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UNITED NATIONS ENVIRONMENT PROGRAMME
REGIONAL OFFICE FOR EUROPE

Forest Damage in Central European Mountains

Final Report of a Large Area Experiment for Forest Damage Monitoring in Europe Using Satellite Remote Sensing

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United Nations Environment Programme

Published by :	United Nations Environment Programme (UNEP), Regional Office for Europe, Geneva, Switzerland.
Citation:	UNEP (1995). *Forest Damage in Central European Mountains - Final Report of a Large Area Operational Experiment for Forest Damage Monitoring in Europe Using Satellite Remote Sensing*. UNEP, Geneva, Switzerland.
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Available from:	UNEP Regional Office for Europe attn: Mr S. Jaakkola 15, ch. des Anémones CH-1219 Chatelaine Genève, Switzerland
Cover Photo:	Landsat TM colour composite, bands 4-3-2 (R-G-B), path/row 192/25 from 01.02. 1987. The image is covering the North-Bohemian Basin with the Ore Mountains stretching diagonally through the upper left part. The whole area is snow covered and coniferous forest can be seen clearly in dark reddish-brown tones. Coal burning power plants can be identified in the industrial area of the Eger Valley. Smoke plumes and industrial smog is visible in the centre of the image.
Printing by :	Lettner KG, Munich Germany. Maps: Wartelsteiner GmbH, Garching-Germany. Printed on environmentally friendly paper.

ISBN:	92-807-1557-7

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List of Abbreviations

AFL	Arbeitsgruppe Forstlicher Luftbildinterpreten - Working Group for Aerial Photointerpretation in Forestry
BR	Brilliance
CIR	Colour Infrared
DARA	Deutsche Agentur für Raumfahrtangelegenheiten GmbH
DEM	Digital Elevation Model
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V. - German Aerospace Research Establishment
DN	Digital Number
ECE	Economic Commission of Europe
EFC	European Forestry Commission
ERS-1	European Remote Sensing Satellite-1
EU	European Union
FAO	Food and Agriculture Organization
FIRS	European Forest Information from Remote Sensing
FIS	Forest Information System
FMP	Forest Management Plan
GIS	Geographic Information System
GPS	Global Positioning System
ICP	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
LAI	Leaf Area Index
LAOE	Large Area Operational Experiment for Forest Damage Monitoring in Europe Using Satellite Remote Sensing
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
PC	Principal Component
RGB	Red Green Blue
RMS	Root Mean Square
SPOT	Système Probatoire d'Observation de la Terre
TM	Thematic Mapper
TWG	Technical Working Group
UN	United Nations
UNEP	United Nations Environment Programme

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1 Introduction

1.1 Background

In the 1970´s, a widespread deterioration in forest health was observed, first for the European fir and, subsequently, also for many other tree species. Now a large proportion of the forests in Europe is affected by forest decline to varying degrees. Intense research on the causes of this decline has been performed from that time on with the result that the decline can not be attributed to one single causal factor but rather is thought to be the result of a multitude of adverse environmental conditions (Hildebrandt, 1992; Skelly and Innes, 1994). Besides the fundamental research work a great variety of damage assessment methods have been developed, and numerous inventories have been carried out. In order to obtain reliable and comparable results on national and international level it has become necessary to monitor the forest damage by applying standardised inventory methods.

Based on the Convention on Long Range-Transboundary Air Pollution of 1979, the "International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests" (ICP-Forest) was established in 1985 by the Executive Body of the Convention. The work is based upon national monitoring inputs using terrestrial damage evaluation methods on sample points. The European governments are provided with statistics on forest condition on annual basis. This programme was funded by UNEP during 1985-1990. Since 1991, the countries finance the inventories themselves.

Besides the statistics obtained through this national and transnational surveys, more detailed data is often required locally. Especially, there is a lack of spatial information of the damage distribution within the European Countries. The mapping of forest condition, displaying the spatial distribution of damage at national and regional level, would be useful for determining the causes of forest decline and in improving the visualisation of damage statistics.

Mapping of forest condition by the means of satellite remote sensing is a technology that should be considered as an additional tool for the ongoing work under the Convention. In various studies satellite remote sensing has been shown to improve the quality of forest change monitoring, and especially its reporting. Today the methodology is ready for large scale operational experiments, but not fully tested for regional damage monitoring.

FAO and ECE have supported, in various forms, work on forest damage monitoring in Europe during the last decade. One reason behind that support was the fear that increasing air pollution would damage forests and disturb the European timber markets.
In their joint meeting in Freiburg, in February 1991, the ECE Timber Committee "Team of specialists on implications of air pollution and other damage to forests for wood supply and markets", and the FAO European Forestry Commission (EFC) "Ad hoc working group: Impact of air pollution on forests", discussed the practical application of satellite remote sensing for forest damage assessment to be carried out in the framework of a proposed large-scale operational experiment involving the Czech Republic, Poland and Germany. An Advisory Board for the experiment was established. The EFC invited UNEP and the three countries to make cost estimates for the experiment for which no new funds were available. In their 49th session the ECE Timber Committee disbanded the Team of Specialists.

In January 1992, UNEP called the first Advisory Board meeting in Prague to launch the **"Large Area Operational Experiment for Forest Damage Monitoring in Europe Using Satellite Remote Sensing" (LAOE).** The three countries agreed to participate by providing their relevant ongoing research projects as contributions to the experiment. The Czech Republic was nominated to be the lead country, and UNEP offered to provide co-ordination and secretarial services. At first, the participating research groups funded their activities by themselves, but in 1994-1995, UNEP provided the Czech and Polish groups with funding (project FP/0312-94-28) as well as with satellite data through a NASA Landsat TM Data Grant.

1.2 Justification of the Study

The necessity to perform forest damage inventories arose with the occurrence of the first forest decline symptoms in large areas. The individual countries, participating in the LAOE, started from the beginning with research work and the establishment of damage assessment methods. These traditional methods are based on terrestrial sample surveys and partly accompanied by the interpretation of aerial photography. The approaches of the inventories, the area coverage and most of all the definition of damage classes varies widely among the countries. Despite of the immense costs and the lacks in providing maps, the biggest deficit is the inability to compare the results of these different damage assessments.

The worst affected countries, like the former Czechoslovakia, already started in the 1950's to develop a national system of damage classification of coniferous tree species in polluted areas (Materna 1958). The damage classification developed until now is based on the ocular estimation of the defoliation and comprises of 6 classes. Since the mid of the 1960's, periodical field assessments have been executed every five years simultaneously with the elaboration of the forest management plans. Additionally, „threat zones“ were determined to estimate the life expectancy in decades of years for spruce stands from the beginning of the immission effect. This system is seen to be of importance for forest management plans in Czech Republic (Kubelka et al 1993). Since 1985 the possibility of using satellite imagery for damage assessment has been tested for particular areas.

In the former GDR a method for damage estimation and forest management was established in regions affected by forest damage in the beginning of the 1970's. Based on a scaling related to the amount of needle loss of single trees (BRA 1978), damage classes for spruce stands were established. The assessment was carried out by terrestrial sampling surveys, since 1979 partly supported by colour infrared-aerial photos and conducted periodically every 5 years (Nienhaus and Liebold 1993, Bieberstein 1995). In order to obtain spatial information for regions, the results of the single spruce stand estimation was transferred into maps with a smaller scale and then subjectively integrated into constructed fume-damage zones („Schadzonen“). Today, the forestry administration is taking a different view of the system, because these classes are generated in a very subjective way by terrestrial estimation. There is a strong demand in having a methodology to monitor changes in a reliable way.

After the first symptoms were observed at the end of the 1970's in Southern Germany, the Forest State Institutes of Bavaria and Baden-Württemberg started with a qualified large area damage inventory in 1983. The inventory was based upon a systematic sampling method of a 4* 4 km grid. The damage was determined by visual estimation of needle loss of single trees. The needle loss was assessed in 5 % steps by an ideal comparison of the crown condition with a healthy tree. The degree of discoloration was added as a second symptom and put together into one damage classification system. In Baden-Württemberg an additional survey by using aerial photography was conducted in order to enable the comparison of the results with the terrestrial survey. In the following year, the terrestrial method was adopted from the other Federal States and performed annually.

