	177.12
2050	257.65	15.23	272.88	245.18	18.80	263.97	212.26	28.10	240.37	181.46	38.09	219.55

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		

	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	23.43	0.19	23.63	23.63	0.19	23.82	24.05	0.20	24.25	24.61	0.21	24.82
2030	150.33	1.90	152.23	151.97	1.91	153.88	155.49	1.94	157.43	160.34	2.01	162.34
2035	277.02	3.58	280.61	281.49	3.62	285.10	291.27	3.74	295.01	305.18	3.93	309.11
2040	407.20	5.23	412.43	415.93	5.34	421.27	435.84	5.67	441.52	464.39	6.21	470.60
2045	542.97	6.99	549.96	557.64	7.21	564.85	591.93	7.85	599.78	642.22	8.83	651.05
2050	679.98	8.61	688.59	702.39	8.96	711.35	754.92	10.00	764.92	830.04	11.45	841.48

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	8.97	0.29	9.26	8.89	0.32	9.21	8.66	0.39	9.05	8.26	0.52	8.78
2030	59.47	2.79	62.26	58.73	2.99	61.72	56.57	3.55	60.12	52.98	4.47	57.44
2035	108.07	5.29	113.35	105.69	5.90	111.59	99.03	7.55	106.58	88.50	10.16	98.66
2040	157.98	8.67	166.65	153.13	9.98	163.11	139.57	13.50	153.07	120.43	18.64	139.07
2045	210.97	12.43	223.40	202.45	14.76	217.21	179.26	20.97	200.23	152.58	28.89	181.48
2050	262.13	16.55	278.69	249.25	20.15	269.40	215.33	29.53	244.86	183.94	39.53	223.47

k) Situation involving C1, C2, C5, and C6 under RCP 4.5 and 8.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.69	0.28	24.97	25.26	0.31	25.56	26.63	0.37	27.00	28.53	0.46	29.00
2030	153.52	1.86	155.38	158.00	2.07	160.08	168.69	2.62	171.31	183.94	3.41	187.35
2035	286.18	3.80	289.97	298.96	4.43	303.39	329.65	6.02	335.67	374.60	8.36	382.96
2040	422.72	6.02	428.74	448.61	7.50	456.11	512.61	11.27	523.88	606.60	16.67	623.28
2045	566.35	8.08	574.42	609.73	10.51	620.23	718.18	16.66	734.84	877.76	25.37	903.13
2050	711.08	10.52	721.60	778.41	14.45	792.85	945.62	24.07	969.69	1180.73	36.61	1217.33

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
------	---	--	--	--	--	--	--	--	--	--	--	--

	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.14	0.35	9.49	9.08	0.38	9.45	8.85	0.44	9.30	8.46	0.55	9.01
2030	57.92	2.30	60.22	57.30	2.50	59.80	55.41	3.02	58.43	52.16	3.82	55.98
2035	106.36	5.07	111.43	104.29	5.72	110.01	98.32	7.40	105.71	88.82	10.00	98.82
2040	155.82	8.02	163.84	151.46	9.53	160.99	138.92	13.45	152.37	121.99	19.59	141.58
2045	208.45	11.75	220.20	200.44	14.51	214.95	178.30	21.71	200.00	155.75	32.87	188.62
2050	258.77	16.50	275.28	246.53	21.24	267.77	214.30	33.65	247.95	189.23	50.05	239.28

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.17	0.26	24.43	24.78	0.30	25.08	26.25	0.41	26.66	28.30	0.57	28.86
2030	154.70	2.20	156.89	159.21	2.42	161.62	169.93	2.97	172.90	185.22	3.79	189.00
2035	286.33	4.21	290.54	299.12	4.83	303.96	329.84	6.40	336.23	374.88	8.70	383.58
2040	423.40	6.40	429.79	449.55	7.89	457.44	514.17	11.65	525.82	608.97	17.02	625.99
2045	567.60	8.81	576.40	612.17	11.39	623.56	723.55	17.92	741.47	887.19	27.15	914.35
2050	714.42	11.17	725.60	783.50	15.26	798.76	954.92	25.39	980.31	1195.56	38.86	1234.43

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.02	0.29	9.30	8.96	0.31	9.27	8.75	0.37	9.13	8.39	0.47	8.86
2030	59.73	2.82	62.55	59.08	3.01	62.09	57.10	3.50	60.59	53.69	4.24	57.94
2035	108.55	5.43	113.98	106.36	6.04	112.40	100.04	7.63	107.67	90.01	10.11	100.12
2040	158.72	9.00	167.72	154.19	10.44	164.63	141.18	14.15	155.34	123.69	19.99	143.68
2045	211.99	13.04	225.03	203.86	15.73	219.58	181.44	22.69	204.13	158.95	33.44	192.39
2050	263.37	17.73	281.10	250.83	22.37	273.20	217.90	34.52	252.42	192.85	50.52	243.37

l) Situation involving C1, C2, C5, and C7 under RCP 4.5 and 8.5

Year	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 4.5
------	---

	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	24.02	0.24	24.27	24.24	0.24	24.48	24.68	0.24	24.93	25.27	0.25	25.52
2030	149.06	1.57	150.63	150.64	1.58	152.22	153.94	1.61	155.55	158.40	1.67	160.06
2035	276.79	3.18	279.97	281.23	3.21	284.44	290.86	3.32	294.18	304.45	3.49	307.94
2040	406.54	4.84	411.38	415.16	4.93	420.08	434.57	5.20	439.76	462.16	5.62	467.78
2045	542.11	6.33	548.44	556.31	6.49	562.80	589.06	6.94	595.99	636.72	7.61	644.33
2050	677.12	8.03	685.15	698.68	8.30	706.98	748.41	9.04	757.45	819.39	10.00	829.39

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 4.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	9.09	0.32	9.41	8.99	0.33	9.33	8.71	0.37	9.08	8.24	0.44	8.67
2030	57.52	2.12	59.64	56.72	2.22	58.94	54.36	2.53	56.89	50.45	3.02	53.47
2035	105.57	4.67	110.24	103.00	5.05	108.05	95.79	6.08	101.88	84.41	7.70	92.11
2040	154.52	7.28	161.80	149.12	8.17	157.29	134.05	10.58	144.62	112.72	14.03	126.75
2045	206.58	10.54	217.12	196.86	12.16	209.03	170.45	16.46	186.91	139.69	21.88	161.56
2050	256.27	14.70	270.98	241.54	17.53	259.08	202.77	24.87	227.64	166.12	32.34	198.46

ear	GHGs Emission (Mt CO ₂ eq) of Northeast region under RCP 8.5											
	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	23.42	0.19	23.61	23.61	0.19	23.80	24.02	0.20	24.22	24.56	0.21	24.76
2030	150.23	1.89	152.13	151.86	1.90	153.76	155.26	1.93	157.20	159.90	1.99	161.88
2035	276.83	3.57	280.41	281.22	3.61	284.82	290.65	3.70	294.35	303.89	3.87	307.75
2040	406.89	5.21	412.09	415.40	5.30	420.69	434.43	5.56	439.99	461.35	5.98	467.33
2045	542.50	6.96	549.46	556.72	7.13	563.85	589.30	7.63	596.93	636.56	8.38	644.93
2050	679.35	8.56	687.91	701.00	8.85	709.85	750.81	9.64	760.46	821.53	10.72	832.25

Year	GHGs Emission (Mt CO ₂ eq) of Central region under RCP 8.5											
------	---	--	--	--	--	--	--	--	--	--	--	--

	BAU			Scenario 2			Scenario 3			Scenario 4		
	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total	CH ₄	N ₂ O	Total
2025	8.95	0.26	9.21	8.86	0.28	9.14	8.59	0.31	8.90	8.14	0.37	8.51
2030	59.33	2.65	61.98	58.50	2.75	61.25	56.07	3.03	59.10	52.03	3.49	55.51
2035	107.76	5.03	112.79	105.07	5.38	110.45	97.54	6.33	103.87	85.65	7.82	93.47
2040	157.40	8.28	165.68	151.81	9.12	160.93	136.24	11.37	147.61	114.24	14.63	128.87
2045	210.02	11.89	221.91	200.08	13.49	213.58	173.11	17.73	190.84	141.84	23.05	164.89
2050	260.74	15.97	276.71	245.56	18.74	264.30	205.67	25.91	231.59	168.33	33.15	201.48

Based on the model projections (Table 4.11), it is presented that the expansion of the SRP area results in an increase in annual SOC stocks in both regions and both climate conditions. The results also demonstrate a similar level of SOC stocks between RCP 4.5 and 8.5.

Table 4.11 The annual SOC stocks in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050 under RCP 4.5 and 8.5

g) Situation involving C1, C2, C3, and C6 under RCP 4.5 and 8.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	114.55	114.57	116.06	116.08	120.02	120.04	125.73	125.75
2030	114.41	114.49	118.87	118.96	130.09	130.23	147.40	147.63
2035	114.40	114.42	122.05	122.08	142.37	142.45	173.18	173.31
2040	114.96	114.93	126.23	126.16	156.58	156.40	203.14	202.82
2045	114.87	114.87	130.84	130.89	172.22	172.39	230.59	230.93
2050	115.50	115.48	136.56	136.59	189.71	189.86	237.03	237.30

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5

2025	111.05	110.88	111.64	111.47	113.11	112.90	115.15	114.97
2030	115.34	115.19	117.01	116.85	113.74	121.06	127.72	127.56
2035	119.40	119.18	122.57	122.36	115.09	130.19	143.24	143.14
2040	123.32	123.02	128.09	127.77	117.03	140.05	163.84	163.46
2045	126.97	126.71	133.64	133.41	119.46	151.25	175.22	175.14
2050	130.55	130.29	139.41	139.17	122.48	164.31	182.30	182.19

h) Situation involving C1, C2, C3, and C7 under RCP 4.5 and 8.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	112.20	112.22	112.43	112.45	113.11	113.13	114.15	114.17
2030	110.82	110.88	111.62	111.69	113.74	113.80	117.16	117.23
2035	109.58	109.59	111.04	111.06	115.09	115.13	121.68	121.73
2040	108.51	108.50	110.75	110.74	117.03	117.02	127.25	127.23
2045	107.22	107.20	110.54	110.53	119.46	119.47	132.51	132.55
2050	106.25	106.20	110.66	110.60	122.48	122.39	133.14	133.02

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	110.18	110.00	110.39	110.22	110.94	110.77	111.80	111.63
2030	114.05	113.89	114.78	114.63	116.66	116.51	119.63	119.47

2035	117.75	117.53	119.19	118.98	122.91	122.74	128.53	128.42
2040	121.17	120.86	123.54	123.22	129.66	129.30	138.33	137.91
2045	124.38	124.10	127.83	127.56	136.63	136.36	145.27	144.97
2050	127.51	127.22	132.26	131.95	144.50	144.14	150.71	150.29

i) Situation involving C1, C2, C4, and C6 under RCP 4.5 and 8.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	114.55	114.11	116.06	115.60	120.03	119.19	125.74	124.20
2030	114.41	113.90	118.86	118.04	130.07	127.95	147.38	142.84
2035	114.39	113.72	122.03	120.65	142.32	138.26	173.05	163.93
2040	114.94	114.08	126.19	124.17	156.45	150.30	202.85	189.30
2045	114.84	113.88	130.76	128.10	171.97	163.44	230.08	212.74
2050	115.46	114.33	136.45	132.90	189.34	177.93	236.44	218.18

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	111.20	111.02	111.86	111.69	113.51	113.34	115.94	115.77
2030	115.54	115.38	117.47	117.29	122.35	122.15	129.94	129.71
2035	119.67	119.45	123.24	123.02	132.14	131.94	146.59	146.42
2040	123.63	123.33	128.95	128.66	142.71	142.43	167.72	167.46
2045	127.35	127.10	134.75	134.54	154.35	154.26	179.47	179.49
2050	130.99	130.74	140.73	140.54	167.96	167.92	186.52	186.56

j) Situation involving C1, C2, C4, and C7 under RCP 4.5 and 8.5

	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region							
--	--	--	--	--	--	--	--	--

Year	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	112.20	111.76	112.43	111.97	113.12	112.28	114.16	112.61
2030	110.82	110.30	111.62	110.76	113.72	111.52	117.13	112.44
2035	109.57	108.89	111.02	109.63	115.03	110.94	121.55	112.34
2040	108.49	107.66	110.71	108.75	116.90	110.92	126.97	113.71
2045	107.19	106.21	110.46	107.74	119.21	110.52	132.00	114.37
2050	106.22	105.05	110.55	106.91	122.11	110.46	132.55	113.90

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	110.32	110.15	110.61	110.43	111.38	111.21	112.60	112.43
2030	114.25	114.09	115.24	115.07	117.80	117.60	121.85	121.62
2035	118.02	117.79	119.86	119.64	124.69	124.49	131.88	131.70
2040	121.48	121.18	124.40	124.10	131.98	131.68	142.21	141.90
2045	124.76	124.49	128.94	128.69	139.58	139.38	149.51	149.31
2050	127.95	127.67	133.58	133.32	147.99	147.75	154.93	154.65

k) Situation involving C1, C2, C5, and C6 under RCP 4.5 and 8.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	114.49	114.51	115.99	116.01	119.91	119.93	125.53	125.55
2030	114.32	114.40	118.73	118.83	129.74	129.89	146.68	146.91
2035	114.28	114.30	121.81	121.84	141.68	141.76	171.63	171.76
2040	114.80	114.77	125.86	125.79	155.45	155.29	200.64	200.34

2045	114.68	114.68	130.32	130.36	170.53	170.68	227.14	227.44
2050	115.27	115.25	135.83	135.85	187.32	187.47	233.19	233.45

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	110.91	110.74	111.42	111.25	112.63	112.46	114.33	114.17
2030	115.09	114.94	116.44	116.28	119.79	119.64	124.92	124.78
2035	118.96	118.74	121.45	121.24	127.41	127.24	137.71	137.58
2040	122.65	122.36	126.22	125.95	135.35	135.13	155.39	155.22
2045	126.04	125.79	130.90	130.72	144.12	144.10	164.72	164.84
2050	129.28	129.05	135.57	135.43	154.36	154.43	170.08	170.25

l) Situation involving C1, C2, C5, and C7 under RCP 4.5 and 8.5

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	112.14	112.16	112.37	112.39	113.00	113.02	113.95	113.96
2030	110.73	110.79	111.48	111.55	113.39	113.46	116.44	116.52
2035	109.46	109.47	110.80	110.82	114.40	114.43	120.13	120.18
2040	108.35	108.35	110.38	110.38	115.90	115.90	124.75	124.75
2045	107.03	107.01	110.02	110.00	117.77	117.76	129.05	129.06
2050	106.02	105.97	109.93	109.86	120.09	120.00	129.30	129.17

Year	Soil Organic Carbon Stock (Mt C yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5

2025	110.03	109.86	110.17	110.00	110.50	110.33	110.99	110.83
2030	113.80	113.64	114.21	114.06	115.23	115.09	116.83	116.69
2035	117.30	117.08	118.08	117.86	119.97	119.78	123.01	122.86
2040	120.50	120.21	121.67	121.39	124.62	124.38	129.88	129.67
2045	123.44	123.18	125.09	124.87	129.35	129.22	134.76	134.66
2050	126.25	125.99	128.42	128.21	134.39	134.26	138.49	138.35

Based on the data presented in Table 4.12, the yield in the northeast and central regions shows variations due to the influence of specific climatic conditions and management practices in each year. The results present a similar level of rice yields when comparing RCP 4.5 and 8.5 under the same management practices.

Table 4.12 The annual rice production in the northeast and central of Thailand according to each scenario for the years 2025, 2030, 2035, 2040, 2045, and 2050 under RCP 4.5 and 8.5

g) Situation involving C1, C2, C3, and C6 under RCP 4.5 and 8.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	18.79	18.52	18.91	18.64	19.25	18.97	19.75	19.46
2030	18.81	18.87	19.16	19.20	20.08	20.06	21.55	21.42
2035	18.81	18.64	19.39	19.17	21.02	20.65	23.60	23.02
2040	19.03	19.02	19.85	19.75	22.19	21.85	25.99	25.31
2045	18.87	19.31	19.94	20.31	22.88	23.10	27.26	27.35
2050	18.88	19.23	20.14	20.56	23.63	24.12	26.92	27.42

Year	Rice yield (Mt yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5

2025	16.64	16.55	16.63	16.54	16.60	16.50	16.55	16.43
2030	16.73	16.62	16.73	16.61	16.72	16.57	16.70	16.51
2035	16.69	16.64	16.68	16.62	16.63	16.54	16.57	16.46
2040	16.58	16.74	16.57	16.77	16.54	16.83	16.64	16.97
2045	16.75	16.49	16.79	16.65	16.87	17.04	17.02	17.48
2050	16.70	16.73	16.75	16.83	16.90	17.10	17.01	17.27

h) Situation involving C1, C2, C3, and C7 under RCP 4.5 and 8.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	18.59	18.33	18.61	18.35	18.68	18.44	18.80	18.56
2030	18.55	18.60	18.65	18.66	18.94	18.85	19.43	19.18
2035	18.46	18.29	18.60	18.40	19.06	18.74	19.87	19.37
2040	18.58	18.60	18.79	18.78	19.47	19.35	20.68	20.37
2045	18.39	18.80	18.69	19.00	19.59	19.64	21.01	20.78
2050	18.41	18.61	18.88	18.83	20.22	19.61	21.43	20.43

Year	Rice yield (Mt yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP	RCP	RCP	RCP	RCP	RCP	RCP	RCP
	4.5	8.5	4.5	8.5	4.5	8.5	4.5	8.5
2025	16.62	16.53	16.60	16.51	16.55	16.45	16.47	16.35
2030	16.69	16.58	16.66	16.55	16.59	16.46	16.47	16.31
2035	16.65	16.60	16.59	16.54	16.44	16.37	16.19	16.12
2040	16.53	16.69	16.48	16.67	16.32	16.60	16.12	16.43
2045	16.69	16.41	16.64	16.46	16.50	16.57	16.28	16.52
2050	16.66	16.65	16.68	16.64	16.69	16.57	16.67	16.43

i) Situation involving C1, C2, C4, and C6 under RCP 4.5 and 8.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	18.73	18.47	18.84	18.59	19.13	18.89	19.54	19.30
2030	18.74	18.81	19.04	19.11	19.79	19.85	20.94	20.98
2035	18.73	18.57	19.23	19.04	20.52	20.27	22.50	22.17
2040	18.93	18.94	19.61	19.58	21.47	21.31	24.41	24.11
2045	18.76	19.22	19.64	20.07	21.91	22.34	25.31	25.80
2050	18.76	19.14	19.76	20.27	22.43	23.18	25.02	25.89

Year	Rice yield (Mt yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	16.46	16.38	16.36	16.28	16.05	15.97	15.55	15.46
2030	16.47	16.37	16.14	16.05	15.27	15.17	13.85	13.77
2035	16.35	16.31	15.82	15.78	14.36	14.34	12.32	12.31
2040	16.18	16.31	15.46	15.57	13.55	13.59	11.64	11.55
2045	16.23	15.94	15.27	15.02	12.84	12.71	11.20	11.22
2050	16.09	16.11	14.93	14.97	12.09	12.19	11.20	11.33

j) Situation involving C1, C2, C4, and C7 under RCP 4.5 and 8.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	18.53	18.28	18.54	18.31	18.56	18.35	18.58	18.41
2030	18.48	18.54	18.53	18.58	18.65	18.64	18.82	18.75
2035	18.38	18.23	18.44	18.27	18.57	18.36	18.78	18.52

2040	18.48	18.52	18.55	18.61	18.75	18.81	19.11	19.17
2045	18.28	18.72	18.39	18.76	18.62	18.89	19.06	19.23
2050	18.29	18.52	18.51	18.54	19.02	18.67	19.53	18.90

Year	Rice yield (Mt yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	16.44	16.36	16.33	16.25	16.01	15.92	15.47	15.38
2030	16.43	16.34	16.08	15.99	15.14	15.06	13.62	13.57
2035	16.31	16.27	15.74	15.71	14.17	14.16	11.94	11.97
2040	16.14	16.26	15.37	15.47	13.33	13.37	11.12	11.02
2045	16.17	15.85	15.12	14.83	12.47	12.23	10.46	10.26
2050	16.06	16.03	14.85	14.78	11.88	11.66	10.86	10.49

k) Situation involving C1, C2, C5, and C6 under RCP 4.5 and 8.5

Year	Rice yield (Mt yr ⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	18.73	18.48	18.85	18.60	19.14	18.91	19.55	19.34
2030	18.74	18.82	19.05	19.12	19.82	19.87	21.00	21.02
2035	18.74	18.58	19.24	19.06	20.58	20.31	22.62	22.28
2040	18.94	18.95	19.63	19.60	21.53	21.38	24.57	24.27
2045	18.78	19.23	19.66	20.10	22.00	22.44	25.51	26.01
2050	18.77	19.15	19.78	20.30	22.49	23.28	25.13	26.07

Year	Rice yield (Mt yr ⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	

	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	16.47	16.39	16.36	16.28	16.06	15.98	15.56	15.48
2030	16.48	16.38	16.16	16.07	15.30	15.24	13.92	13.90
2035	16.38	16.33	15.89	15.86	14.55	14.53	12.66	12.67
2040	16.20	16.34	15.53	15.64	13.74	13.80	11.95	11.89
2045	16.26	15.97	15.35	15.11	13.06	12.95	11.53	11.58
2050	16.13	16.15	15.03	15.08	12.34	12.47	11.50	11.68

l) Situation involving C1, C2, C5, and C7 under RCP 4.5 and 8.5

Year	Rice yield (Mt yr⁻¹) of Northeast region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	18.54	18.29	18.55	18.32	18.57	18.37	18.60	18.45
2030	18.48	18.55	18.54	18.58	18.68	18.66	18.88	18.78
2035	18.39	18.24	18.45	18.29	18.62	18.40	18.90	18.63
2040	18.49	18.53	18.57	18.63	18.81	18.87	19.27	19.33
2045	18.29	18.73	18.41	18.79	18.71	18.98	19.27	19.44
2050	18.30	18.53	18.52	18.57	19.08	18.77	19.64	19.07

Year	Rice yield (Mt yr⁻¹) of Central region							
	BAU		Scenario 2		Scenario 3		Scenario 4	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
2025	16.45	16.36	16.34	16.25	16.01	15.93	15.49	15.40
2030	16.44	16.35	16.09	16.02	15.17	15.12	13.69	13.69
2035	16.34	16.30	15.81	15.78	14.36	14.36	12.28	12.33
2040	16.16	16.29	15.44	15.55	13.52	13.57	11.44	11.36
2045	16.20	15.88	15.21	14.92	12.69	12.48	10.79	10.62

2050	16.09	16.07	14.95	14.89	12.13	11.94	11.17	10.84
------	-------	-------	-------	-------	-------	-------	-------	-------

Appendix 5: Table 6.2. Amounts of water use in rice cultivation under different scenarios and cultivation practices with yearly data during 2025-2050.

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
CP	CON-SC1	2025	3,632.63	4,997.33	5,442.04	14,071.99
		2026	3,601.08	4,979.07	5,408.52	13,988.68
		2027	3,644.57	5,020.53	5,463.63	14,128.73
		2028	3,668.52	5,025.34	5,484.12	14,177.99
		2029	3,635.03	5,000.40	5,445.51	14,080.94
		2030	3,596.33	4,954.57	5,391.58	13,942.48
		2031	3,605.47	4,973.23	5,408.60	13,987.30
		2032	3,629.41	4,965.81	5,422.40	14,017.62
		2033	3,589.78	4,965.52	5,392.68	13,947.98
		2034	3,642.33	5,001.97	5,451.81	14,096.11
		2035	3,550.96	4,885.36	5,319.90	13,756.23
		2036	3,558.41	4,895.26	5,330.86	13,784.52
		2037	3,591.46	4,888.17	5,351.64	13,831.27
		2038	3,588.19	4,903.54	5,357.60	13,849.33
		2039	3,564.70	4,896.78	5,336.39	13,797.87
		2040	3,524.35	4,831.33	5,270.50	13,626.17
		2041	3,503.10	4,809.82	5,242.89	13,555.81
		2042	3,496.53	4,806.71	5,236.29	13,539.53
		2043	3,494.29	4,791.01	5,226.03	13,511.34
		2044	3,557.04	4,831.88	5,295.18	13,684.10
		2045	3,387.92	4,698.33	5,096.02	13,182.27
		2046	3,448.72	4,714.90	5,150.43	13,314.05
		2047	3,446.46	4,757.36	5,171.96	13,375.77
		2048	3,453.48	4,721.81	5,157.76	13,333.05
		2049	3,507.54	4,765.76	5,222.11	13,495.42
		2050	3,413.90	4,681.86	5,106.39	13,202.14
	CON-SC2	2025	3,564.11	4,902.72	5,339.19	13,806.02
		2026	3,533.16	4,884.80	5,306.32	13,724.28
		2027	3,575.82	4,925.48	5,360.37	13,861.68
		2028	3,599.33	4,930.20	5,380.49	13,910.02
		2029	3,566.47	4,905.74	5,342.61	13,814.82
		2034	3,449.32	4,714.85	5,150.85	13,315.02

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2035	3,240.13	4,426.15	4,836.95	12,503.23
		2036	3,247.17	4,435.27	4,847.19	12,529.62
		2037	3,277.21	4,429.05	4,866.20	12,572.46
		2038	3,273.93	4,442.69	4,871.20	12,587.82
		2039	3,252.61	4,436.50	4,851.92	12,541.03
		2040	3,093.82	4,185.11	4,596.02	11,874.94
		2041	3,074.07	4,165.75	4,570.70	11,810.51
		2042	3,068.47	4,163.10	4,565.08	11,796.65
		2043	3,067.21	4,150.05	4,557.00	11,774.26
		2044	3,121.62	4,185.45	4,616.94	11,924.02
		2045	2,847.01	3,873.71	4,241.66	10,962.38
		2046	2,899.71	3,889.19	4,289.43	11,078.32
		2047	2,896.54	3,922.87	4,305.48	11,124.90
		2048	2,904.83	3,895.57	4,296.73	11,097.13
		2049	2,950.74	3,932.48	4,351.16	11,234.39
		2050	2,742.56	3,665.29	4,049.79	10,457.64
	CON-SC3	2025	3,379.75	4,634.68	5,055.12	13,069.56
		2026	3,350.55	4,617.78	5,024.10	12,992.43
		2027	3,390.81	4,656.16	5,075.12	13,122.09
		2028	3,413.28	4,660.80	5,094.41	13,168.49
		2029	3,382.26	4,637.70	5,058.64	13,078.60
		2030	2,907.12	3,914.19	4,308.63	11,129.95
		2031	2,914.42	3,928.80	4,322.06	11,165.27
		2032	2,934.08	3,923.71	4,333.93	11,191.72
		2033	2,901.50	3,922.36	4,308.90	11,132.76
		2034	2,945.56	3,952.64	4,358.32	11,256.52
		2035	2,428.27	3,188.36	3,554.58	9,171.21
		2036	2,434.57	3,195.56	3,563.21	9,193.34
		2037	2,456.63	3,191.91	3,577.66	9,226.19
		2038	2,452.93	3,200.56	3,579.64	9,233.13
		2039	2,437.40	3,195.84	3,565.47	9,198.71
		2040	1,965.11	2,477.47	2,820.39	7,262.98
		2041	1,949.04	2,463.61	2,800.82	7,213.47
		2042	1,946.03	2,462.20	2,797.82	7,206.05
		2043	1,947.51	2,456.26	2,795.67	7,199.44
		2044	1,979.89	2,477.24	2,831.29	7,288.42
				2045	1,441.63	1,765.21
				2046	1,472.55	1,777.13

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
				2047	1,467.62	1,788.91
				2048	1,478.09	1,781.86
				2049	1,502.62	1,800.50
				2050	964.96	1,089.88
			CON-SC4	2025	3,093.23	4,202.77
				2026	3,066.89	4,187.52
				2027	3,103.24	4,222.13
				2028	3,124.29	4,226.81
	CON-SC4			2029	3,096.25	4,205.95
				2030	2,121.61	2,711.47
				2031	2,126.79	2,721.35
				2032	2,141.63	2,719.08
				2033	2,116.99	2,716.33
				2034	2,151.67	2,739.72
				2035	1,188.94	1,381.94
				2036	1,193.44	1,385.97
				2037	1,203.60	1,385.58
				2038	1,200.08	1,387.64
				2039	1,193.09	1,385.21
				2040	289.02	360.80
				2041	286.58	358.73
				2042	286.15	358.53
				2043	286.41	357.71
				2044	291.13	360.76
				2045	0.00	0.00
				2046	0.00	0.00
				2047	0.00	0.00
				2048	0.00	0.00
				2049	0.00	0.00
				2050	0.00	0.00
			SRP-SC1	2025	152.21	134.19
				2026	153.04	136.20
				2027	154.56	137.68
				2028	155.60	138.67
	SRP-SC1			2029	156.21	140.68
		2030	203.15	182.60	319.86	705.61
		2031	205.04	182.06	321.17	708.26
		2032	205.95	185.65	324.67	716.27

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2033	203.59	183.23	320.73	707.55
		2034	207.52	187.30	327.32	722.14
		2035	263.66	238.53	416.29	918.48
		2036	265.15	240.89	419.41	925.45
		2037	265.19	240.44	419.11	924.75
		2038	265.64	242.24	420.86	928.75
		2039	264.39	238.12	416.65	919.16
		2040	320.32	291.72	507.20	1,119.24
		2041	321.70	290.36	507.43	1,119.49
		2042	318.90	295.11	508.45	1,122.45
		2043	317.46	293.42	505.89	1,116.77
		2044	314.58	291.75	502.04	1,108.37
		2045	373.68	354.30	602.14	1,330.12
		2046	376.00	349.61	600.73	1,326.35
		2047	375.50	353.96	603.54	1,333.00
		2048	378.13	351.61	604.16	1,333.90
		2049	379.06	351.09	604.60	1,334.75
		2050	432.01	402.96	691.17	1,526.14
	SRP-SC2	2025	226.62	201.46	355.15	783.23
		2026	227.92	204.55	358.63	791.10
		2027	230.16	206.77	362.31	799.23
		2028	231.62	208.20	364.70	804.52
		2029	232.57	211.27	367.85	811.69
		2030	419.23	389.45	669.53	1,478.20
		2031	422.68	387.69	671.34	1,481.71
		2032	425.46	396.31	680.29	1,502.06
		2033	420.71	391.18	672.17	1,484.06
		2034	428.15	399.53	685.13	1,512.81
		2035	617.15	570.89	983.82	2,171.87
		2036	621.17	576.98	992.00	2,190.15
		2037	620.72	575.51	990.49	2,186.72
		2038	622.02	580.12	995.11	2,197.25
		2039	619.77	570.35	985.77	2,175.88
		2040	817.99	767.88	1,312.36	2,898.24
		2041	820.95	763.54	1,311.78	2,896.26
		2042	816.48	778.87	1,319.21	2,914.57
		2043	811.34	773.45	1,310.51	2,895.30
		2044	801.50	767.72	1,297.35	2,866.58

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2045	1,010.55	986.51	1,649.60	3,646.65
		2046	1,015.49	971.64	1,642.94	3,630.07
		2047	1,016.16	985.68	1,654.04	3,655.88
		2048	1,020.10	976.51	1,650.75	3,647.36
		2049	1,022.97	975.04	1,652.23	3,650.24
		2050	1,216.46	1,164.78	1,968.73	4,349.98
	SRP-SC3	2025	429.05	388.41	677.62	1,495.09
		2026	431.79	394.66	684.77	1,511.22
		2027	435.92	398.90	691.66	1,526.48
		2028	438.32	401.45	695.74	1,535.51
		2029	440.24	407.61	702.08	1,549.94
		2030	985.13	934.50	1,587.77	3,507.40
		2031	992.55	929.40	1,590.66	3,512.61
		2032	1,000.49	951.50	1,614.34	3,566.33
		2033	989.50	939.23	1,595.26	3,523.99
		2034	1,005.95	958.79	1,624.73	3,589.47
		2035	1,547.65	1,457.46	2,486.45	5,491.55
		2036	1,558.81	1,473.86	2,508.78	5,541.44
		2037	1,556.51	1,469.33	2,503.33	5,529.17
		2038	1,560.29	1,481.71	2,515.99	5,557.98
		2039	1,556.06	1,456.93	2,493.64	5,506.63
		2040	2,123.43	2,019.35	3,426.20	7,568.99
		2041	2,130.46	2,007.08	3,423.37	7,560.90
		2042	2,121.94	2,050.52	3,448.15	7,620.61
		2043	2,106.89	2,035.18	3,423.11	7,565.18
		2044	2,078.56	2,018.64	3,385.17	7,482.38
		2045	2,652.53	2,600.40	4,338.13	9,591.07
		2046	2,664.99	2,560.52	4,319.57	9,545.09
		2047	2,667.52	2,598.26	4,350.06	9,615.84
		2048	2,676.66	2,573.10	4,339.50	9,589.26
		2049	2,684.30	2,569.22	4,343.50	9,597.03
		2050	3,257.79	3,101.81	5,259.28	11,618.88
	SRP-SC4	2025	747.06	687.24	1,188.05	2,622.34
		2026	752.23	698.79	1,201.35	2,652.37
		2027	759.27	706.21	1,213.25	2,678.73
		2028	762.87	710.39	1,219.63	2,692.89
		2029	766.42	721.68	1,231.27	2,719.38
		2030	1,879.94	1,800.43	3,042.77	6,723.14

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2031	1,893.50	1,789.83	3,047.08	6,730.41
		2032	1,909.87	1,833.64	3,094.61	6,838.12
		2033	1,889.07	1,810.05	3,058.20	6,757.31
		2034	1,919.55	1,847.30	3,113.56	6,880.41
		2035	2,948.23	2,763.33	4,726.84	10,438.41
		2036	2,968.95	2,794.00	4,768.46	10,531.41
		2037	2,965.16	2,785.81	4,758.93	10,509.90
		2038	2,972.09	2,808.97	4,782.50	10,563.56
		2039	2,963.31	2,761.90	4,739.39	10,464.60
		2040	3,951.85	3,624.54	6,276.52	13,852.91
		2041	3,968.22	3,606.78	6,278.03	13,853.04
		2042	3,936.61	3,668.98	6,295.99	13,901.59
		2043	3,917.29	3,646.88	6,262.03	13,826.20
		2044	3,878.90	3,624.72	6,210.81	13,714.42
		2045	4,231.60	3,998.07	6,808.26	15,037.94
		2046	4,258.54	3,946.08	6,793.71	14,998.33
		2047	4,251.90	3,994.18	6,823.67	15,069.75
		2048	4,283.24	3,969.03	6,833.16	15,085.43
		2049	4,293.63	3,963.06	6,838.08	15,094.76
		2050	4,277.18	3,956.88	6,818.61	15,052.67
NE	CON-SC1	2025	7,235.95	4,222.03	5,122.75	16,580.74
		2026	7,309.41	4,262.41	5,179.65	16,751.48
		2027	7,296.28	4,251.58	5,175.50	16,723.36
		2028	7,290.14	4,251.64	5,169.00	16,710.77
		2029	7,277.91	4,241.48	5,162.85	16,682.24
		2030	7,194.79	4,197.06	5,100.74	16,492.59
		2031	7,232.43	4,222.50	5,129.75	16,584.68
		2032	7,251.22	4,224.71	5,145.00	16,620.93
		2033	7,246.00	4,227.93	5,141.48	16,615.42
		2034	7,231.13	4,221.32	5,130.26	16,582.71
		2035	7,051.26	4,123.81	4,999.65	16,174.72
		2036	7,294.92	4,244.13	5,176.64	16,715.68
		2037	7,128.83	4,167.98	5,055.63	16,352.43
		2038	7,127.37	4,166.69	5,054.91	16,348.97
		2039	7,206.88	4,201.33	5,112.84	16,521.05
		2040	7,042.69	4,118.37	4,994.35	16,155.41
		2041	7,071.34	4,134.90	5,015.68	16,221.92
		2042	7,101.74	4,144.36	5,041.78	16,287.89