On European level the monitoring of forest damages is carried out in the framework of UN/ECE and EU since 1986. Today the countries, participating in the LAOE, take part in the Europe-wide survey and carry out annual assessments. This common large scale monitoring has the objective to obtain statistics on the European forest condition.
The health condition of trees is monitored at sampling points systematically distributed over the total forested area. Grid densities vary from country to country (1 x 1 km to 16 x 16 km). The collected parameters defoliation and discoloration are assessed for 20 trees per sample point and aggregated into 5 classes. A major improvement in the field of terrestrial forest damage assessment is the fact that methodologies and criteria for sampling, monitoring and analysis of the effects of air pollution on forests is harmonised and laid down in the ICP-Forests Assessment Manual.

One of the most important deficits of the above mentioned systematic terrestrial sampling surveys is the inability to record the spatial extent and distribution of forest damages. This deficit can only be solved by an additional mapping approach for which satellite remote sensing analysis is an appropriate tool. Besides that, mapping is a necessary prerequisite to the analysis of the effecting mechanisms.

The analysis of the literature shows that satellite remote sensing has been applied successfully in various forest decline mapping studies. Affected trees are characterised most conspicuously by discoloration and foliage loss, accompanied by leaf pigment, morphological and water content changes. It is generally acknowledged that these factors influence the spectral reflectance and that this can be registered by multispectral scanner systems (Hildebrandt, 1992). For spruce and fir stands the spectral properties are highly correlated with the severity of the damage, measured by terrestrial means or aerial photography. This has been demonstrated in numerous investigations (Rock et al., 1986; Khorram et al., 1990; Brockhaus et al., 1993; Ekstrand 1990 , Lambert et al. 1995 and others). Several authors have shown that it is possible to distinguish 3 to 4 damage levels (Kadro, 1990; Förster, 1989; Häusler, 1991). The basis for the separation of distinct levels relies on the traditional classification scheme, with few exceptions. Therefore, these studies lack in the ability to compare the classification results in terms of damage class definitions. Satellite remote sensing, on the other hand, focuses on stands or groups of trees as the basic object and has the advantage to detect deforestation and opening-up of stands as an additional damage symptom. Therefore there is a strong demand in the development of new standardised damage levels, which can reliably be derived from spectral information and which can easily be compared.

In conclusion, although the use of satellite remote sensing in forest decline mapping has been demonstrated in a number of studies, it has proven to be operational only in specific cases, in restricted areas and with certain assumptions. It has never been tested for large areas with a harmonised classification scheme. In the participating countries, investigations on forest damage assessment by satellite remote sensing have been carried out since several years but only on locally limited areas. Due to the individual methods applied and the different definitions of damage classes, the comparison of the results is still impossible. Therefore, special emphasis has to be given to the development of a harmonised classification system and the definition of comparable damage classes on a regional level, which implies the need for further operational tests.

1.3 Objectives of the Experiment

The aim of the project "Large Area Operational Experiment for Forest Damage Monitoring Using Satellite Remote Sensing" was to propose, develop and test methods and systems for classifying forest damages for large areas in Europe. For the purpose of this experiment, forest damage is defined by destruction of forest canopy and forest decline.

The main interest was to identify damage levels which can be reliably classified by the means of satellite remote sensing and to propose a standardised mapping system as a complement to ongoing European damage monitoring programmes.

Specifically, the project goals were:

- to provide additional spatial information on heavily damaged mountain forests in Central Europe
- to develop damage classifications based upon field observations and satellite image interpretation
- to evaluate and verify the accuracy of the methods applied.

1.4 Test Sites

For this investigation such test sites were chosen where national projects for forest damage classification with remote sensing are already in progress of being carried out. The work to be performed was closely related to the investigations of the national projects. The experiences gathered from there could be incorporated into the LAOE.

The Advisory Board agreed to restrict the work to the most endangered low-mountain ranges of the participating countries. The following areas were selected as test sites:

1. Sudety Mountains (Polish project)
2. Ore Mountains (Czech project: Krušné Hory; German project: Erzgebirge)
3. Šumava Mountains (Czech project)
4. Krkonoše Mountains (Czech project)
5. Harz (German project)
6. Fichtelgebirge (German project)

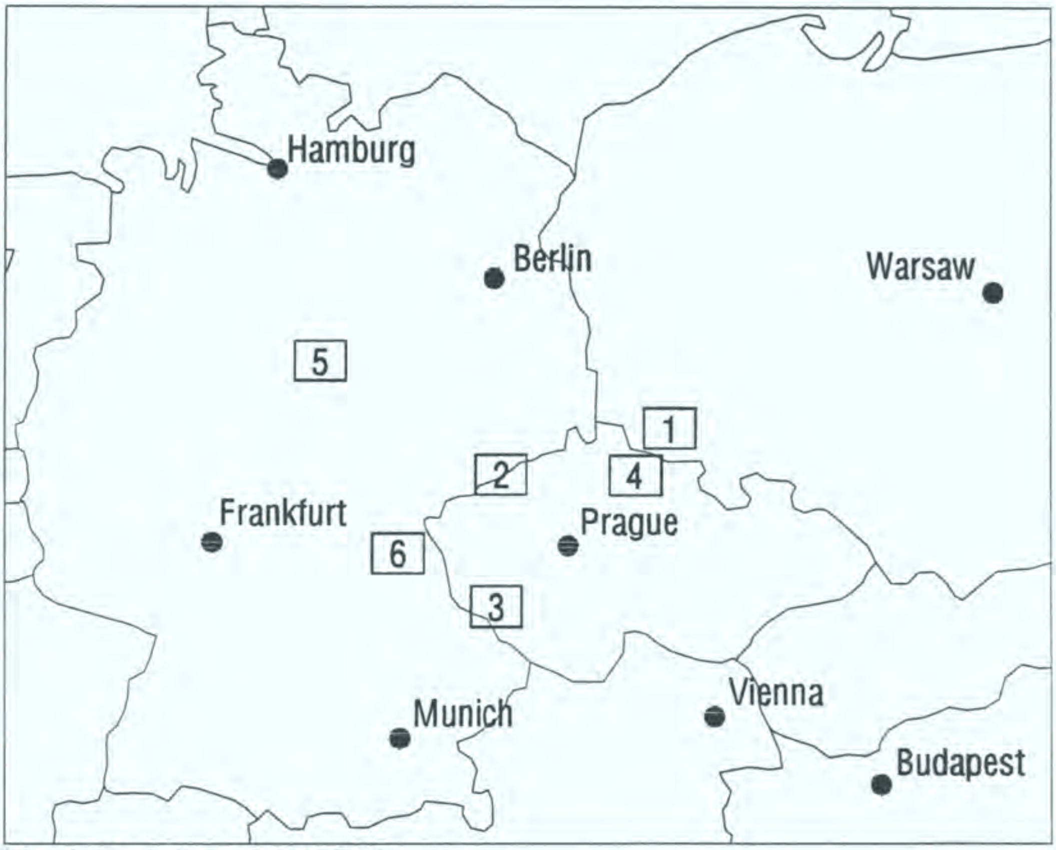

Fig. 1: Test sites of the LAOE

1.5 The Participating Research Teams

The work for the Czech test sites was performed by **the Czech Forest Management Institute, LESPROJEKT,** in Brandys nad Labem under the contracts No. G/CON/94/19UNEP and G/CON/95/02-UNEP as part of the UNEP Programme in Europe. The project was carried out in close co-operation with the firm **Stoklasa Tech.**

The Polish experiment was performed within the contracts G/CON/94/18-UNEP and G/CON/95/01-UNEP by the **Remote Sensing and Spatial Information Centre, OPOLIS**, of the Institute of Geodesy and Cartography. IGiK, in Warsaw.