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2043	7,051.33	4,119.61	4,998.25	16,169.19
		2044	7,039.13	4,113.74	4,991.07	16,143.95
		2045	7,005.46	4,088.14	4,968.39	16,061.99
		2046	7,013.93	4,092.26	4,977.93	16,084.12
		2047	7,022.04	4,099.58	4,984.85	16,106.47
		2048	7,027.09	4,102.17	4,990.09	16,119.34
		2049	7,087.06	4,126.40	5,027.36	16,240.82
		2050	6,893.29	4,036.79	4,888.66	15,818.75
	CON-SC2	2025	7,143.06	4,179.03	5,048.34	16,370.43
		2026	7,214.88	4,218.63	5,103.98	16,537.48
		2027	7,201.27	4,207.54	5,099.49	16,508.30
		2028	7,195.43	4,207.76	5,093.21	16,496.39
		2029	7,183.07	4,197.53	5,086.98	16,467.58
		2030	6,938.34	4,068.45	4,896.21	15,903.01
		2031	6,974.11	4,092.92	4,923.74	15,990.76
		2032	6,991.14	4,094.37	4,937.69	16,023.20
		2033	6,986.01	4,097.63	4,934.22	16,017.86
		2034	6,972.14	4,091.46	4,923.77	15,987.37
		2035	6,651.64	3,918.04	4,681.41	15,251.09
		2036	6,878.76	4,030.23	4,845.53	15,754.52
		2037	6,724.36	3,959.72	4,733.55	15,417.63
		2038	6,722.41	3,958.31	4,732.51	15,413.22
		2039	6,796.88	3,990.42	4,786.50	15,573.80
		2040	6,490.24	3,830.17	4,554.05	14,874.45
		2041	6,515.85	3,845.14	4,573.00	14,933.99
		2042	6,540.92	3,852.03	4,595.05	14,988.01
		2043	6,499.47	3,831.80	4,558.41	14,889.69
		2044	6,487.00	3,825.89	4,551.08	14,863.97
		2045	6,273.58	3,708.72	4,386.92	14,369.22
		2046	6,277.99	3,710.86	4,393.37	14,382.23
		2047	6,284.34	3,717.22	4,398.88	14,400.44
		2048	6,287.36	3,718.84	4,402.58	14,408.78
		2049	6,344.28	3,742.05	4,437.59	14,523.92
		2050	5,981.74	3,550.05	4,165.25	13,697.04
	CON-SC3	2025	6,890.11	4,045.79	4,850.16	15,786.06
		2026	6,958.08	4,083.43	4,902.80	15,944.31
		2027	6,943.61	4,071.98	4,897.66	15,913.25
		2028	6,938.47	4,072.52	4,891.92	15,902.92

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2029	6,925.92	4,062.25	4,885.57	15,873.74
		2030	6,280.74	3,713.27	4,380.82	14,374.83
		2031	6,311.87	3,735.05	4,404.65	14,451.56
		2032	6,325.25	3,735.22	4,415.94	14,476.41
		2033	6,320.36	3,738.42	4,412.60	14,471.38
		2034	6,308.71	3,733.17	4,403.80	14,445.68
		2035	5,572.45	3,321.51	3,841.93	12,735.89
		2036	5,757.80	3,413.02	3,973.97	13,144.78
		2037	5,632.39	3,356.27	3,884.14	12,872.80
		2038	5,629.70	3,354.82	3,882.62	12,867.13
		2039	5,691.07	3,380.55	3,926.54	12,998.16
		2040	4,971.27	2,975.54	3,390.78	11,337.58
		2041	4,989.68	2,986.57	3,404.13	11,380.38
		2042	5,003.31	2,988.52	3,417.27	11,409.10
		2043	4,980.94	2,977.95	3,395.74	11,354.63
		2044	4,969.06	2,972.47	3,388.79	11,330.32
		2045	4,363.05	2,629.26	2,939.80	9,932.11
		2046	4,361.13	2,628.28	2,941.02	9,930.43
		2047	4,363.94	2,632.19	2,943.62	9,939.75
		2048	4,363.50	2,632.13	2,944.52	9,940.15
		2049	4,408.78	2,651.29	2,971.88	10,031.94
		2050	3,671.83	2,198.63	2,448.97	8,319.43
	CON-SC4	2025	6,523.23	3,847.68	4,561.48	14,932.38
		2026	6,585.68	3,882.46	4,609.82	15,077.97
		2027	6,569.96	3,870.51	4,603.75	15,044.22
		2028	6,565.89	3,871.52	4,598.82	15,036.22
		2029	6,553.02	3,861.19	4,592.25	15,006.46
		2030	5,262.28	3,145.44	3,593.67	12,001.39
		2031	5,286.48	3,162.99	3,611.96	12,061.43
		2032	5,294.87	3,161.66	3,619.62	12,076.15
		2033	5,290.40	3,164.63	3,616.52	12,071.55
		2034	5,281.87	3,160.65	3,610.04	12,052.56
		2035	3,932.75	2,358.06	2,622.15	8,912.96
		2036	4,059.08	2,420.32	2,709.93	9,189.32
		2037	3,973.96	2,382.14	2,650.29	9,006.38
		2038	3,971.04	2,380.90	2,648.64	9,000.58
		2039	4,013.45	2,398.09	2,678.26	9,089.81
		2040	2,680.91	1,603.71	1,742.90	6,027.52

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2041	2,690.11	1,609.29	1,749.26	6,048.67
		2042	2,692.32	1,607.71	1,752.81	6,052.84
		2043	2,688.83	1,606.43	1,747.22	6,042.48
		2044	2,680.23	1,602.47	1,742.24	6,024.93
		2045	1,651.60	973.37	1,039.43	3,664.40
		2046	1,647.33	971.22	1,037.55	3,656.10
		2047	1,646.68	971.70	1,037.38	3,655.76
		2048	1,644.29	970.57	1,036.29	3,651.16
		2049	1,666.54	980.77	1,049.33	3,696.63
		2050	1,634.37	965.15	1,028.95	3,628.47
	SRP-SC1	2025	285.61	150.22	153.49	589.31
		2026	280.69	147.75	150.75	579.20
		2027	288.50	151.21	155.18	594.89
		2028	289.59	151.96	155.84	597.39
		2029	289.85	151.87	156.02	597.74
		2030	395.30	205.16	214.01	814.47
		2031	399.23	207.03	216.26	822.52
		2032	396.90	205.89	214.95	817.75
		2033	397.26	206.07	215.15	818.49
		2034	392.37	203.85	212.32	808.53
		2035	479.19	247.36	260.43	986.98
		2036	475.64	245.80	258.31	979.74
		2037	489.25	252.21	266.06	1,007.52
		2038	477.17	246.42	259.28	982.87
		2039	486.78	250.96	264.69	1,002.43
		2040	602.55	310.17	328.39	1,241.11
		2041	599.74	308.24	326.99	1,234.97
		2042	596.48	307.58	325.07	1,229.14
		2043	600.41	309.27	327.17	1,236.85
		2044	594.78	306.22	324.12	1,225.12
		2045	664.50	342.26	362.26	1,369.02
		2046	667.33	343.76	364.07	1,375.15
		2047	669.46	344.50	365.29	1,379.25
		2048	667.29	343.91	364.06	1,375.26
		2049	675.65	347.35	368.76	1,391.75
		2050	756.60	388.85	413.39	1,558.84
	SRP-SC2	2025	423.33	216.96	235.88	876.17
		2026	415.87	213.28	231.66	860.80

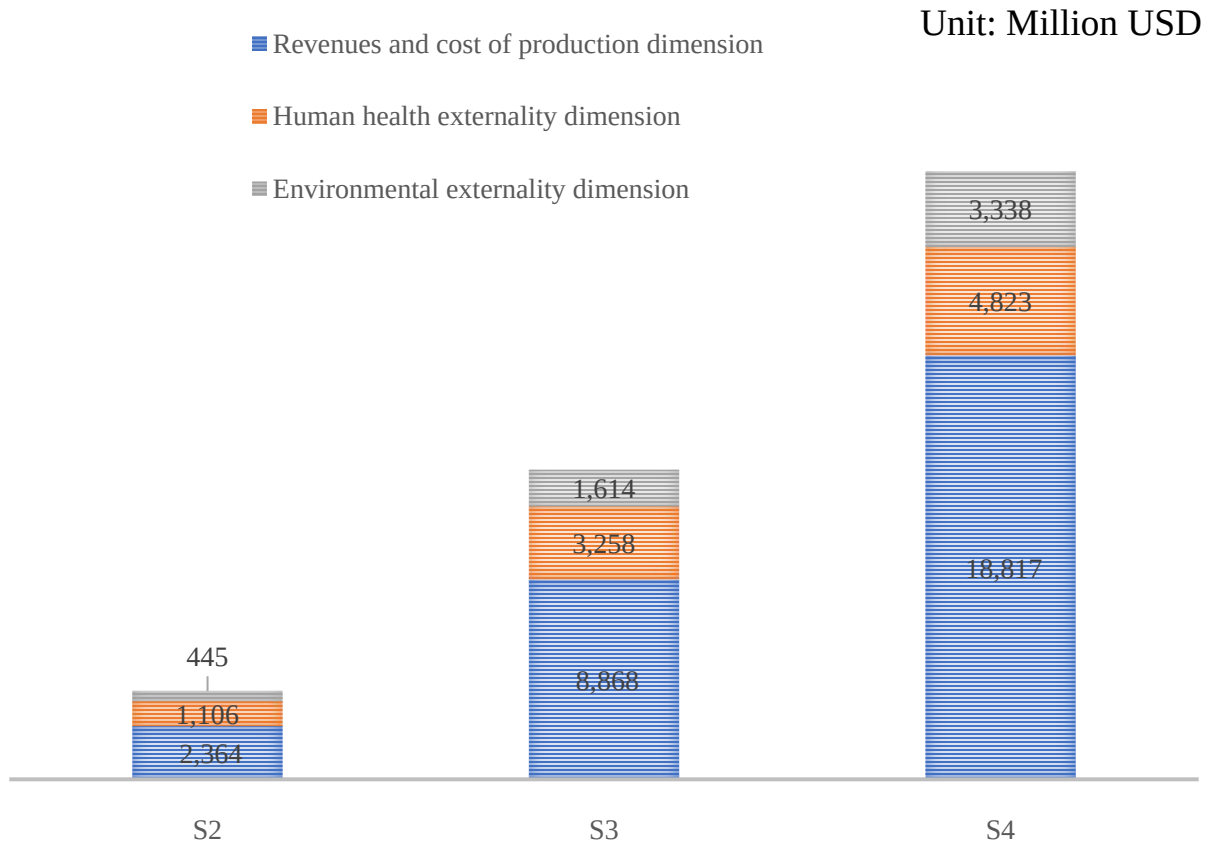
Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2027	428.14	218.79	238.70	885.63
		2028	430.11	220.00	239.85	889.96
		2029	430.76	220.06	240.26	891.08
		2030	783.50	402.26	441.92	1,627.68
		2031	792.04	406.34	446.84	1,645.21
		2032	787.13	403.94	444.03	1,635.11
		2033	787.78	404.28	444.40	1,636.46
		2034	777.04	399.37	438.17	1,614.58
		2035	1,089.99	562.83	616.40	2,269.21
		2036	1,080.31	558.54	610.73	2,249.59
		2037	1,114.12	574.42	630.22	2,318.76
		2038	1,084.97	560.50	613.50	2,258.97
		2039	1,108.19	571.40	626.84	2,306.43
		2040	1,454.46	754.47	823.66	3,032.59
		2041	1,448.51	749.95	820.50	3,018.96
		2042	1,440.39	748.72	815.57	3,004.67
		2043	1,449.10	752.25	820.54	3,021.89
		2044	1,435.47	744.74	812.87	2,993.07
		2045	1,783.81	931.26	1,009.52	3,724.60
		2046	1,794.45	936.95	1,015.73	3,747.14
		2047	1,800.88	939.06	1,019.51	3,759.45
		2048	1,795.18	937.93	1,016.10	3,749.21
		2049	1,818.08	946.86	1,029.41	3,794.35
		2050	2,164.37	1,133.63	1,224.57	4,522.57
	SRP-SC3	2025	804.49	413.16	454.87	1,672.51
		2026	790.01	406.02	446.60	1,642.63
		2027	813.97	416.74	460.44	1,691.15
		2028	818.06	419.25	462.78	1,700.08
		2029	819.38	419.37	463.61	1,702.36
		2030	1,787.97	928.51	1,015.61	3,732.10
		2031	1,807.95	938.06	1,027.14	3,773.15
		2032	1,796.62	932.49	1,020.63	3,749.74
		2033	1,798.35	933.39	1,021.62	3,753.37
		2034	1,772.94	921.83	1,006.88	3,701.64
		2035	2,750.49	1,442.42	1,553.61	5,746.52
		2036	2,726.46	1,431.91	1,539.54	5,697.91
		2037	2,811.54	1,471.83	1,588.58	5,871.96
		2038	2,737.61	1,436.47	1,546.18	5,720.27

Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2039	2,796.14	1,463.92	1,579.81	5,839.87
		2040	3,782.03	1,987.87	2,116.14	7,886.04
		2041	3,766.59	1,975.52	2,108.19	7,850.31
		2042	3,745.75	1,973.33	2,095.52	7,814.59
		2043	3,769.17	1,982.69	2,108.65	7,860.51
		2044	3,733.31	1,962.58	2,088.71	7,784.61
		2045	4,733.51	2,502.85	2,616.43	9,852.79
		2046	4,757.08	2,515.81	2,630.73	9,903.62
		2047	4,775.11	2,521.67	2,641.19	9,937.97
		2048	4,760.01	2,518.99	2,632.37	9,911.36
		2049	4,819.28	2,541.66	2,666.27	10,027.21
		2050	5,730.83	3,033.60	3,135.03	11,899.47
	SRP-SC4	2025	1,361.91	706.32	774.20	2,842.43
		2026	1,337.01	693.99	759.93	2,790.92
		2027	1,378.10	712.23	783.74	2,874.07
		2028	1,385.30	716.75	787.83	2,889.89
		2029	1,387.46	716.80	789.19	2,893.44
		2030	3,350.06	1,757.13	1,889.98	6,997.17
		2031	3,387.15	1,774.87	1,911.37	7,073.38
		2032	3,366.09	1,764.49	1,899.31	7,029.89
		2033	3,369.74	1,766.37	1,901.39	7,037.50
		2034	3,322.30	1,744.86	1,873.87	6,941.04
		2035	5,275.13	2,789.22	2,906.63	10,970.98
		2036	5,234.03	2,771.53	2,882.26	10,887.81
		2037	5,388.97	2,844.30	2,970.89	11,204.16
		2038	5,251.43	2,778.28	2,893.04	10,922.75
		2039	5,359.76	2,829.21	2,954.50	11,143.47
		2040	7,330.54	3,857.47	3,955.46	15,143.46
		2041	7,297.06	3,832.20	3,939.31	15,068.56
		2042	7,258.58	3,827.84	3,916.39	15,002.81
		2043	7,307.97	3,848.41	3,942.45	15,098.83
		2044	7,238.17	3,809.40	3,905.03	14,952.59
		2045	8,843.58	4,660.15	4,690.44	18,194.18
		2046	8,872.24	4,676.32	4,710.16	18,258.71
		2047	8,904.43	4,687.24	4,728.31	18,319.97
		2048	8,875.70	4,680.87	4,712.37	18,268.94
		2049	8,983.28	4,723.30	4,771.80	18,478.38
		2050	8,845.41	4,658.74	4,697.18	18,201.33

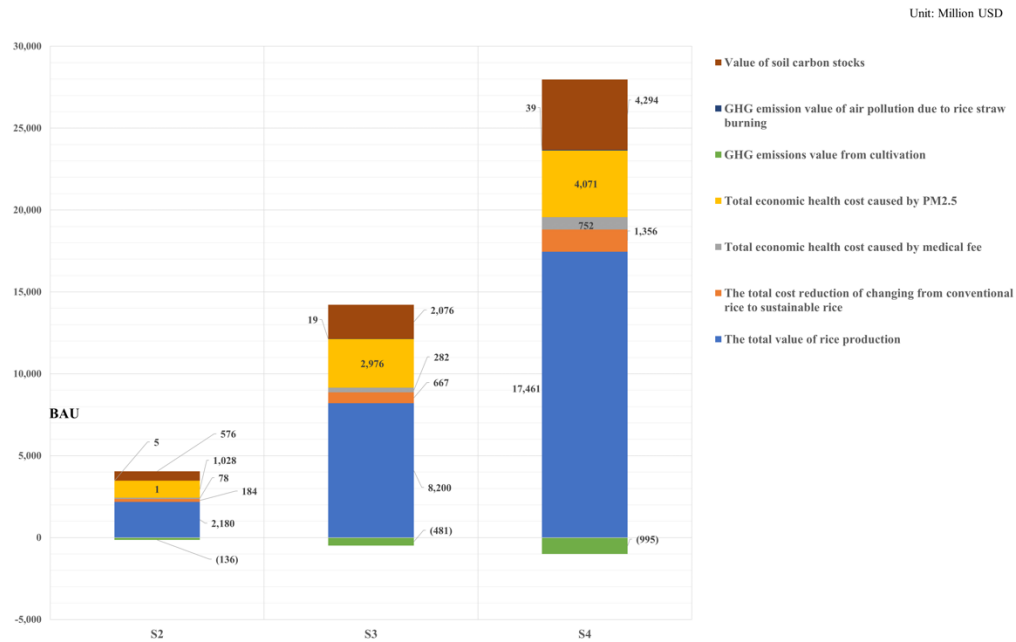
Region	Cultivation practice	Year	WU green (10 ⁶ x m ³)	WU blue (10 ⁶ x m ³)	WU grey (10 ⁶ x m ³)	WU total (10 ⁶ x m ³)
		2040	7,330.54	3,857.47	3,955.46	15,143.46
		2041	7,297.06	3,832.20	3,939.31	15,068.56
		2042	7,258.58	3,827.84	3,916.39	15,002.81
		2043	7,307.97	3,848.41	3,942.45	15,098.83

Appendix 6: The value of GHG emission was represented by average closing spot prices of Thailand Greenhouse Gas Management Organization

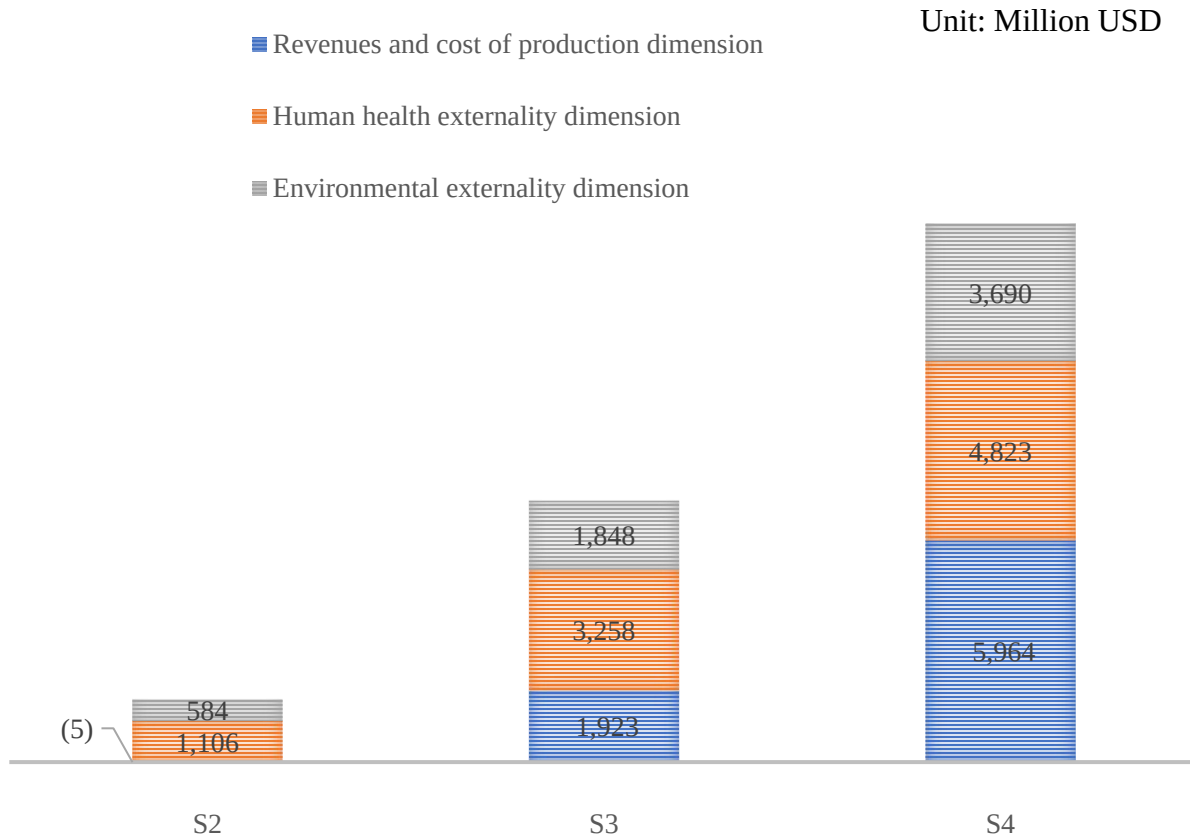
The value of GHG emission was represented by average closing spot prices of Thailand Greenhouse Gas Management Organization: TGO (2021) average price of carbon credit at about \$5 per ton of carbon.



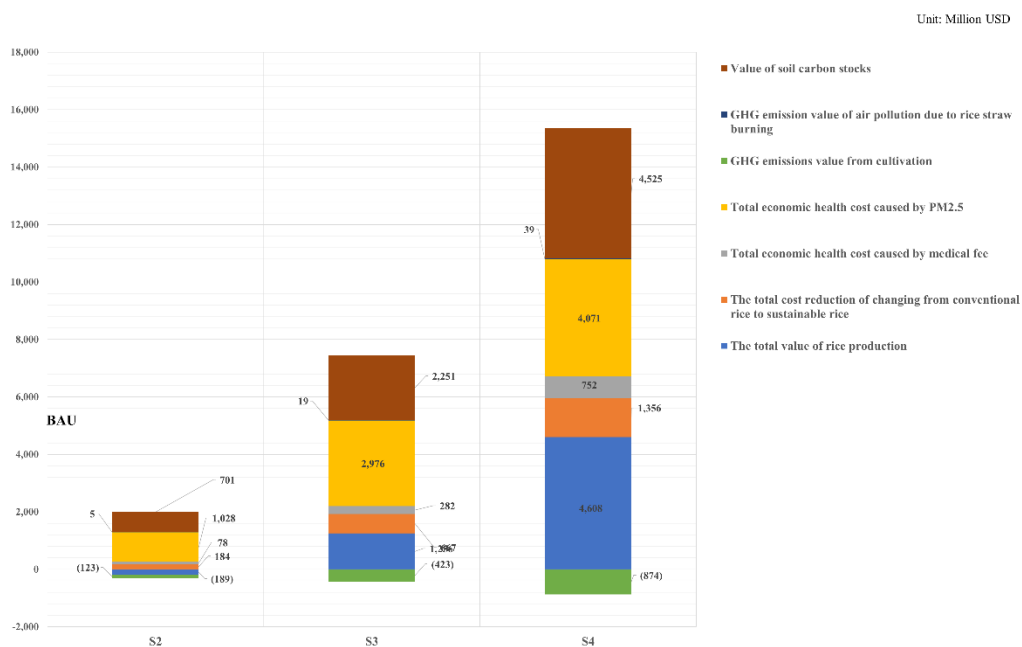
Appendix 6.1 the overall benefit values of double crops option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



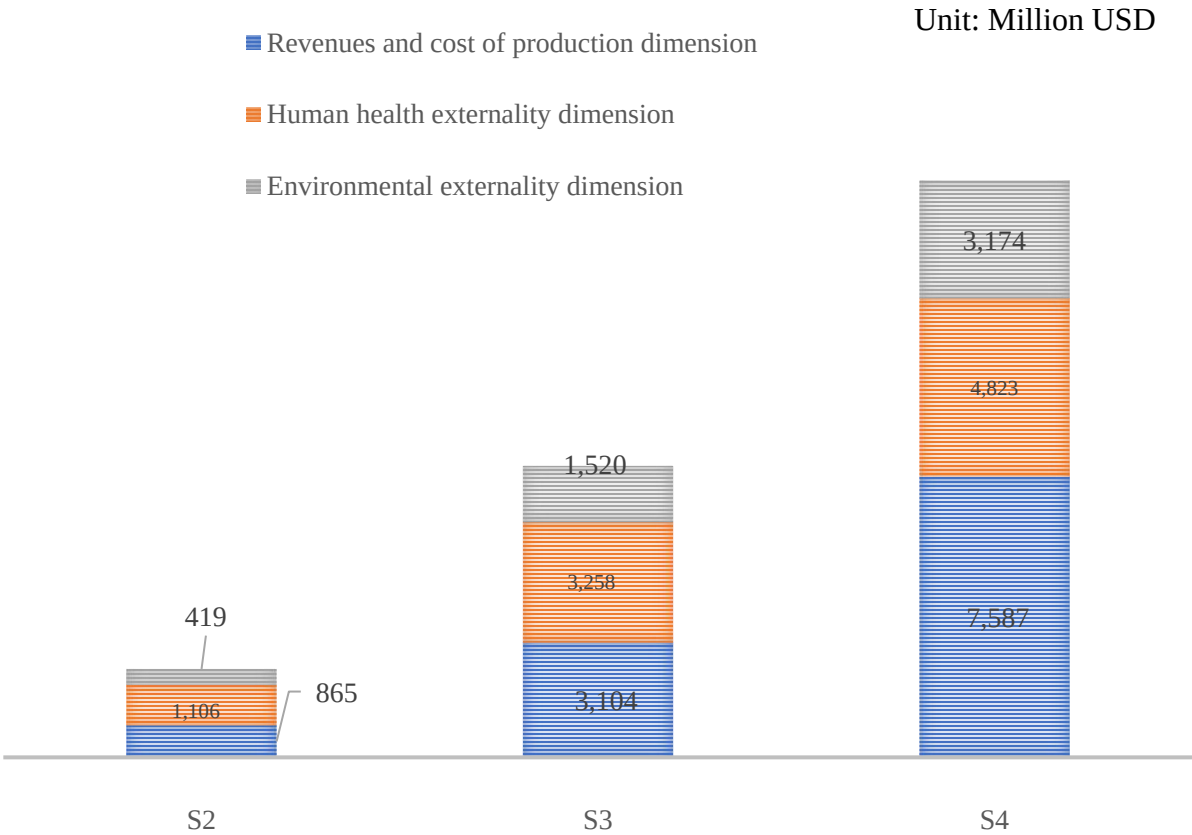
Appendix 6.2 the overall benefit values of double crops option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



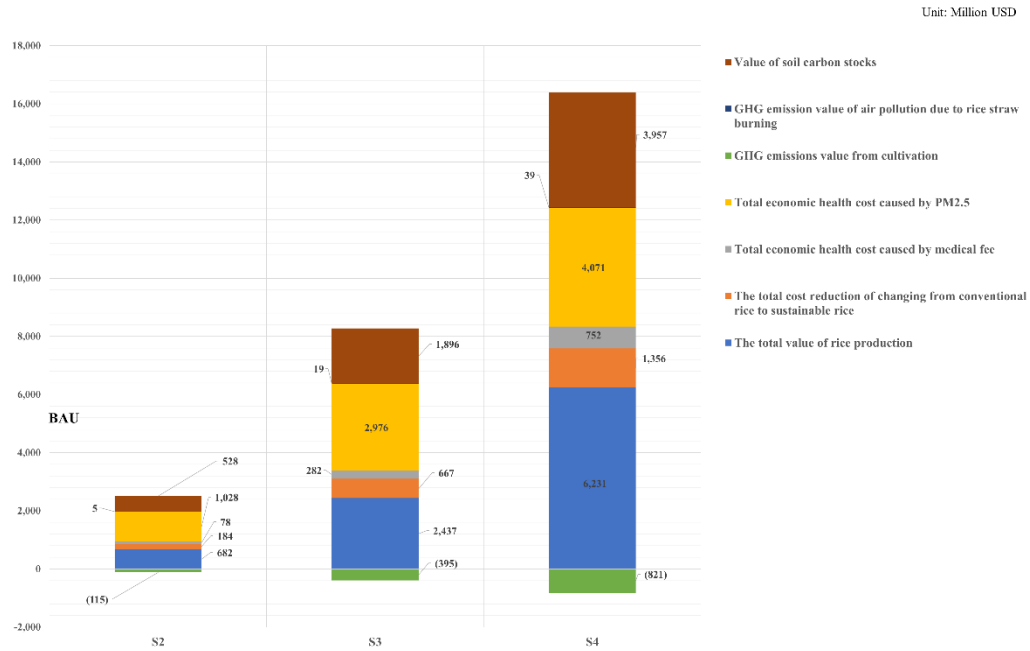
Appendix 6.3 the overall benefit values of rice-maize option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



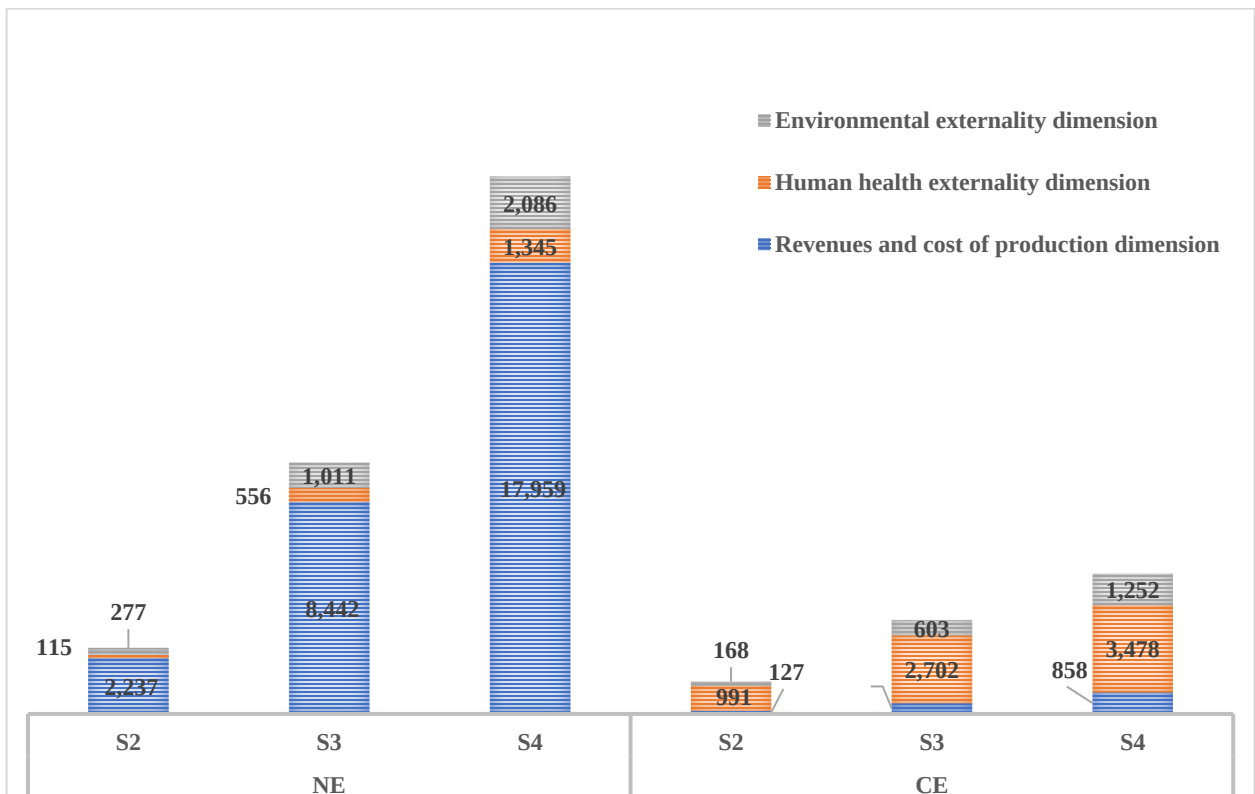
Appendix 6.4 the overall benefit values of rice-maize option in more details in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



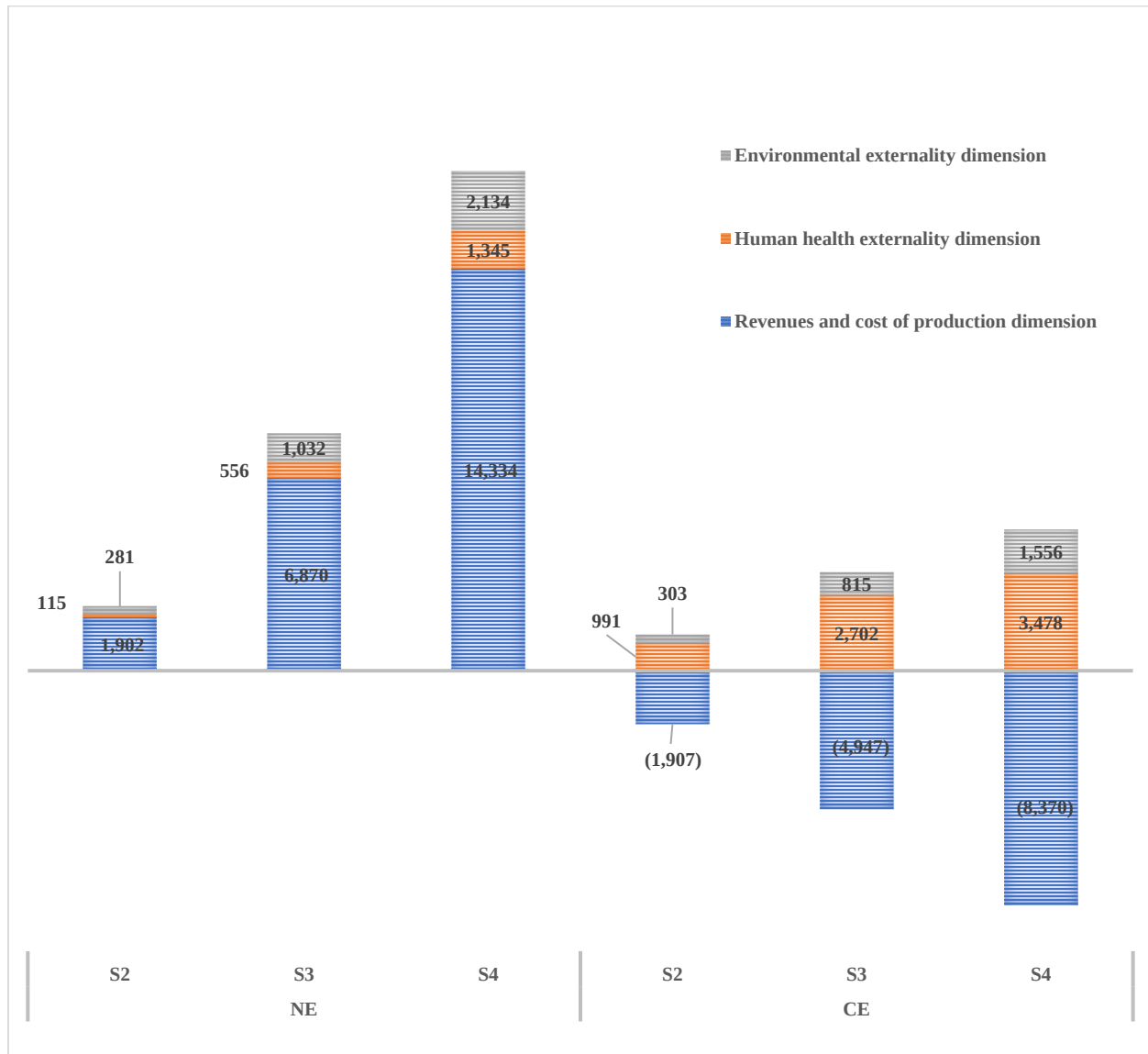
Appendix 6.5 the overall benefit values of rice-sunn hemp option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