The German Harz Mountains were investigated by the research team of the **Institut für Landschafts und Freiraumplanung of the Technical University, TU Berlin.** The research project was funded by the Federal Ministry for Research and Technology, BMFT, under the project no. 0339347A.

The project team for the German test sites Fichtelgegirge and Erzgebirge consists of the partners **Company for Applied Remote Sensing, GAF Ltd. - Munich, the Bavarian and Saxon State Institutes of Forestry, LWF-Freising and LAF-Graupa**, respectively. The project is financed by the German Space Agency, DARA, and the Bavarian and Saxon Forest Ministries under the project no. E-50K9207-ZA.

All the investigations were carried out in close co-operation with research groups from Sweden, Finland, France and the USA.

1.6 Methodology

The Advisory Board appointed a Technical Working Group (TWG), with scientists from the Czech Republic, Poland, Finland and Germany to develop a methodology and prepare guidelines for the harmonisation of the various classification approaches for regional applications. Their meetings took place in Harz (Germany), in Brandýs (Czech Republic) and in Warsaw (Poland). The elaboration of the standardised methodology was based on the exchange of experiences obtained from national projects within the TWG meetings.

For the operational part of the project only the damage on spruce were considered since this tree species is the most-investigated so far.
The classification of forest damage on beech (Fagus sylvatica) and Scots pine (Pinus sylvestris) is also of great interest, because damages on these tree species were observed increasingly. Since the investigations are still in a research phase, the mapping of these tree species were excluded from the experiment until the study results within the national projects will lead to operational damage classification procedures.

The recommendations of the TWG were structured according the following issues:

- choice of the appropriate remote sensing data

- problems of damage classification and role of ancillary data
  - separation of forest and non-forest (problem of forest definition)
  - separation of other tree species
  - elimination of negative topographical influences

- harmonisation of damage class definitions according to
  - needle loss of single trees
  - needle loss of stands or pixels
  - decreasing crown density of stands or pixels (deforestation)
- proposals of damage class definition to be applied in the test sites

- classification of the satellite data
  - evaluation of the feasibility of the proposed damage class definitions
  - evaluation of the role of ancillary data

- verification of the results

Following these guidelines and recommendations, the standardised methods had to be tested in smaller, yet representative areas within the national projects. One important factor that had to be considered in this procedure was the feasibility to transfer the classification methods to larger forest areas. The results had to be presented in standardised maps with a harmonised legend.

2 Description of Test Sites and Damage Situation

2.1 Polish Sudety Mountains

The Sudety Mountains, located in south-western Poland along the Czech border, are the site of one of the most heavily damaged forests in Europe. The rapid development of forest decline damage in the western part of the Sudety Mountains has been described as an ecological disaster region (Ciolkosz and Zawila-Niedzwiecki, 1990). These mountains are located in the "Black Triangle" (also so called "Dirty Triangle") of Europe - one of the most polluted regions of the world.
The Forest Districts included in the present study are Swieradow, Szklarska Poreba, Piechowice and Sniezka, as well as Karkonosze National Park covered by spruce stands (Picea abies).

According to estimates of the Forest Research Institute in Warsaw, 75% of the sulphur introduced into this region is emitted abroad, especially in Czech Republic and Germany. Constant heavy air pollution in this area during the past 40 years is one of the major causes of the forest decline and damage, which has increased since the end of the 1970's.

Measurements made in 1969, across the border in the former Czechoslovakia, indicate that annual dry deposition of "industrial dust" ranged from 75 to 150 tons per km^2. The western Sudety Mountains fall within the zone for which "injurious gas" concentrations exceed twice the tolerable levels (Vins and Pospisil, 1973). Brown coal-burning power plants in Turoszow (Poland), Hirschfeld and Bergsdorf (Germany-former GDR), as well as Chomutov and Most (Czech Republic) emit very high level of sulphur dioxide and soot, and the prevailing south-west winds transport the bulk of these gaseous and solid wastes into the Sudety Mountains.

Remote sensing techniques were applied for forest inventory purposes in the western Sudety Mountains, for the first time in 1984, in response to a Polish Forest Service request. The study was conducted by OPOLIS, using aerial photographs (Bychawski et al., 1984; Polawski and Zawila-Niedzwiecki, 1987). Based on the use of aerial photography, maps and forest inventory data, a change detection study was performed for the period between the years 1947-1984. The following classes within forested areas were distinguished: dead stands, stands with open canopy due to foliage loss, windfalls, clear-cuts, afforestation and dwarf mountain pine (Pinus mugho). Moreover spruce stands were divided into several classes of forest quality, according to the percentage of dying and dead trees; deciduous and mixed forests, which were not evaluated, were also distinguished (Bychawski et al., 1984). Using CIR film, all spruce stands over 40 years of age were evaluated. Results of this evaluation were presented on maps, utilising percentage index of dead and dying trees in specific stands (W index). Three damage classes were discriminated: dying spruce stands (W>50%), heavily impaired spruce stands (10%<W<50%) and slightly impaired spruce stands (W<10%). Analysis of the 1984 aerial photographs revealed a generally low quality of the stands, as indicated by change of colour of almost all tree crowns. Trees with colour typical for healthy stands were found at low elevation sites in the central area.

The largest area of dead and dying stands was observed at Karkonosze National Park (7% of forest area), while only small patches were found at Sniezka Forest District. Heavily impaired stands covered an extensive area: 35% of forest at the Szklarska Poreba Forest District, 22% at the Karkonosze National Park and Swieradow Forest District, 10% at Piechowice and 13% at the Sniezka Forest Districts. Stands of the best quality (W<10%) were found at the Sniezka and Piechowice Forest Districts (about 60% of forest area).

In 1991, thanks to a NASA Grant NAGW 1245, a team of researchers from the University of New Hampshire conducted field assessment activities co-ordinated with OPOLIS works at several study sites in the Swieradow and Szklarska Poreba Forest Districts (Rock et al., 1992). These activities were focused on the collection of branch and needle samples in order to characterise the spectral reflectance properties associated with increasing levels of visual symptoms (chlorosis and foliage loss) of forest decline in spruce occurring on these sites. The spectral reflectance data confirm the extensive damage to Sudetic forests. Rock et al. (1992) stated that based on visual site evaluation, the only healthy stands of Norway spruce occur at low elevation, below 700 m.

2.2 Ore Mountains (Krušné Hory, Erzgebirge)

The Ore Mountains stretch over more than 100 km in south-west/north-east direction along the border between Saxony/Germany and Czech Republic. In western direction they border more or less on the Bavarian Fichtelgebirge, in east direction they are continued by the Iser- and Riesengebirge (Jizerske and Krkonoše Hory). The Ore Mountains belong to the crystalline Bohemian Massif system. The elevation ranges from 600 m to 1240 asl.. The highest mountains of the Ore Mountains are Keilberg/Klinovec with 1240 m on the Czech side and Fichtelberg with 1214 m on the Saxon side. The highest elevation in the north-eastern part is the Saxon Kahleberg with 905 m asl. (Kubelka et al. 1993, Forstamt Altenberg 1995).

The natural forest composition in the past was dominated by oak/beech mixed forest stands in lower regions. Beech forests occurred mainly in the middle elevation zone, up to the higher altitudes followed by mixed forest stands with beech, fir and spruce and pure spruce stands at the mountain ridge. Since the Middle Age manmade devastations of the forests changed the composition of the tree species into nearly pure spruce stands. Thus, since the beginning of this century the Ore Mountains are dominated by spruce forests, where beech is given a share of only about 5%.