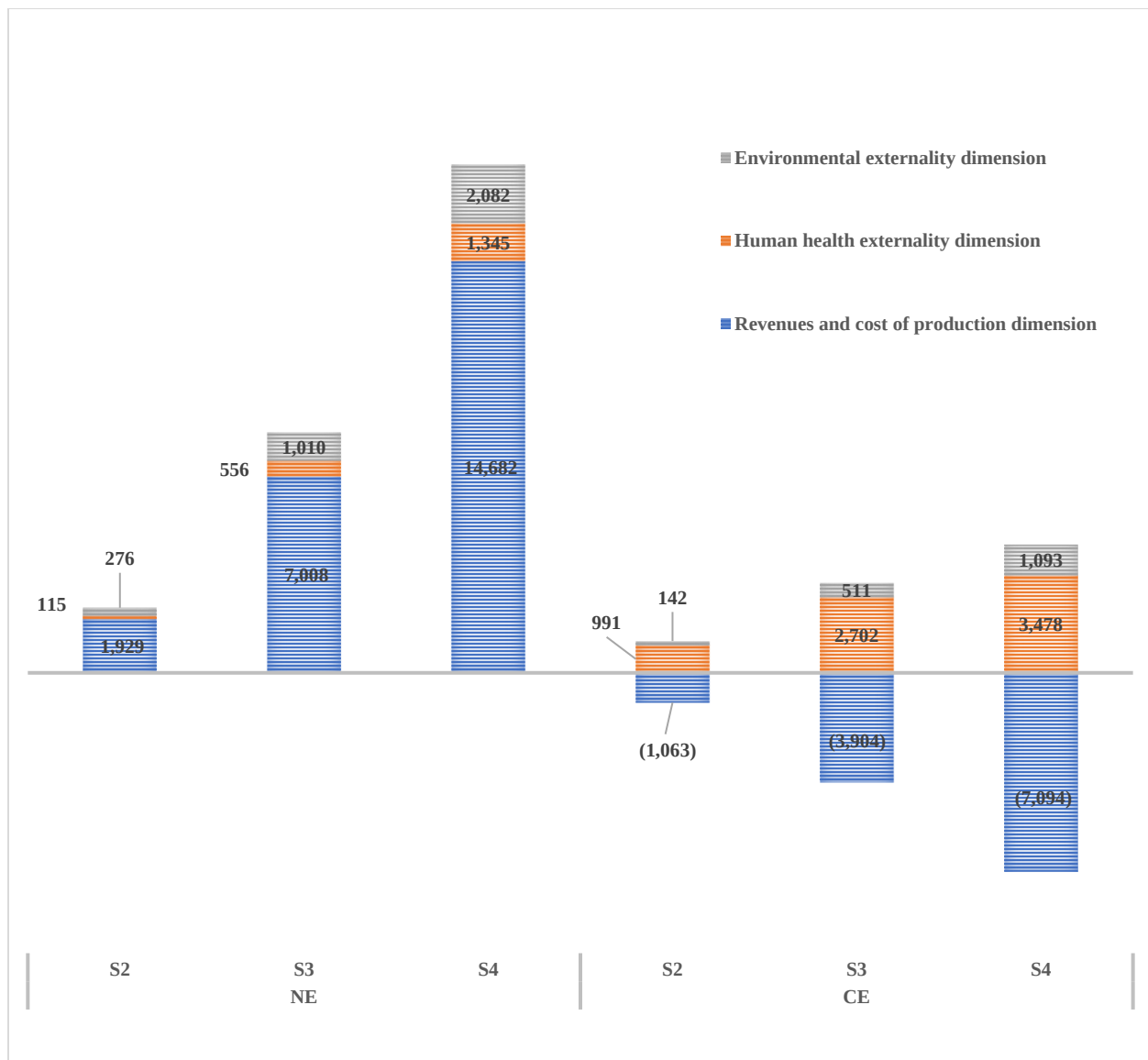
Appendix 6.6 the overall benefit values of rice-sunn hemp option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



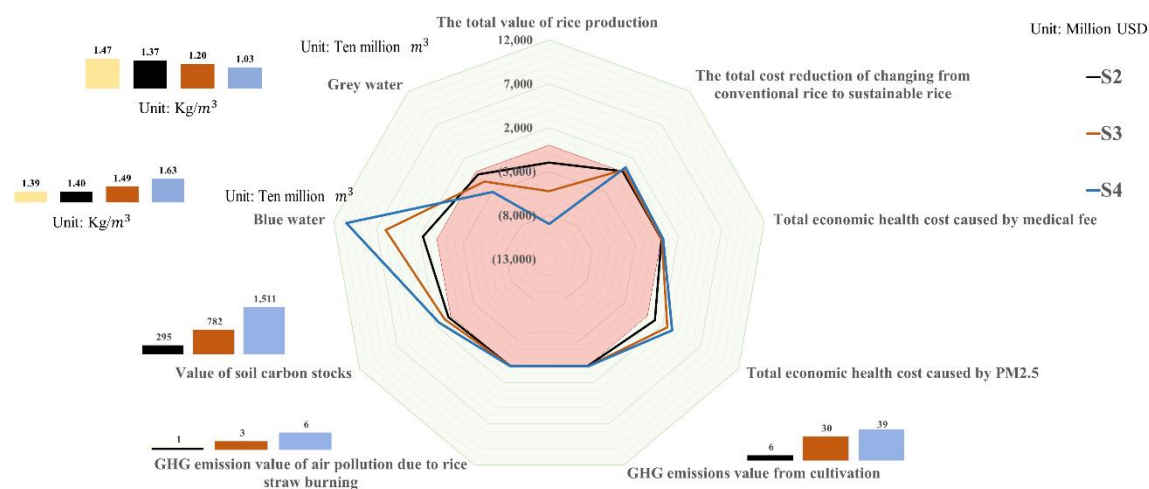
Appendix 6.7 the net benefit values of double crops option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



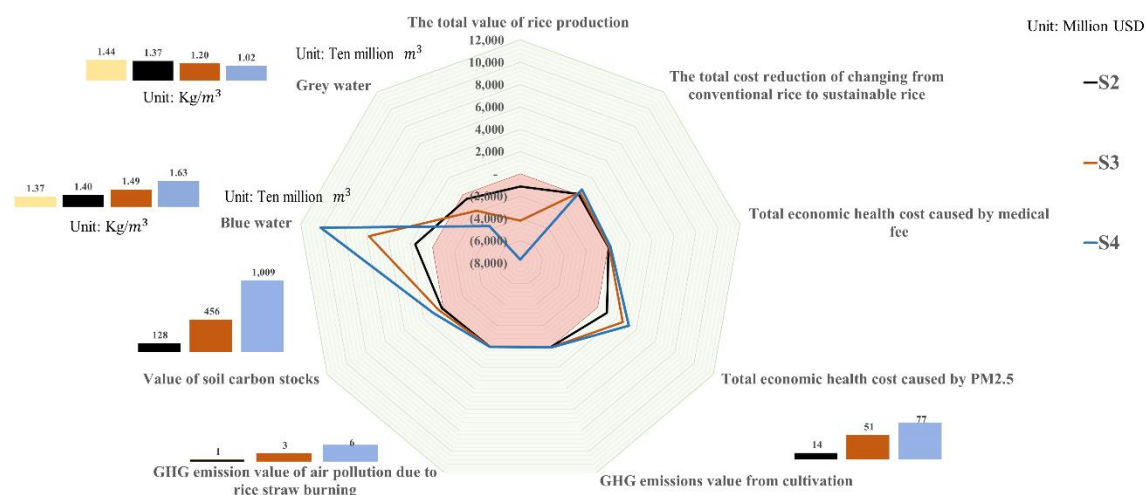
Appendix 6.8 the net benefit values of rice-maize option comparing between the northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



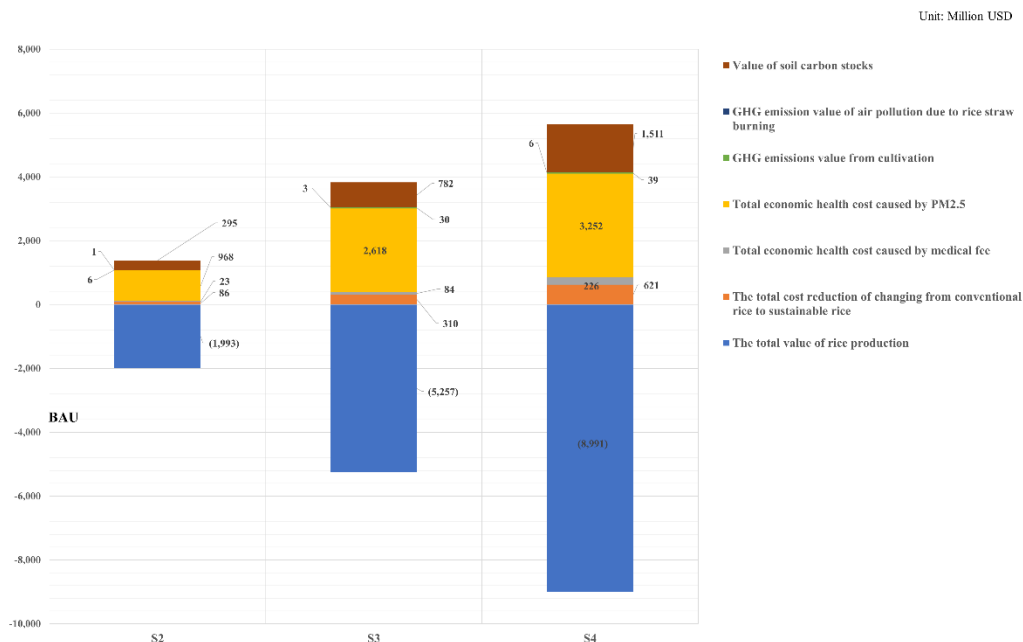
Appendix 6.9 the net benefit values of rice-sunn hemp option comparing between northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$5 per ton



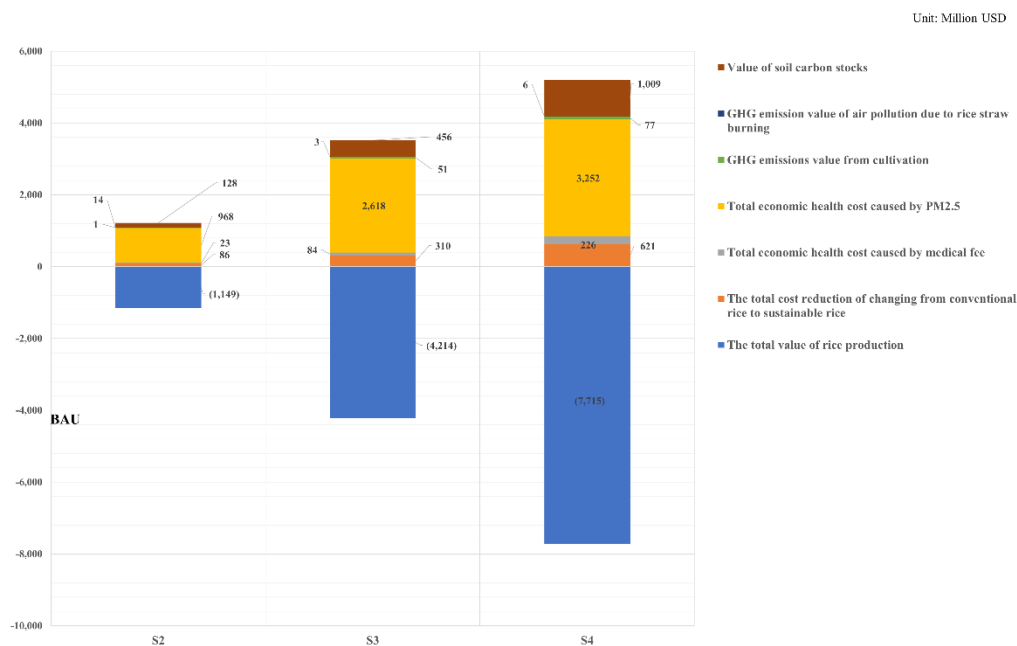
Appendix 6.12 The shapes of trade-off chart with rice-maize option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton



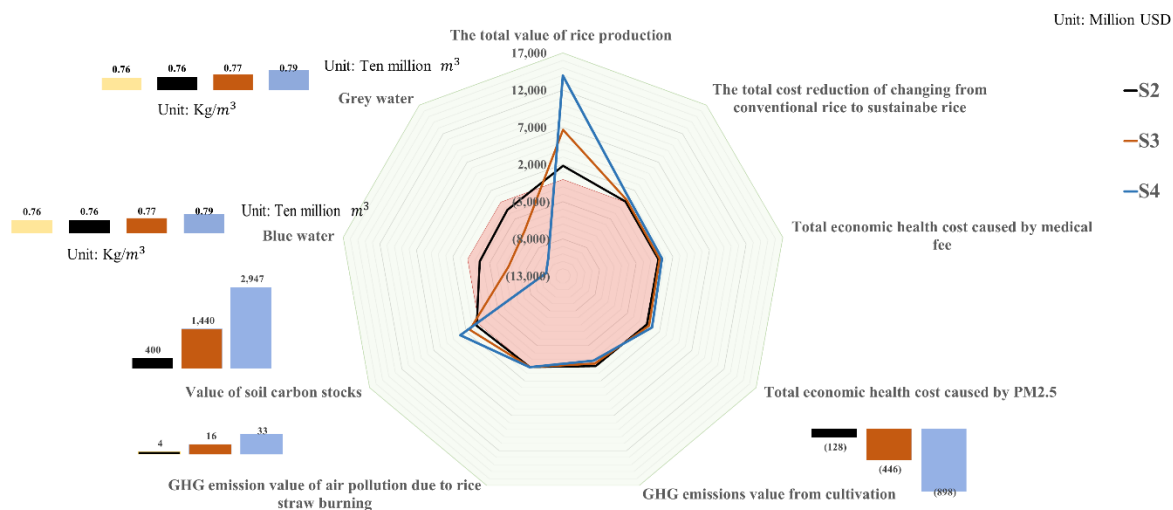
Appendix 6.13 The shapes of trade-off chart with rice-sunn hemp option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton



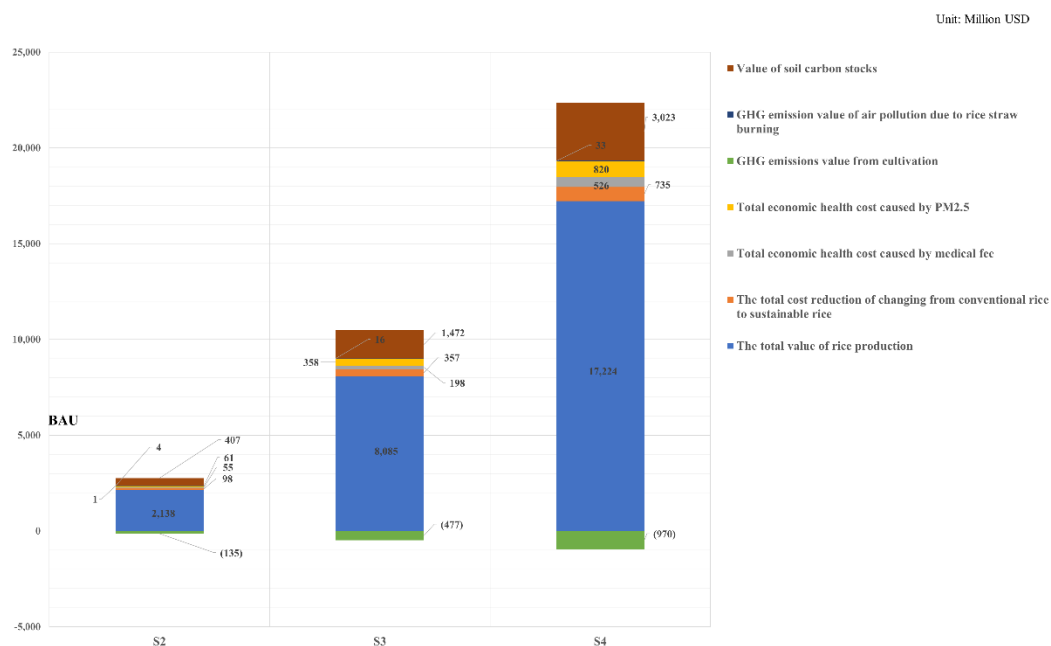
Appendix 6.14 The scenario analysis based on values with rice-maize option in more details in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton



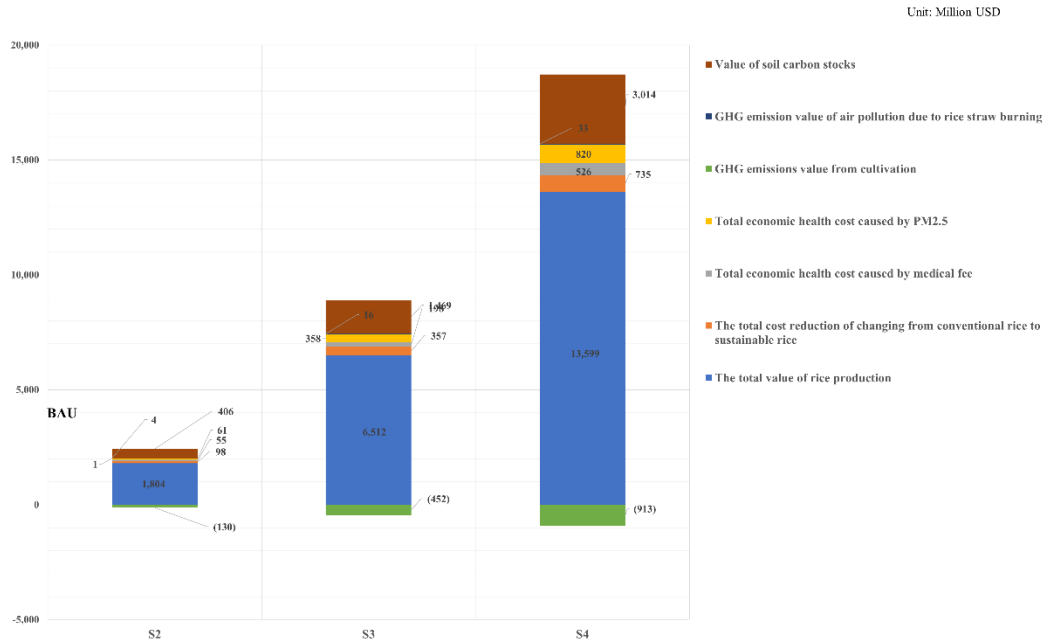
Appendix 6.15 The scenario analysis based on values with rice-sunn hemp option in more detail in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton



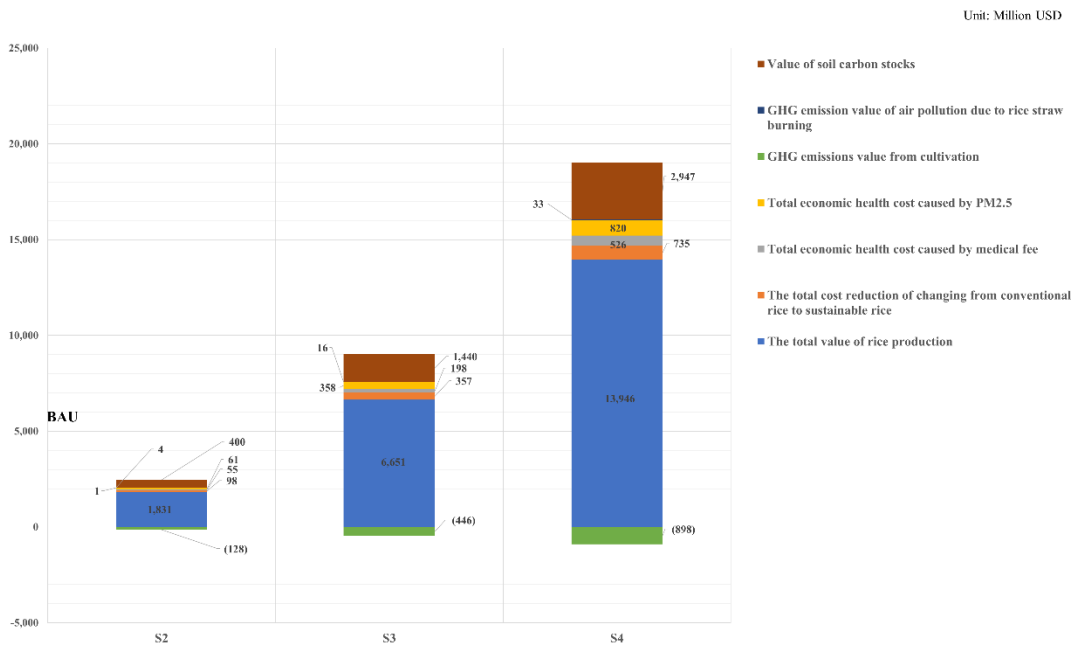
Appendix 6.18 The shapes of trade-off chart with rice-sunn hemp option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton



Appendix 6.19 The scenario analysis based on values with double crops option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton

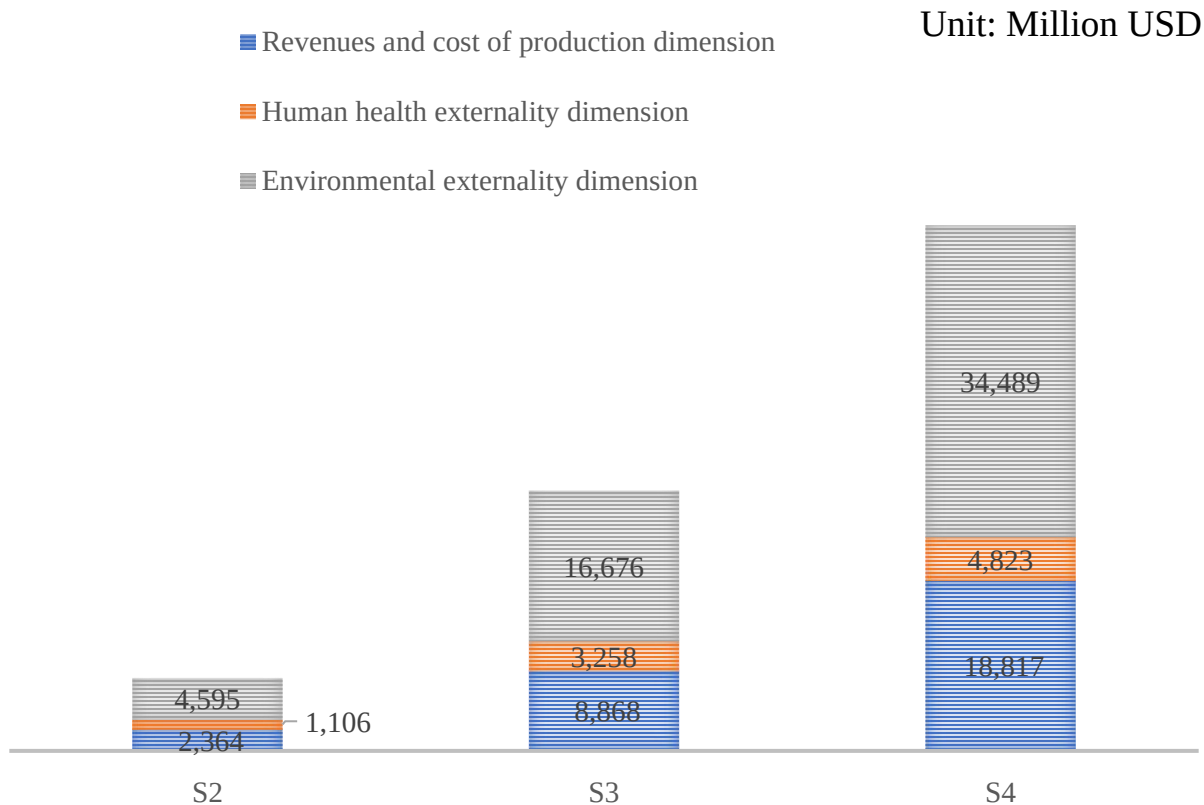


Appendix 6.20 The scenario analysis based on values with rice-maize option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton

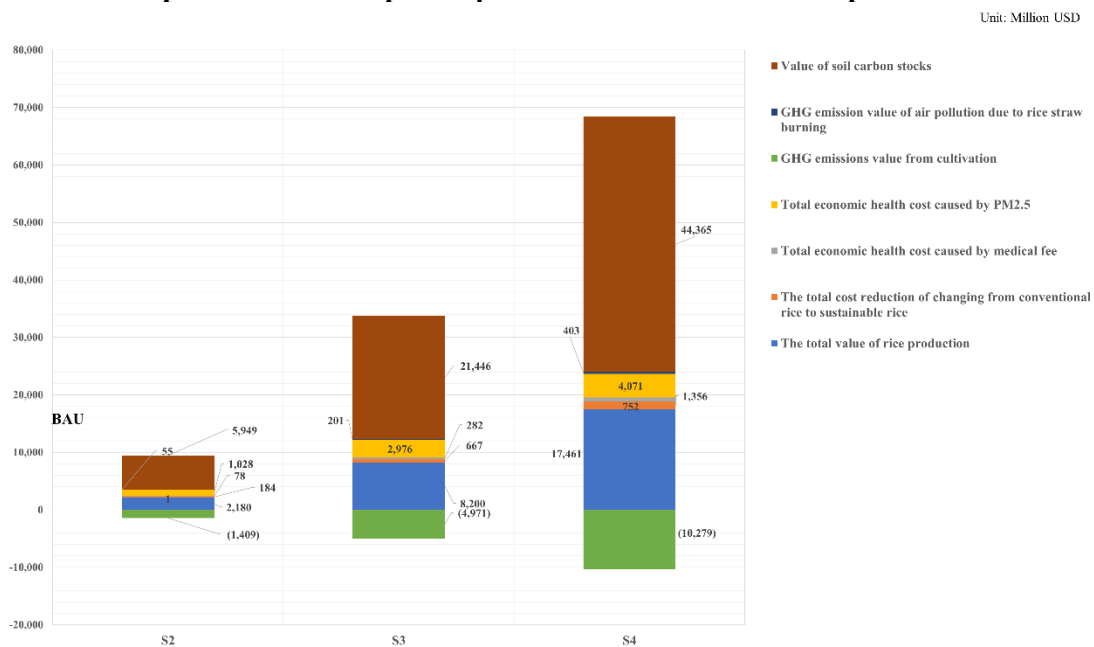


Appendix 6.21 The scenario analysis based on values with rice-sunn hemp option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$5 per ton

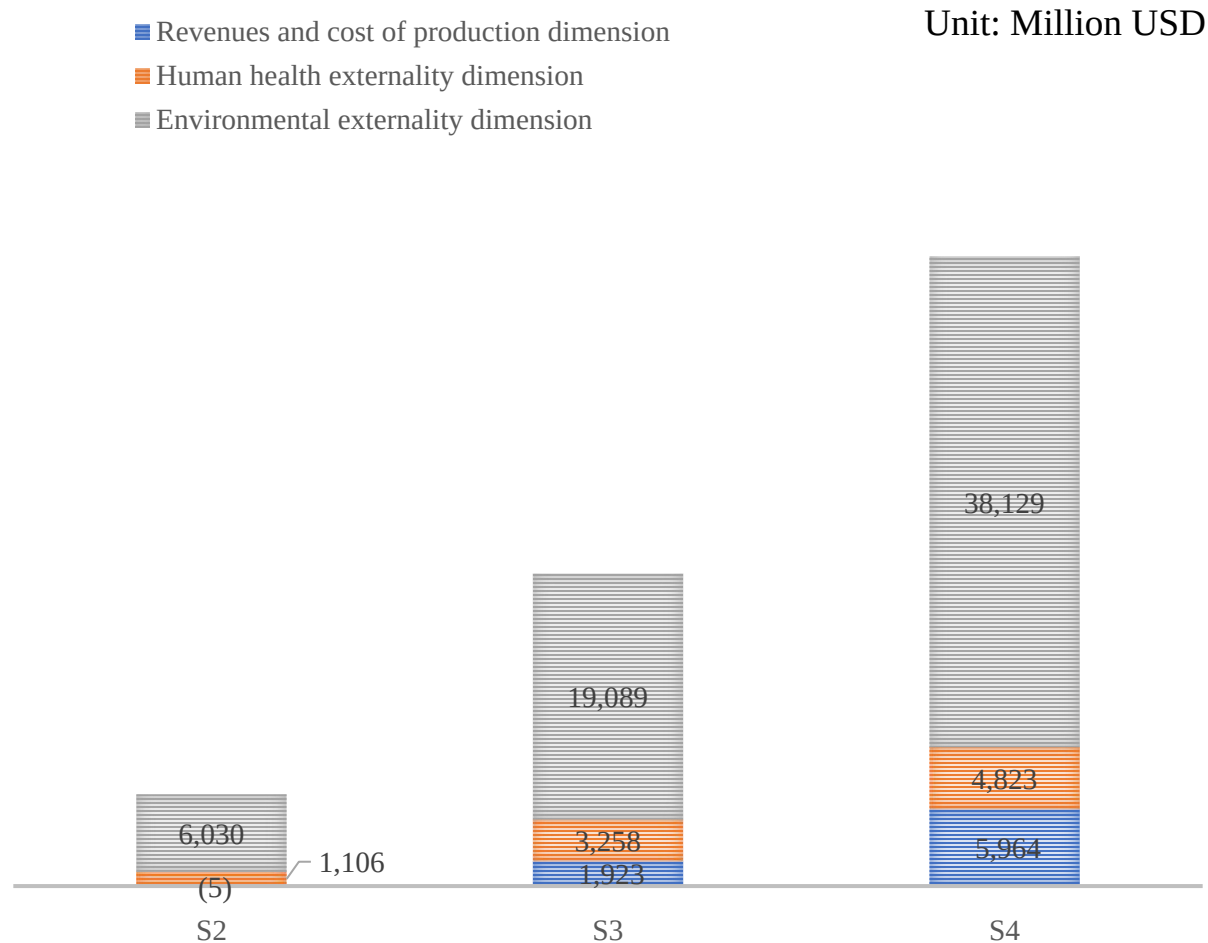
The value of GHG emission was represented by average closing spot prices of the social cost of carbon SCC (2017) average price of carbon credit at about \$51 per ton of carbon.



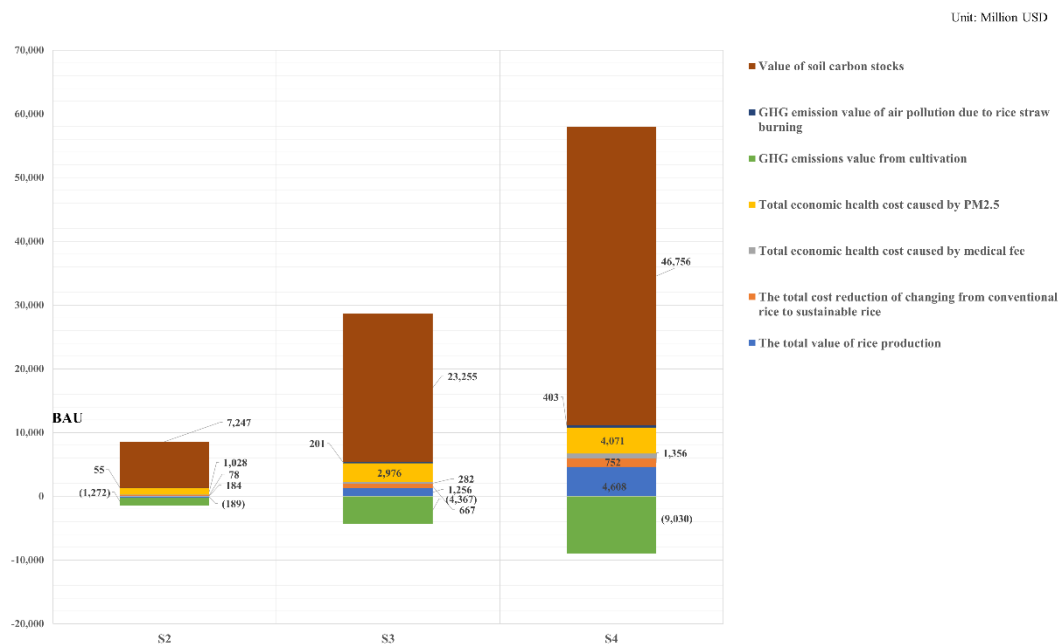
Appendix 6.22 the overall benefit values of double crops option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



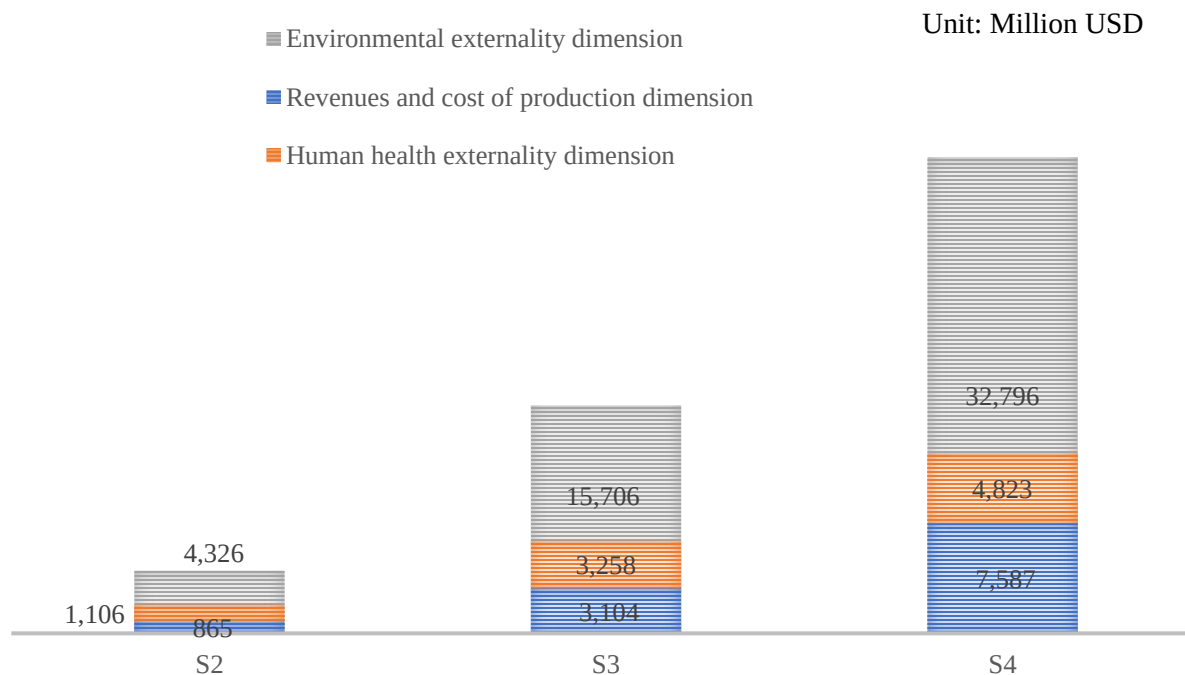
Appendix 6.23 the overall benefit values of double crops option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