Already in the past century forest damage was observed in the vicinity of the Saxon industrial areas. Since the middle of our century, the increasing industrialisation and utilisation of brown coal as a source of energy in the industrial centres of North Bohemia (Most/Chomutov), around Halle/Leipzig and in the Lausitz caused high rates of immission loads affecting the forest ecosystems. The annual SO_2 pollution ranges from about 50 to 90 $\mu g/m^3$ at various localities in the eastern part of the Ore Mountains, registered from 1978 to 1989. Compared to that the threshold value for spruce is given with 30 $\mu g/m^3$ (Forstamt Altenberg 1995). During that time the catastrophic damage to forest stands took place and was followed by extensive cuttings, clearings and reforestations. Especially the period between 1978 and 1987 is marked with a collapse of the spruce stands on the plateau and mountain ridge areas.

Spruce forests from non-adapted seed material or not suited for the sites increased the amount of damage. During the last 30 years about 30,000 ha of forests died and had to be cleared in the Saxon and Czech part of the Ore Mountains. The remaining forests show damage symptoms as well and are unstable in their structure (Hering 1993, Forstamt Altenberg 1995). Extensive reforestation and fertilisation programs - supported by utilising exotic tree species injured to SO_2 -had to be carried out.

2.3 Šumava Mountains

Located in West Bohemia the central part of this region is formed by the National Park of Šumava in the neighbourhood of the Bavarian National Park. The elevation varies between 850 and 1350 m asl.

In general, the ridge is covered by spruce stands - mostly local ecotypes - with an admixture of beech and fir in some localities. The relatively wet climate allows high quality wood production of spruce. Some dwarf-pine stands can be found on peat bogs (Plíva et Zlábek, 1986.). The former forest enterprise Kašperské Hory (32 088 ha) is the focus area of the LAOE. The investigated region is overlapping to military forests in the neighbourhood.

The Šumava mountains is the least polluted area in comparison to the other test sites. Nevertheless, the damage shows a relatively rapid increasing trend in the past five years, but highest damage degrees, caused by air pollution, are rare in the area. No dead stands, killed by pollution, have been recorded there. Since the chemical composition of the air pollution differs from the other Czech regions, the forest damages might be an effect of a transboundary pollution from the West.
Other serious problems of forest damage occurred in the course of the last few years, which are caused by the bark beetle. The focus of the bark beetle outbreak is in the Bavarian National Park near the country's boundary.

2.4 Krkonoše

This test site belongs to a mountain ridge located along the Czech/Polish border in North-East Bohemia. These are the highest mountains in the Czech Republic with elevations from 500 to 1603 (Snezka) meters asl. The mountains are protected in the National Park of Krkonoše.

The climate is relatively wet, reaching to an alpine vegetation zone on the mountain tops. Some beech forest stands can be found between large areas of spruce, whereas spruce is a mostly inadequate ecotype. Dwarf pine is located at and above the tree line. (Plíva et Zlábek, 1986.)

The region is not as heavily polluted as the area in Ore Mountains. Forest decline started before the 1980´s, probably initiated by the surprisingly deep drop of temperatures - with approximately 25 ° C during 12 hours (31. Dec. 1978). Now, the situation seems to be stable. The entire range of damage degrees can be found in the area.
The western part of the Krkonoše was recommended for the damage classification project. The entire area of the Krkonoše forest enterprises (Harrachov - 24 713 ha, Vrchlabí - 21 480 ha, Maršov - 21 018 ha of forests) was studied, since this region is in the middle stage of the damage evolution and financial funds fully covered the maps digitisation.

Since 1980 the forest damage is being assessed and mapped in this region by using the national damage classification system. The period of assessment is 5 years. The area served as test site for the satellite imagery based classification since 1987.

2.5 Harz

The Harz - one of the most severely damaged regions in Germany- is located between Hannover, Magdeburg and Göttingen. Its forest area comprises 94,000 ha. The Harz was selected as an important test area in several major experiments at international and national level.

The main tree species of the test site are spruce (Picea abies) occurring in the higher regions of the Harz and beech (Fagus sylvatica) growing in the lower parts. In the higher regions the silvicultural treatment is particularly performed as group selection felling system, which resulted in multilayered stands of different ages. With these few exceptions the stands mainly occur as homogeneous stands and in the lower parts they are managed by clear felling. The pure spruce stands are the most frequent results of silviculture in the former mining area of the Harz.

The Harz shows very different climatic conditions. All climatic stages from collin to sub-alpine, oceanic to continental can be found. The highest mountain, the Brocken, is 1142 m asl. and characterises the natural timber line. Rainfalls varies from 400 to 600 mm per year in the eastern parts up to 1400 mm per year in the higher regions.

The site characteristics of the area are extremely diverse with practically all variations from dry lime soils in the south-western parts to well drained brown soils and podzols. In higher regions peat-bogs in different stages of development can be found. The water supply of the forest stands is very variable, due to the differing site and climate conditions.

The forest decline symptoms have been clearly identified since 1980 and they have spread alarmingly until now, particularly in the higher regions. The forest stands show a variety of forest damage ranking from almost no injuries in the lower regions to most severe damages, like opening-up of stands and deforestation symptoms, in the higher regions. The strongly affected stands are additionally damaged by storm and beetle calamities (Ips typographus).

2.6 Fichtelgebirge

The Fichtelgebirge is located in Northeast Bavaria. It can be seen as the centre of three central European mountain ranges, the Ore Mountains in the Northeast, the Oberpfälzer Wald / Bavarian Forest in the Southeast and the small mountain region Frankenwald in the Northwest. It covers an area of about 1000 km² and ranges from about 500 m asl. at its lower parts up to the highest mountains with an elevation of about 1000 m asl. (Schulze et al. 1989).
The soils can be described as mostly acidic and poor in nutrients. The geology is dominated by metamorphic, acidic granite, gneiss and schist. Especially the higher elevations of the Fichtelgebirge show the typical rough, chilly and humid climate of a mountain range at the highest altitudes. The mean precipitation ranges between 1000 and 1400 mm per year. Frost and snow events occur up to 150 days per year. The Fichtelgebirge is most exposed to winds coming from the western side. Weather conditions with low exchange and inversion layers mostly occur between January and March. (Schulze, et al., OFoD. Bayreuth 1992).

The natural forest vegetation existing until the 16th century was dominated by beech together with other deciduous tree species and fir. Spruce occurred naturally only at the highest altitudes and at other extreme site conditions. The forests were severely depleted over the last 400 years due to mining, iron smelting, charcoal burning, glass and porcelain industry, need for firewood and building timber. In the last century reforestations of large areas were carried out mostly with spruce. This lead to the present forest composition with more than 90% of this tree species.

The Fichtelgebirge also seems to be influenced by the immission load from the highly industrialised centres. The main air pollution sources are steel and chemical industries and coal fired power plants, presumable located in the Czech Republic and Saxony (Schulze et al. 1989). First symptoms of forest decline were observed at the end of the 1970's. Since 1982 a rapid increase of the damage at higher elevations of the Fichtelgebirge is reported (Koch 1986). The annual average values for SO_2 reached up to 60$\mu g/m^3$ at the beginning of the 1980's (OFoD. Bayreuth 1992). Compared to the mean value for Germany with about 25 $\mu g/m^3$ at that time, the Fichtelgebirge can be seen as one of the most polluted and endangered regions in Germany. Due to the far distance to the sources of air pollution, the situation is not as bad as in the Ore Mountains. But nevertheless, approximately 3000 ha of spruce stands were damaged or destroyed in their structure. The reasons behind the damages are generally thought to be a result of the air pollution in combination with unfavourable climate conditions and unsuitable plant material. As a consequence, the forest management had to carry out a costly reforestation program.

3 Harmonised Approach for the Experiment

3.1 Introduction

The following section describes the results of the discussions of the Technical Working Group (TWG). Based on the findings of other research studies and the experience from their own national projects, the members of the TWG developed guidelines for the harmonisation of the various damage classification approaches for the regional application. In the following, recommendations for a standardised methodology for applying satellite data for forest damage assessment are presented.