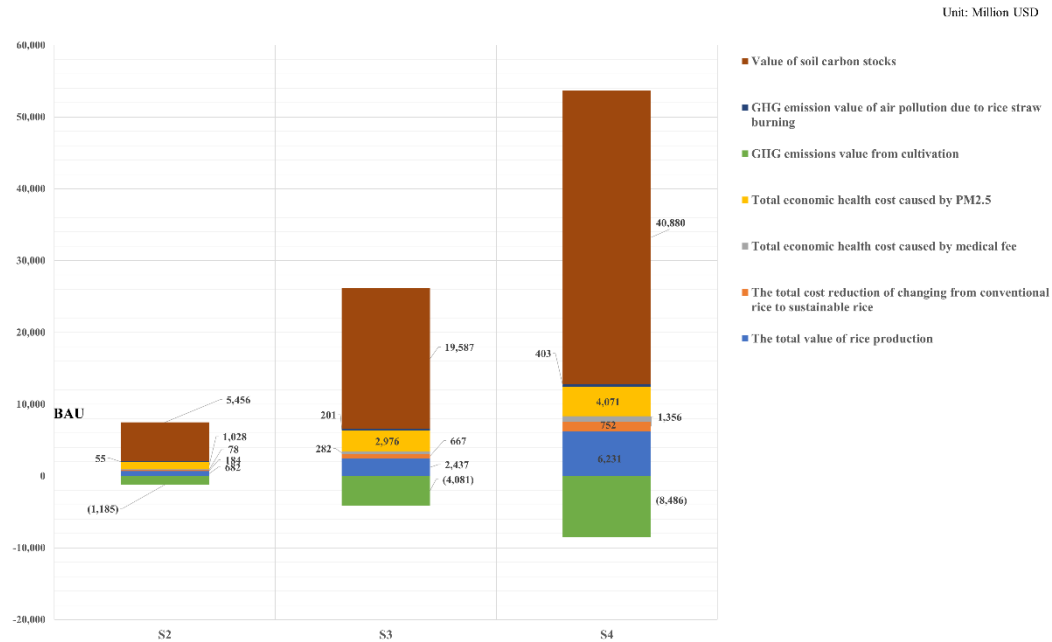
Appendix 6.24 the overall benefit values of rice-maize option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



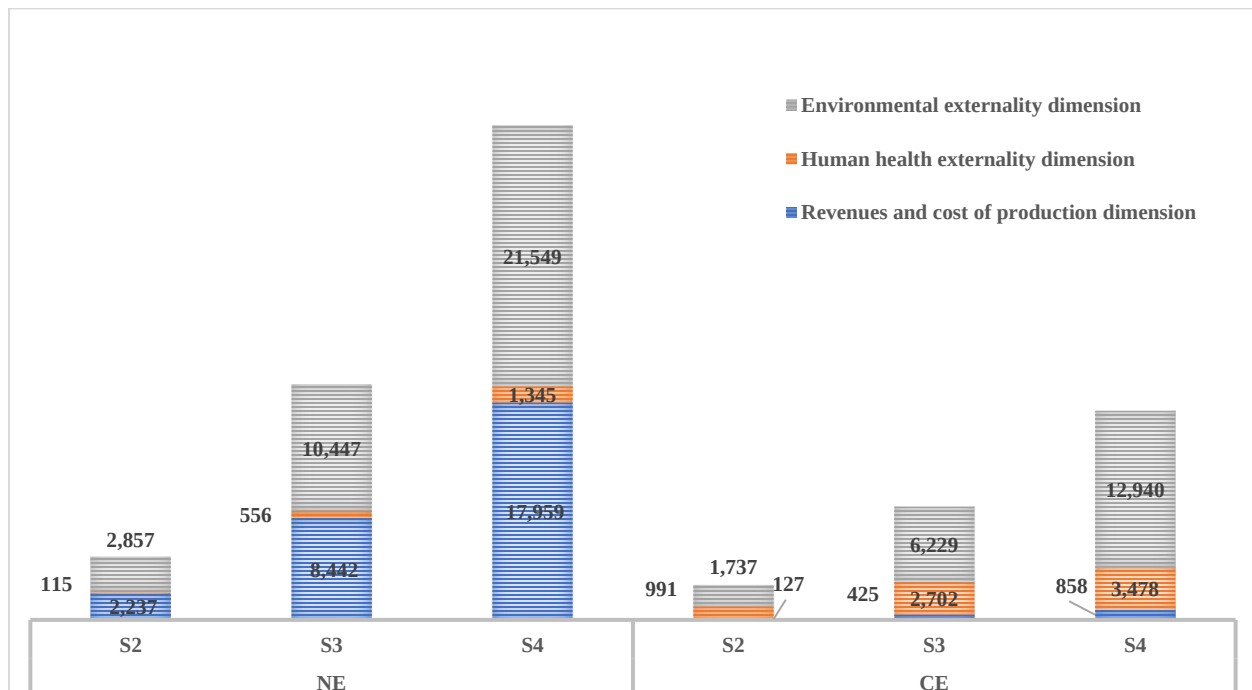
Appendix 6.25 the overall benefit values of rice-maize option in more details in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



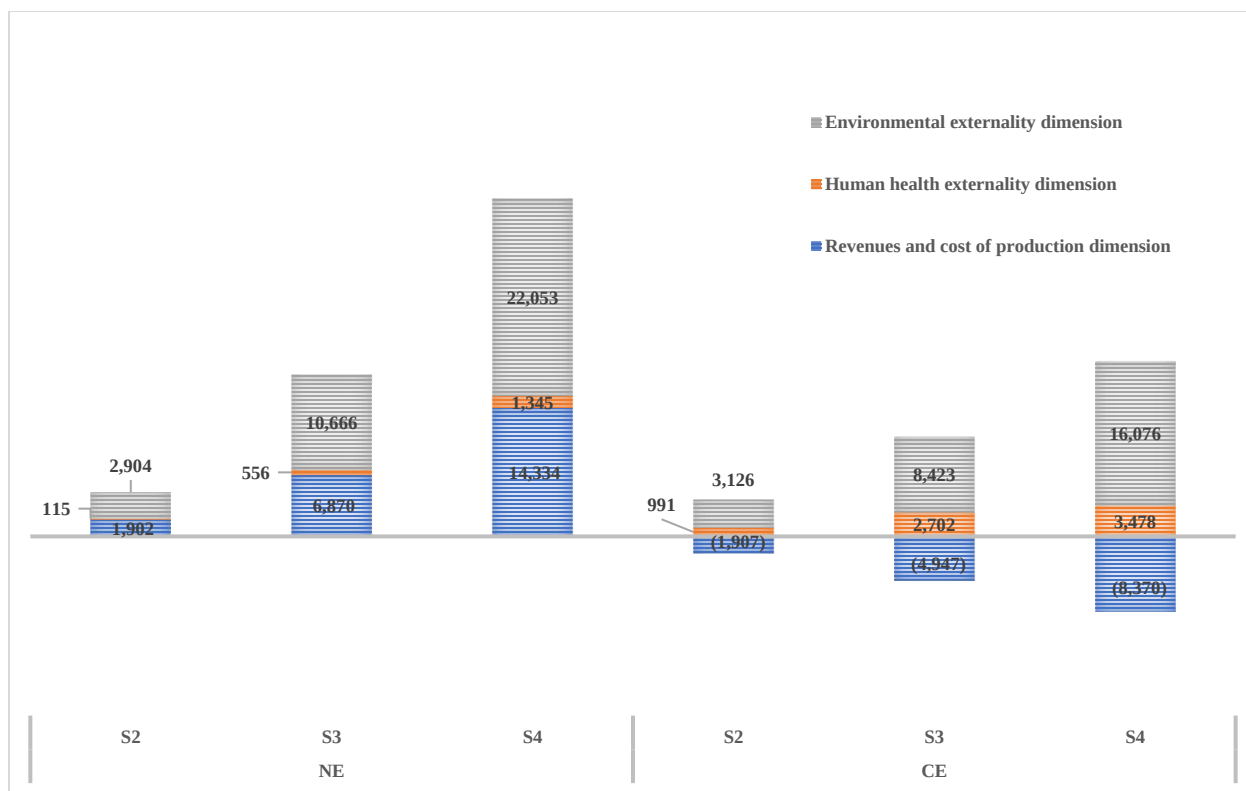
Appendix 6.26 the overall benefit values of rice-sunn hemp option in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



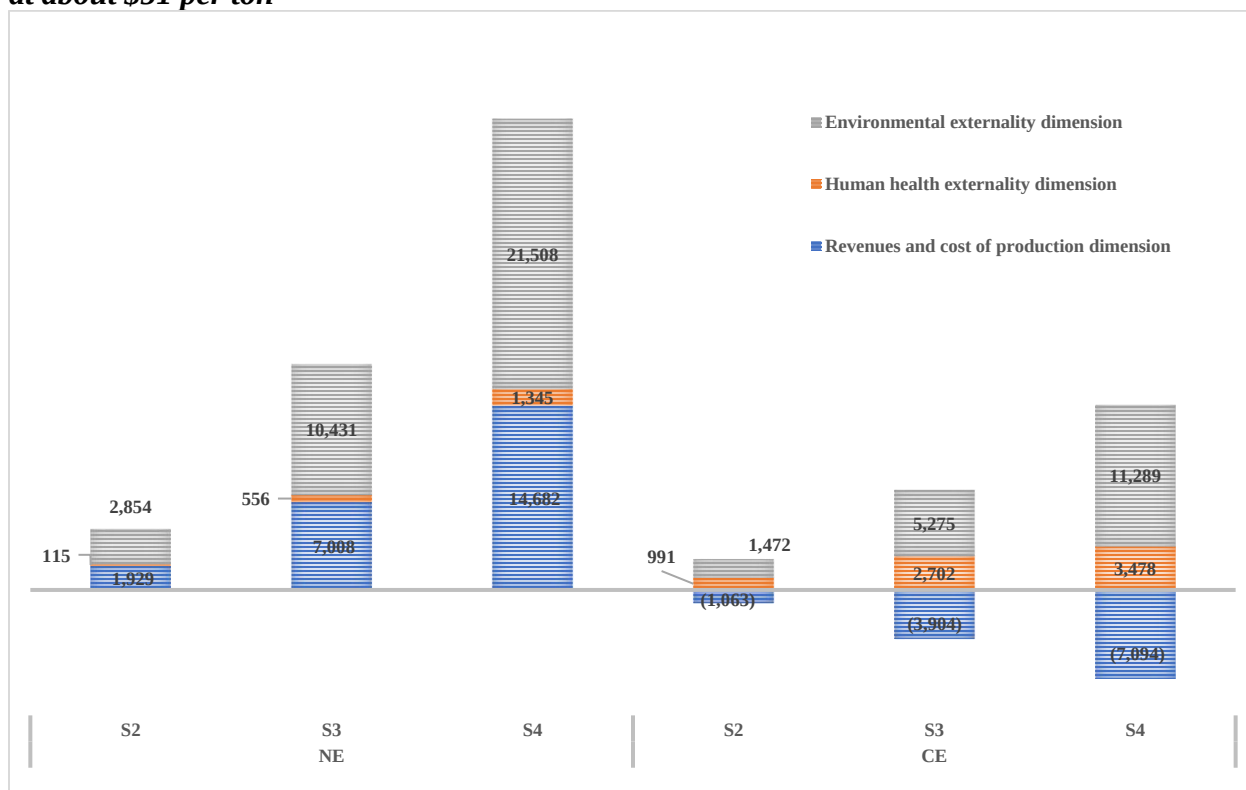
Appendix 6.27 the overall benefit values of rice-sunn hemp option in more detail in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



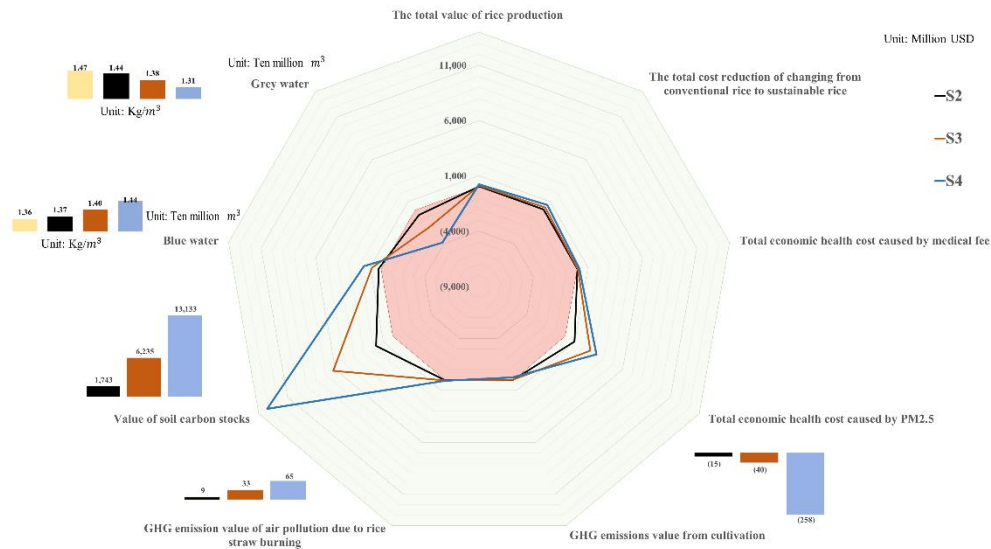
Appendix 6.28 the net benefit values of double crops option comparing between northeast and central region in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



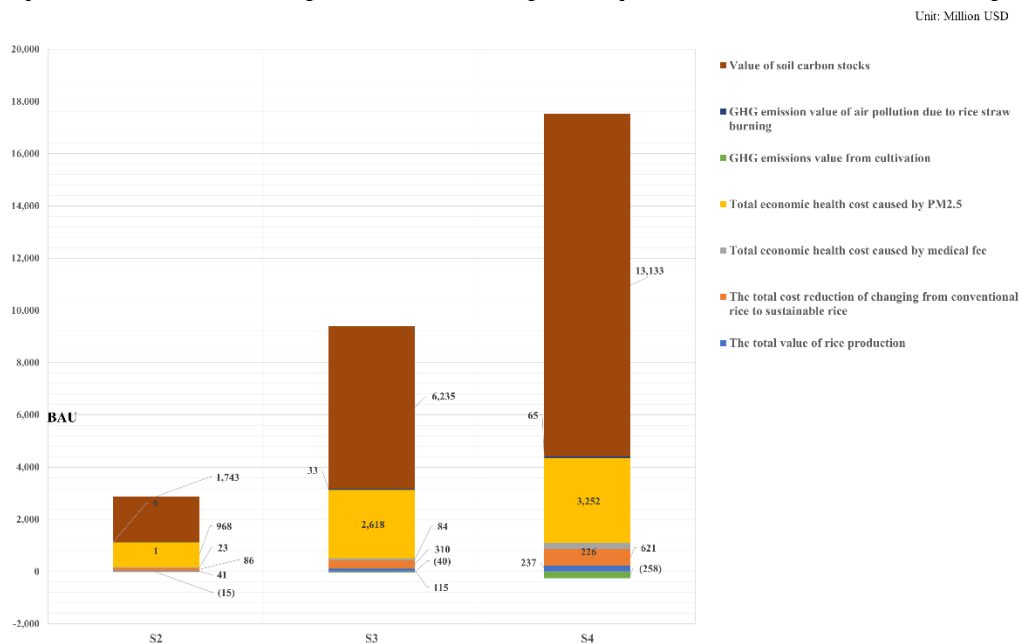
Appendix 6.29 the net benefit values of rice-maize option comparing between the northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



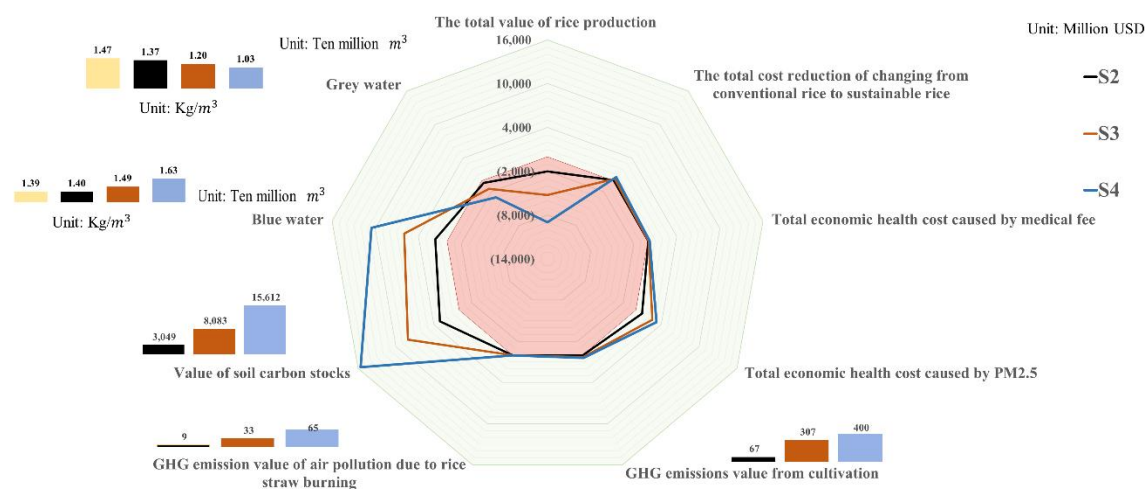
Appendix 6.30 the net benefit values of rice-sunn hemp option comparing between northeast and central regions in each scenario from 2021 to 2050 compared to BAU at price of carbon credit at about \$51 per ton



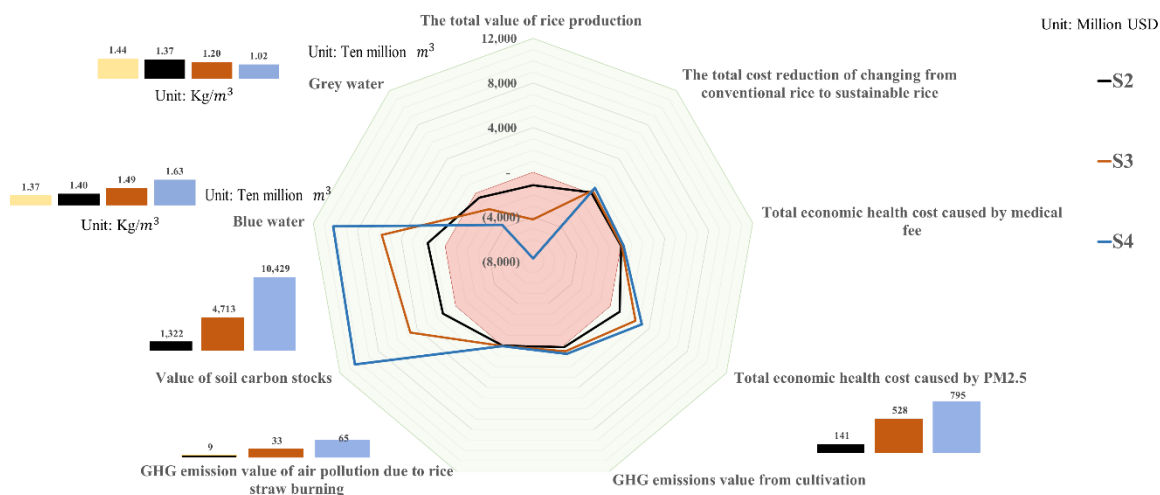
Appendix 6.31 The shapes of trade-off chart with rice-rice option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



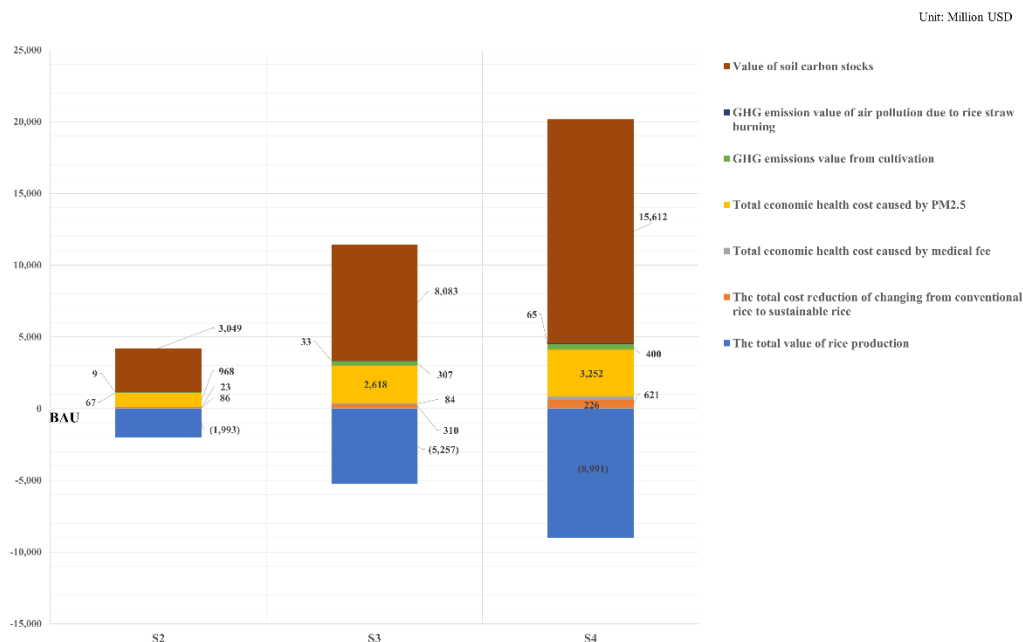
Appendix 6.32 The scenario analysis based on values with rice-rice option in more details in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



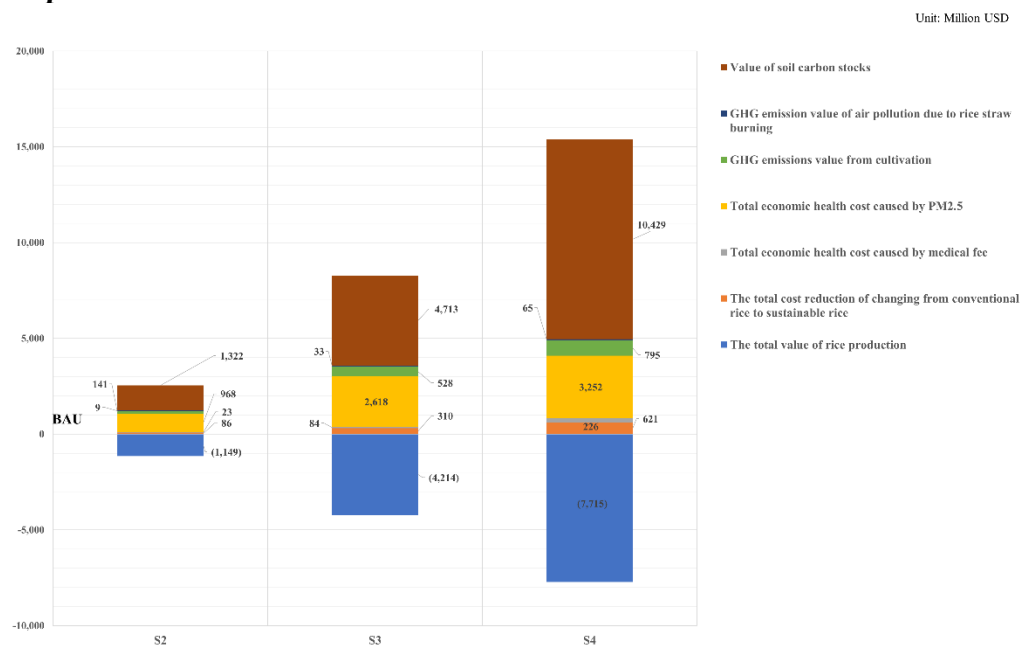
Appendix 6.33 The shapes of trade-off chart with rice-maize option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



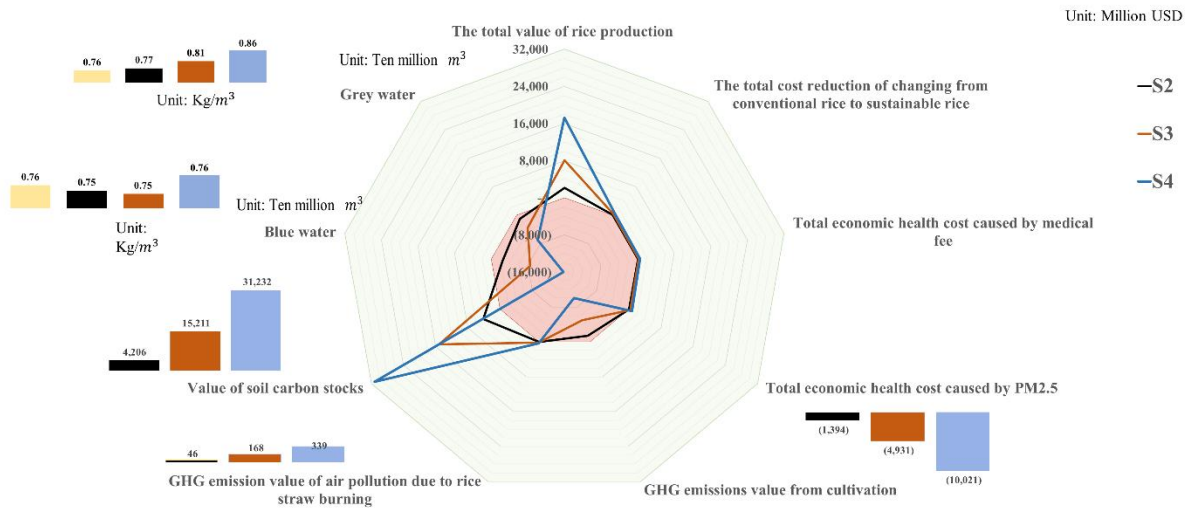
Appendix 6.34 The shapes of trade-off chart with rice-sunn hemp option in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



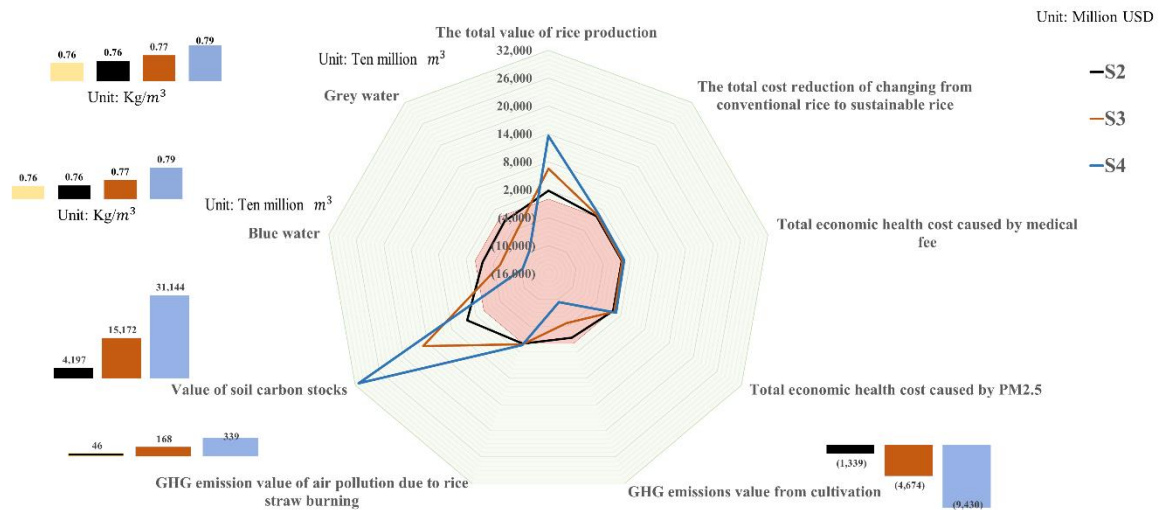
Appendix 6.35 The scenario analysis based on values with rice-maize option in more details in central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



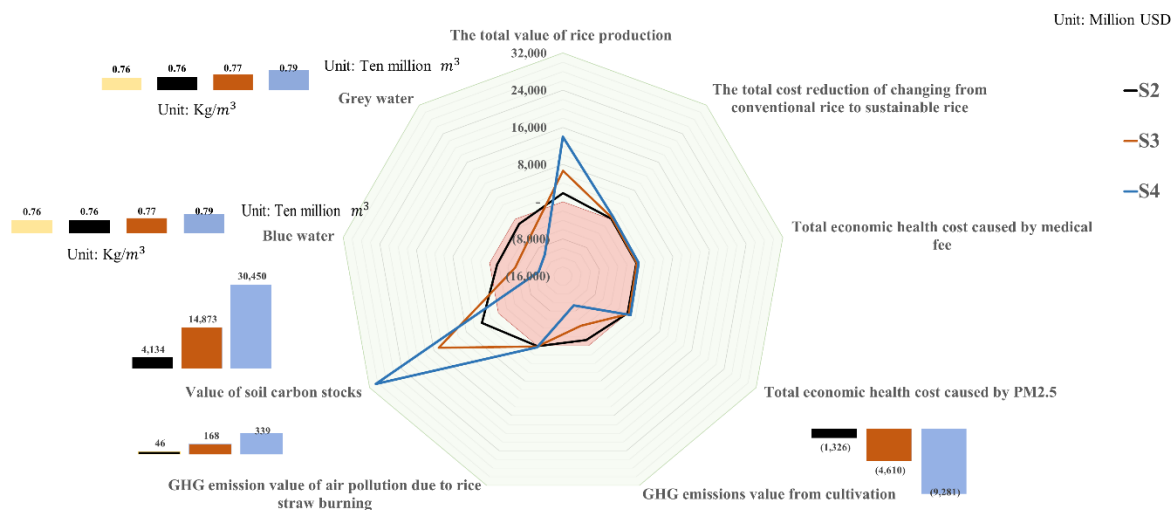
Appendix 6.36 The scenario analysis based on values with rice-sunn hemp option in more detail in the central region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



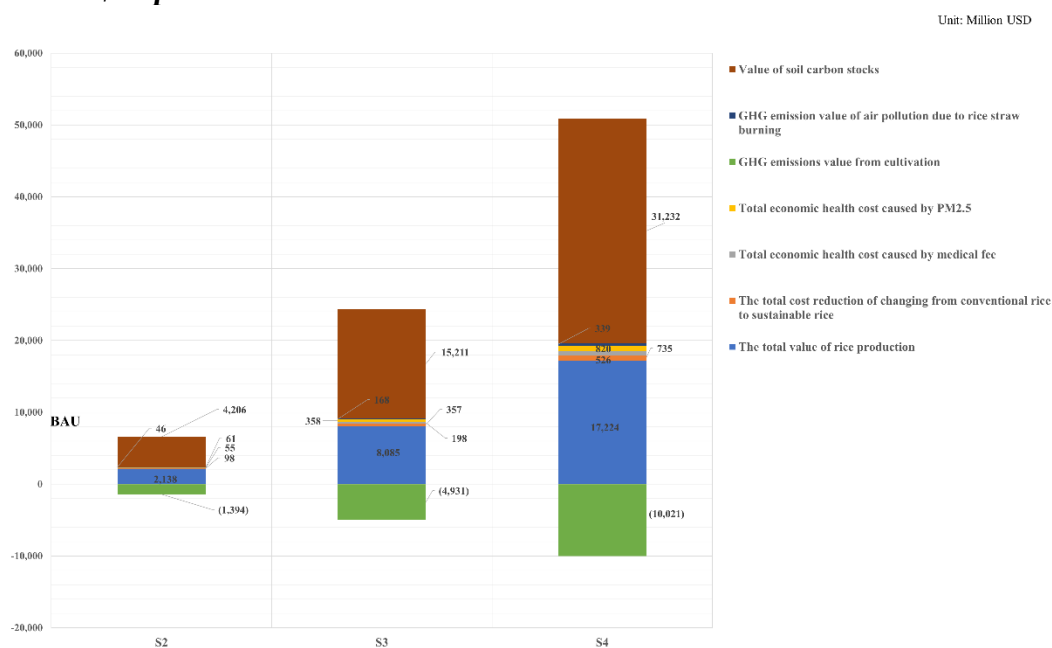
Appendix 6.37 The shapes of trade-off chart with rice-rice option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



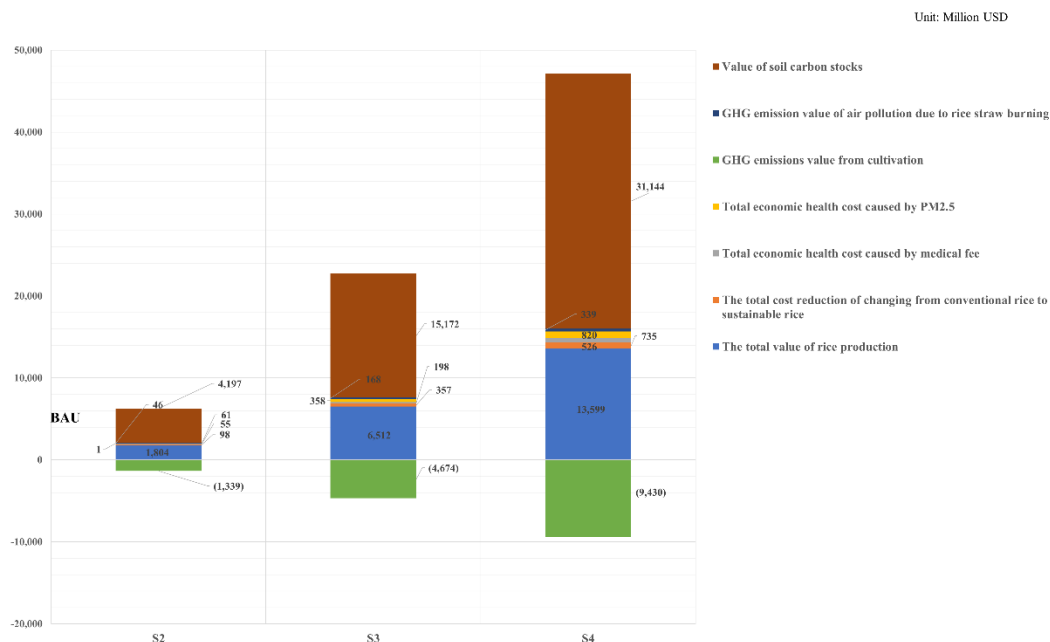
Appendix 6.38 The shapes of trade-off chart with rice-maize option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



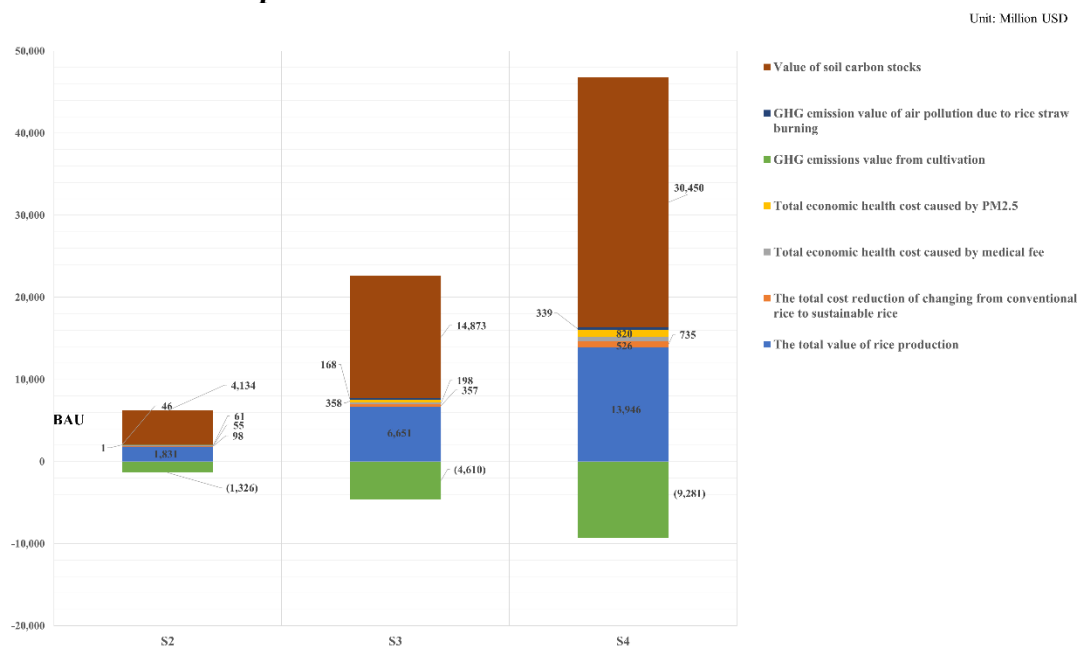
Appendix 6.39 The shapes of trade-off chart with rice-sunn hemp option in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



Appendix 6.40 The scenario analysis based on values with double crops option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



Appendix 6.41 The scenario analysis based on values with rice-maize option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton



Appendix 6.42 The scenario analysis based on values with rice-sunn hemp option in more detail in the northeast region in each scenario from 2021 -2050 compared to BAU at price of carbon credit at about \$51 per ton