3.2 Remote Sensing Data

Due to the large area to be covered and the spectral complexity of forest damage classification, Landsat TM data were recommended by the TWG in this particular experiment. The spectral resolution of these data has been proven to be useful for forest damage classification in various studies and the main damage areas can be covered at reasonable costs. Since the sensor shows a spatial resolution of 30 * 30 metres, a mapping scale of 1:50,000 can be provided accurately. More detailed inventories on local level by means of infrared aerial photographs or feasibility studies with other satellite sensor data can be performed within the national projects and are not an element of the LAOE.

Infrared aerial photographs are explicitly recommended for supporting the determination of suitable training areas for the digital classification and for verification. The application of the AFL interpretation key ensures the standardised evaluation of damage levels by visual photo-interpretation. For financial reasons, infrared aerial photographs should only be taken for relatively small forest areas, giving a representative survey of different degrees of damages, types of forest management and topographic conditions.

3.3 Problems of Classification and Ancillary Information

Forest damage is only one of a number of factors influencing the spectral response of stands. If the separation of damage classes is not possible by relying on spectral signatures only, ancillary information, if available, is needed for obtaining a more precise classification result. Particularly, in classifying different forest-damage levels whose spectral characteristics differ only marginally, the overlapping of object-typical (damage typical) spectral information by other parameters might be so severe that a satisfactory classification into many different damage classes without ancillary data is very difficult. Because of the diverging data in the different countries, it can not be assumed that the availability and quality of ancillary information is homogeneous among the participating countries. This fact was not seen as a major problem by the TWG as long as different kinds of ancillary data do not inevitably lead to results which are no longer comparable.
The TWG came to the conclusion that the incorporation of ancillary information is quite helpful in improving the classification accuracy but only those ancillary data should be used, that are already available in digital format. Digitising large amounts of data, just for the purpose of optimising satellite classification, is too time-consuming and thus not feasible for small-scale classifications.

The results of the ICP-forest damage inventory provide very detailed statistical data of forest decline for large areas. These kind of data can not be used as ground truth information for the satellite classification, because the inventory method is based on sample information with a spatial resolution of 16 km * 16 km and is not representative for the size of training areas. Furtheron, these random-sampling points can not be merged and overlaid exactly with satellite photos; and most of all, they do not give any information on the stage of deforestation, one of the damage symptoms which must be taken into account in order to judge the condition of a stand.

Miss-classifications that could be expected in satellite-based mapping of forest damages are discussed below.

3.3.1 Separation of Forest and Non-Forest

Basically, a separation of closed forest and non-forest using TM data is possible. However, using the signatures only, it is not possible to separate areas with severe or total deforestation with vital and lush grass vegetation from some agricultural areas, like grassland. Therefore, ancillary information regarding the forest distribution is advantageous in order to support the separation of forest and non-forest.

Some ambiguity arose with respect to the definition of forest. Definitions vary from country to country and depend on the objectives of the particular inventory. The term forest stand generally refers to a group of trees having a mutual ecological relationship, sufficient homogeneity in terms of species mixture, stand development, horizontal and vertical structure, and have a certain minimal area ensuring a specific micro-climate.

A number of criteria are common to forest definition in all European countries: minimum forest area, minimum forest width, minimum tree height and canopy density. These criteria, however, are not agreed upon quantitatively. The "minimum area" criterion varies from 3 trees to 100 ha; the minimum "tree height" from 5 to 7 m at maturity age in continental Europe, and 3 m in sub-alpine and sub-polar zone.

Within the context of the development of a standardised monitoring procedure using satellite remote sensing the definition of forest was discussed in the TWG, intensively.
Finding a single forest definition that meets all requirement in the individual counties is difficult. When using satellite sensors as data source, such a definition depends on the radiometric differentiation capabilities and the ground resolution of the sensor system.

The TWG agreed on the following:

Size and shape

In all countries, the smallest dimension of forest units still defined as forest is too small for the Landsat-TM system with its geometrical resolution of 30 m * 30 m to classify it as forest. The postulation of the minimal size of forest areas should therefore be made dependent on the restrictions of the satellite system, since the demand for an integration of all those forest areas included in the definition of forest by the administrations cannot be met.

For a precise separation of forest and non-forest the means of Landsat TM the minimal size of the area must be 30 m * 30 m. For a multi-temporal evaluation by the means of historical Landsat TM (Landsat MSS) data of at least 80 m * 80 m (more than 100 m * 100 m) is required. In small-scale investigations these restrictions are only of marginal significance, but for evaluating the degree of classification accuracy they must be taken into account; this problem cannot be solved by integrating ancillary information.

Forest Density

The significant separation of forest and agricultural areas by spectral signatures alone can only be made with a canopy density of at least 20 - 40% (depending on the type and distribution of ground vegetation). However, since more severely damaged, deforested areas with a low crown closure and a not yet closed canopy or clear-cut areas must be integrated, ancillary information is needed. If a separation of forest/non-forest is not possible because ancillary information is not available, a multi-temporal approach with TM- or MSS-data of different years (before and after the occurrence of forest damages) could be the alternative. With historical remote sensing data only those areas can be integrated which were still relatively closed at the time of the first flight, i.e. which show a clear forest signature in the historical satellite image. This assumption is met by highly damaged areas which, however, were largely undamaged at the time of the first flight and by cultures or clear-cut areas still stocked with older stands at that time.

For areas in higher altitudes along the dispersion line of the forest with a natural low crown closure, a multi-temporal approach is not appropriate, but this phenomenon only occurs in the Sudetic Mountains. These areas can be integrated by the means of digital maps, if available, or by delineating these areas interactively.

3.3.2 Pre-Stratification of Tree Species

Associated tree species in spruce stands may result in a confusion of damage classes. For example, the spectral behaviour of undamaged pine stands is similar to particular damage classes of spruce stands. If both tree species occur in the investigated areas, a pre-stratification is necessary in order to avoid a mis-classification. This could be done by incorporating ancillary information on the distribution of tree species.

Mixed forest stands consisting of spruce or beech should not be included in the classification. A spectral stratification of pure spruce stands from spruce/beech mixed stands is only possible with a percentage of beech exceeding 20%. Digitised forest maps were available only for small parts of the test sites, except in the Harz. Consequently, stands with a deciduous mixture below 20% and pine stands are included in the classification.

Because of the expenditure of work, it was not recommended to digitise forest maps for large areas, in order to optimise the classification. If spruce is mixed with pine in the investigated area and no digital forest map is available, it must be specified in the classification results that the mapping is only valid for the tree species "spruce".

3.3.3 Elimination of Negative Topographical Influences

Topography strongly influences the reflection of forest stands. Missclassifications have to be expected and thus, the separation of damage levels may therefore be more difficult in mountainous areas. The differences in illumination can be taken into account by modelling and subsequent correction of the disturbing effects by using digital elevation models (DEM). But the availability, resolution and accuracy of digital elevation models differs widely within the participating countries. For example in the Czech Republic no DEM is available and in Poland only the forest maps give details on topographic parameters. Digitised forest maps are available only for a restricted area, but since in this project methods for damage classification of large forest areas are to be developed, the integration of forest maps is unrealistic at the moment. For some parts of Germany digital height models at a resolution of 80 m * 80 m are available.

It was not recommended by the TWG to generate DEM for larger forest areas, because this would be too cost- and labour-intensive. An alternative would be to make use of the synergetic effects of band ratioing for minimising illumination differences in the data set (Crippen 1987, Crippen et al. 1988, Häusler 1991).

3.3.4 Summarising

The availability of ancillary information differs widely in the participating countries. This means that the harmonisation of classification procedures is neither possible nor really necessary as long as the use of differing data does not impede the harmonisation of damage-level definitions. However, with ancillary data of differing precision or scope of details, the precision degree of the classification must be indicated separately for the respective country or even for individual areas.

3.4 Harmonisation of Damage Classes

The most important point of discussion was the definition of harmonised damage classes which should correspond both to the requirements of satellite remote sensing and to the needs of the forest administration for forest damage inventories. Remote sensing means measurement of spectral signatures, which in forest stands are mainly influenced by the amount of needle biomass per pixel. In damaged forest stands this parameter results from stand density, the average degree of defoliation of the remaining trees and the occurrence and composition of ground vegetation. Stand density as a (possible) damage symptom is completely neglected by field-sampling methods, whereas with remote sensing methods it can and must be taken into account. The parameters "needle loss" and "deforestation" were given special consideration by the members of the TWG. The results of the discussion can be summarised as follows.

3.4.1 Classification of Defoliation

Satellite classifications of forest damage using Thematic Mapper data cannot give any information on the defoliation stages of single trees because from picture elements with a spatial resolution of 30 m * 30 m only an integrated information on approximately 10 to 50 trees (dependent on tree age) can be derived. Because of the heterogeneous spatial distribution of defoliation stages most of the pixels integrate trees that belong to different defoliation classes. Therefore it was examined whether these stages must be assigned to categories according to their respective portion of different defoliation classes or to categories containing a single defoliation class. The latter class definition is only possible if defoliation classes are distributed homogeneously so that mainly one defoliation class occurs within one pixel. The different types of damage classes used in the participating countries will be discussed below.

3.4.1.1 Damage Class Definition According to Needle Loss of Single Trees

<u>A. AFL-Standard</u>

A common damage-class definition based on the needle loss of single trees was established by a working group for aerial photo interpretation (AFL, 1988, or VDI, 1990) and is by now accepted as an international standard for forest damage assessment by the means of aerial photo interpretation:

Tab. 1: Damage class definition according to AFL interpretation key

Damage degree	Description	Needle loss
S0	not defoliated	0-10%
S1	slight defoliation	10-25%
S2	moderate defoliation	25-60%
S3	severe defoliation	> 60%
S4	dead	

B. Czech System

Another damage-class definition discussed in the working group was suggested by the Czech part:

Tab. 2: Damage class definition used in the Czech Republic

Damage class	Description	Needle loss
S0	not defoliated	0-10%
S1	slight defoliation	10-25%
S2	moderate defoliation	25-50%
S3	severe defoliation	50-75%
S4	dying	75%
S5	dead	

It was one of the main points of the discussion how to adapt the AFL and Czech classification systems, which show differences in damage classes S2 and S3 of up to 15% needle loss.

The differences can be minimised by merging the damage classes into groups with more or less comparable needle loss ranges:

Tab. 3: Comparison of the AFL-key and the Czech scheme

AFL-key		Czech scheme	
Damage class	Needle loss	Damage class	Needle loss
S0	0-10%	S0	0-10%
S1	11-25%	S1	10-25%
S2+	25-45%	S2	25-50%
S2-/S3	>45%	S3/S4	>50%
S4	dead	S5	dead

From this example it can be deduced that the differences of both systems would be acceptable when combining the classes S3/S4 (Czech system) respectively S2-/S3 (AFL-system). Without combining these classes the differences would be more significant because of the large discrepancy between the damage classes S2- (AFL system) - S3 (Czech system) and S3 (AFL system) - S4 (Czech system).

The Polish classification of needle loss is carried out in 5% steps (as in ICP-forest) and is thus compatible with both systems.

C. Agreement of the TWG on the Definition of Needle Loss for Single Trees

In order to obtain comparable damage classes within classes representing severe damages as well (S2-/S3 -AFL- and S3/S4 -Czech) it was suggested to collect the ground truth data by means of aerial photo interpretation using the AFL interpretation key. Where it is not possible to use aerial photographs and to apply the AFL key, the merge of damage classes as mentioned above has to be performed.

3.4.1.2 Damage Class Definition According to Needle Loss of Stands or Pixels

It was the consistent opinion of the members of the technical group that the damage cannot be defined as one single damage class, because of the unhomogeneous distribution of damages within stands or picture elements of the satellite data. The classes must rather be defined as the portion of differently damaged trees.

There are different possibilities to describe the damage of stands or pixels, which are all based on definitions describing the damages of single trees (3.4.1.1). Defoliation categories which meet the conditions of the spatial resolution of satellite images are described better using the damage class definitions explained below:

A. Suggestion of the TU Berlin

In the first phase of the German Harz project the defoliation categories were defined as the portion of strongly damaged trees belonging to the defoliation classes S2, S3 and S4 (based on the definition of Förster 1989).

Tab. 4: Needle loss categories proposed by TU Berlin

Defoliation class	Description	Indication
C0	healthy stand	0-10% of strongly damaged trees (S2+,S2-,S3, and S4, AFL)
C1	slight damages	11-33% of strongly damaged trees (S2+,S2-,S3, and S4, AFL)
C2	moderate damages	34-66% of strongly damaged trees (S2+,S2-,S3, and S4, AFL)
C3	severe damages	67-100% of strongly damaged trees (S2+,S2-,S3, and S4, AFL)

Advantages of this definition:

All damage situations within stands or pixels will be included by this definition. Another advantage would be that the Czech damage-class definition according to needle loss of single trees could be used combining the Czech damage classes S2 to S5 representing needle-loss percentages of over 25%, too.

Disadvantages of this definition:

Overlap between classes can be large when summarising the damage classes 2+ to 4. For example, the best stands in C2 (34% S2+, AFL) are much better than the most damaged stand in C1 (33% S1, AFL). When applying this definition to training areas used for the classification of the Harz test site and on former stand wise forest damage inventories performed by the Forest Research Organisation of Niedersachsen it could be determined that the overlap between neighbouring damage classes are insignificant. This is due to the significantly higher share of severely damaged trees (S2- and S3) in the stand wise damage classes C2 and C3 compared to the classes C0 and C1. That means: with increasing percentage of damaged trees (S2 + - S4), the share of severely damaged trees is also increasing (S2- -S4).

B. Suggestion of the Czech Working Group

Another stand wise damage-class definition according to needle-loss symptoms, which is very well adapted to the damage situation in the Czech Republic, was suggested:

The different degrees of needle-loss are based on the Czech needle loss categories of single trees mentioned above. The more or less corresponding damage class according to the AFL-key is indicated in brackets.

Tab. 5: Needle loss categories proposed by the Czech working group

Stand damage degree	Description	Degree 0 (AFL 0)	Degree 1 (AFL 1)	Degree 2 (AFL 2+)	Degree 3-4 (AFL 2-/3)
0	healthy stand	100	0	0	0
0/I	stand with starting damage symptoms	100-80	0-20	0	0
I	slightly damaged stands	80-10	20-55	0-30	0-5
II	moderately damaged stands	10-0	55-15	30-55	5-30
IIIa	severely damaged stands	0	15-0	55-50	30-50
IIIb	extremely damaged stands	0	0	50-30	50-70
IVa	dying and dead stands	0	0	30-0	70-100

Advantages of this definition:

This definition does not allow any overlap between neighbouring damage classes. Overlapping of signatures caused by an ambiguous definition can be excluded. This damage definition is very suitable for the conditions of the Czech Republic. The matrix shows that just as in the definition according to the suggestion of the TU Berlin the share of highly damaged trees increases with increasing level of damage.

Disadvantages of this definition:

To investigate the applicability of this definition under conditions of the Harz, the damage-class distribution of the training and verification stands of the Harz test site were integrated into this damage-class system. For this calculation the comparability of the AFL and the Czech classification system was assumed as in the example demonstrated above ("Damage-class definition of needle loss according to single trees").

This investigation showed that only 25% of the investigated stands of the Harz can be covered by this classification system. Healthy stands, mainly consisting of trees belonging to S0 and S1 with a certain percentage of damage class 2+ and stands consisting of trees belonging with more than 55% to S2+ did not fit the Czech classification system.

C. Choice of Damage Class Definition

After intensive discussions, the TWG decided to accept Förster's damage-class definition for determining needle loss. This procedure has three main advantages:

1. The differences in the description of single trees between the AFL-key and that one used in the Czech Republic can only be balanced by pooling all the trees with a needle loss of more than 25%. In this range both interpretation keys are compatible.

2. In all project test areas the share of severely damaged trees increases with a generally increasing stand- damage level, and therefore there is no danger that neighbouring damage classes will overlap too much.

3. As opposed to the Czech approach, this definition of damage classes includes all potential damage conditions in the stand. It is not optimised for one region and thus can be applied. universally. This advantage is of special importance for small-scale forest-damage mapping not limited to a single country, as it is the case in this project. Apart from that the definition is easy to be understood by everyone.

3.4.2 Classification of Deforestation / Crown Density

The question of the necessity and practicability of integrating deforestation stages as a damage symptom into the classification was also discussed intensively in the working group. The members of the working group decided to integrate this parameter into the damage-class definition.

It was suggested that deforestation due to decreasing crown density can be defined as the percentage of crown cover. The maximal crown cover-percentage of a stand without any gap can be assumed to be 84 - 88% (Assmann, 1961). Only in very young stands (thickets and young pole timbers) a crown-cover percentage of more than 88% occurs.

The TWG has decided to test the following combined damage class definition, that integrates stand wise damage classes, as suggested by TU Berlin (see table 4), and deforestation symptoms.

Tab. 6: Damage class definition by combination of stand wise needle loss and deforestation

Crown closure more than 60 %	Classification into Defoliation Classes C0, C1, C2, C3+/-
Crown closure 41-60%	Deforestation class 1
Crown closure 21-40%	Deforestation class 2
Crown closure below 20%	Deforestaion class 3

By this definition, damages with a crown closure of more than 60% are classified exclusively according to needle loss as proposed by the TU Berlin (C0 to C3). Those with a crown closure below 60% are classified exclusively according to deforestation symptoms expressed by the canopy density.

The practical applicability of integrating deforestation symptoms into the damage class definition had to be investigated in this project. The advantages and the disadvantages were also discussed intensively.

Advantages of the damage class definition:

The term 'deforestation' is appropriate for a canopy density below 60%, since the stability of stands below this range is no longer guaranteed, and only a few silvicultural procedures are intended to operate at such a low canopy density.

As in former forest-damage inventories, the important information on needle loss of single trees in terms of the portions of different damage classes (S2-S4) will be integrated.

The very important information of the stand density which indicates the stability of a stand will also be considered. For a correct interpretation of these new damage classes, knowledge of the classified area must be taken into account, or digitised forest maps must be superimposed on the classification results in order to know which state the stand is supposed to be in.

The picture elements of the satellite data integrate trees (more or less damaged) as well as shadow in less deforested stands or ground information in stands with a decreased crown density. A damage class definition that integrates deforestation is therefore more adequate to the signal which is measured by the sensor. It is not possible to isolate the defoliation symptoms from picture elements integrating defoliation as well as deforestation features. This operation is only possible with the classification of defoliation categories within one deforestation stage.

There is a consensus among the members of the working group that a classification according to needle loss categories of stands with a crown closure of below 60% is either not possible at all or only with an unsatisfying degree of precision. One of the reasons for this is that the potential differences in reflection caused by needle loss are superimposed by the reflection of the ground vegetation, which strongly influences the signature in open stands. However, it can be assumed that these stands show strong damages and thus belong predominantly to the category C3 (damaged trees more than 66%). It can be assumed that C3+ will often be find in the deforestation class 1 (solution of damage degree "improvement" after damaged trees are taken out) and C3- in the deforestation class 2. Thus a subdivision into different needle-loss categories is not necessary.

Disadvantages of the damage class definition

The disadvantage of the damage-class definition just described is that in stands with a canopy density of more than 60% the influence of the needle loss on the signature can still be superimposed strongly by the influence of varying degrees of crown closure (in this case = percentage of shaded parts of the crown). As mentioned above, it is not possible to isolate the defoliation symptoms from picture elements integrating defoliation as well as deforestation features. A precise separation of defoliation categories is only possible with the classification within one deforestation stage. Unfortunately, these both effects may superimpose each other and thus lead to a less satisfying classification result of the needle loss. Subject matter of this investigation is therefore the quantification of this influence. If this influence is not as high as expected, this damage class definition should be performed for a large scale experiment.

The problem of recognising damages caused by air pollution among clearcuts, windthrow areas or other damages leading to a decreasing crown density cannot be solved if information on regular cutting operations and on disaster (storm, snow, ice, insect attacks etc.) is not available.

A decreasing canopy density leads to an increasing influence of ground vegetation on the reflection of forest stands. The typical reflection characteristic of forest stands can be modified strongly by different types and phenological stages of ground vegetation. Thus, a lower classification accuracy of deforestation and defoliation categories can be expected in stands with low stand densities. Therefore, for stands with very low canopy density no assessment of different defoliation categories is possible. Detailed field information and knowledge about the reflection characteristic of the forest floor is necessary to estimate the influence of ground vegetation on the classification accuracy.

3.5 Classification

In the final phase of the project the damage-class definition had to be tested. It must be made sure that only those methods are applied which are also operational for small-scale classifications (total test area), since the classifications in the pilot studies were carried out for smaller investigation areas only. This is particularly important for the integration of ancillary information available for smaller test areas but not covering the entire region.

It is not necessary to use the same classification algorithm for all the test areas as long as it is ensured that the classification of forest damages is carried out according to the damage classes mentioned above.

3.6 Verification

The verification of the classification result must be directed towards the "Ground Truth" available for the test area (e.g. aerial photographs or field experiments). Methods therefore cannot be standardised.

Irrespective of the method applied, it must be ensured that for all the verification areas in the entire test region the damage symptoms "needle loss categories in percentage" are recorded and "crown density" according to the percentage of canopy density. Only then there can be a guarantee that the classification of the damage class definition described above can be verified. One of the verification results is to be the analysis of the causes of mis-classifications so that the classification results can be analysed in detail by the user.

4 Results of the Pilot Studies

4.1 Sudety Mountains Case Study

4.1.1 Objectives

Since 1987 the OPOLIS's representatives have participated in a ECE/FAO Experts Group, which was established in order to explore possibilities for the use of satellite data for forest damage assessment in Europe.

The Polish part of the LAOE was carried out in the Sudety Mountains - one of the most deteriorated regions in Europe. Due to the scale of environmental changes in this region, new performance methods of forest assessment and monitoring are requested. The remote sensing methods can be an answer to these needs. Large extents of damage occurring in the Sudety region implies the use of satellite data, which can provide quick and synthetic information of the state of environment. However, the application of a new technique and resulting data provokes further needs: new tools for storing and processing both traditionally collected forest inventory data and digitally registered images are needed. Therefore, forestry oriented Geographic Information Systems (GIS), integrating all available data and including image processing modules, will play an increasing role in this activity.

4.1.2 Remote Sensing Data and Ancillary Information

4.1.2.1 Generation of a Data Base

The investigation was based on comparison of ground truth data with satellite images, on which different image processing procedures where undertaken. It was expected that sophisticated image processing can provide a set of information, which combined with existing statistical forest inventory data would be useful in describing the condition of the forest at regional scale. Colour maps, resulting from the processed satellite images, showing a spatial distribution of damage in the forest, can explain some existing statistical data.

Guiding principles for ground forest inventory within the reported project have been defined jointly with BULIGL-Forest Management and Geodesy Bureau and IBL-Forest Research Institute in Warsaw (Grzyb and Dmyterko, 1990), following the directives described by the Team of Experts of the UN-Economic Commission for Europe on Satellite Detection of Forest Damage.

It was assumed that each test site should include: stands at four main age classes, young stands, uneven-aged stands and understorey regeneration. The test site should comprise stands characterised by different sites (dry, well-drained and marshy). All observations within the Sudety test site were performed on 520 homogeneous test areas.

The minimum surface of a test area was determined by the resolution of the satellite data. A 3x3 kernel of Landsat-Thematic Mapper pixels represents a ground area of approximately 0.9 ha. So field plots were designed to match the ground coverage of this 3x3 pixel matrix. Following this, the minimum surface of a test area was 1 ha. A surface of 10 ha was determined as a maximum.

Each test area was described on the basis of 1 to 3 circular sample plots. The description of each test area includes the following elements:

1. Terrain description (type, shape, slope, aspect, height above sea level, type of soil and site, ground cover).

2. Stand description (structure, species, age, mixture, density, height, d.b.h., height of first living branch, number of trees per area unit, number of dead and dying trees and occurrence of cones).

3. Assessment of forest condition - described by defoliation index (Df), discoloration of needles (index Dc) and damage index (Dm). Df and Dc indices were assessed following the recommendations of the Inter national Co-operative Programme on Assessment and Monitoring Air Pollution Effects on Forests (ICP-Forest). Dm was calculated on the basis of defoliation, height increment and vitality assessment (Dmyterko and Grzyb, 1990).

4.1.2.2 Remotely Sensed Data

The set of remotely sensed data comprises of three types of information:

- spectral field measurements,
- aerial photographs,
- satellite images.

Some field spectral measurements were performed in order to evaluate the leaf area index (LAI), as well as to determine the condition of trees, as needle reflectance highly correlates with chlorophyll levels, the extent of cellular damage, the amount of foliar water and the degree of senescence (Rock et al., 1992). A detailed description of these investigations is given in Annex A of this report.

As far as aerial data is concerned, both archived and up-to-date colour infra-red (CIR) photographs (taken in 1984 and 1992) have been used. Furthermore maps of the forest condition (1:25,000) based on CIR aerial photographs taken in 1984 are used during the project process.
Within the project, different types of satellite data were used. Landsat Thematic Mapper-TM and Multispectral Scanner-MSS (USA), SPOT (France), Cosmos (Russia) as well as ERS-1 (European Space Agency) images were collected. Such a number of satellite data permitted an assessment of utility of different types of images. The collection of this large set of satellite images was possible thanks to joint efforts of many institutions. Some Landsat, SPOT and Cosmos scenes were provided by IGIK-OPOLIS. Some other TM data sets were available through the NASA Pathfinder Project, co-ordinated by the University of New Hampshire, while ERS-1 images were provided by European Space Agency in the scope of pilot project PP-PL-3 "Forest Decline Monitoring in Ecological Disaster Area - Sudety Mts. Case Study", carried out in OPOLIS.

4.1.2.3 Data Processing

The satellite data was interpreted, using both digital and hybrid (visual/digital) methods of image classification, in order to assess actual forest state status as well as to evaluate the rate of change over time. Satellite spectral characteristics were statistically compared with ground measurements in order to find out the relationships between these two levels of data collection.

The results of ground truth observations and measurements were analysed in relation to the spectral responses of the test areas, derived from original TM bands as well as from ratio transformations (TM5/4 and TM4/3), normalised vegetation index (NDVI=(TM4-TM3)/(TM4+TM3)), brilliance ($BR=\sqrt{(TM3)^2+(TM4)^2}$) and principal components (PC1, 2, 3).

As it was proved (Rock and Vogelmann, 1989; Zawila-Niedzwiecki, 1989) TM4/3 ratio can serve to describe the changes in green biomass, whereas TM5/4 ratio can help in describing a damage of forest. NDVI and BR are used to assess green biomass while principal components are used to compress the data from seven TM bands to 3 PC channels for eliminating redundant information. In case of the TM image of the Sudety Mts. the newly created PC1 aggregates 90% of information from seven original bands, PC2 contains more than 9% and PC3 below 1%. However, this does not mean, that PC3 or PC2 should be eliminated from further analysis, since they can also contain some relevant information about the environment.

The analysis of spectral characteristics versus stand and site parameters was performed for the entire data set and separately for each aspect (nine classes), slope (six classes) and aspect and jointly for particular aspect, slope and class of age. The location of the particular stands against sun illumination play an important role due to the shadow, evident at the mountainous terrain, while satellite images are registered at 10.30-10.40 am, which can be a source of miss-classification. Both, regression analysis and multivariate analysis were applied.

Computer based spatial analysis with the use of digital terrain model (DEM), maps of slopes and aspects resulted in information on directions and range of forest decline within the investigated area.

It should be pointed out that the analysis of satellite data was possible only in comparison with additional ground measured data (like defoliation index).

4.1.3 Classification of Damage

4.1.3.1 Signature Analysis

Analysis of spectral data collected by Thematic Mapper scanner in relation to stand parameters was possible thanks to the GIS database built in the framework of the project executed in the Laboratory of Remote Sensing and Forest Management - University of Gent. Satellite images were overlaid on forest stand maps, which were digitised before and transformed to the raster format. Next the spectral responses of particular stands were related to the forest inventory data located in the relational database (Zawila-Niedzwiecki, 1994).

Only a limited number of significant linear regressions describing statistical relationships between elements which were analysed, have been found. The strongest connections were found between spectral responses versus damage, defoliation and discoloration indices. The most interesting results are presented in Annex B.

As expected, good relations exist between the spectral characteristics of stands and damage classes, when the forest is situated on S and SW aspects (sun illumination). Following linear regression analysis, we can conclude, that on the illuminated slopes (S, SE, SW) the condition of the stands could be interpreted quite well using only proper TM channels, but on the shaded slopes (N) the use of ratio bands (especially NDVI, PC and BR) could be profitable. No significant relations were found as far as other stand parameters are concerned. However all these results should be interpreted very carefully because the linear correlation does not prove the relationship in such complicated ecosystem sufficiently. It seems to be evident that interaction effects play an important role within the measured elements, therefore the multivariate analysis can give a more precise description of the studied phenomena.

In contrast to the linear regression, multivariate analysis comprises of stand parameters as dependent and spectral characteristics as independent variables. As far as defoliation and damage models are concerned, a high correlation coefficient is noted: R^2adjusted (R^2a) exceeds 0.90 and on the S-aspects even reaches 0.97. Only in the case of expressions describing discoloration of needles in the stands located on E, SE and W slopes, the R^2a value does not exceed 0.55 and in the best correlated formulas (concerning N-aspect) reaches 0.87. The use of proper TM channels, for describing Df and Dm, results in R^2a values exceeding 0.9 for almost all slopes (with exception for E-aspects).

No significant improvement of correlation was observed by using the ratio bands. Rather surprising is the fact that the expressions presented did not contain any ratio channels which according to our previous studies (Zawila-Niedzwiecki, 1989) seemed to be useful in order to assess the spruce forest condition. This allows the conclusion, that in such heavy impaired forests even proper TM channels enable to delineate the damage zones.

During the calculation, the ground measured stand parameters were included into the expressions as one of the variables. The presented models show that only the age of forest stands has an influence, but in many cases this was also eliminated during the computation. This variable is important on N, E, SW and NW aspects only.

It can be concluded that linear regression does not explain sufficiently the relationships between stand parameters and spectral responses, recorded by TM scanner. Nevertheless multiple correlation could describe the variability of the studied elements in relation to spectral data. For instance expression (13), in the Annex B, presents that on the south aspects 97% of the sum of the squares of the deviations of the Df values about their mean is attributed to the relationship between Df and TM1, 2, 5. In other words, 97% of the variability of defoliation index, on the south aspects, could be derived from spectral characteristics registered in TM1, 2 and 5. It should clearly be said that the parameters in the presented models are not universal and relate only to the investigated plots.

The defoliation and damage indices seem to be the most useful for further works on satellite based assessment of forest condition. Especially the damage index, proposed by the Forest Research Institute in Warsaw (Dmyterko and Grzyb, 1990), is correlated well with spectral characteristics derived from TM data. On the contrary, the needle discoloration is not considered as significant enough to describe the forest condition in relation to the satellite data.

Analysis of different TM band combinations led to the conclusion that particular bands provide suitable information for forest inventory and damage assessment. TM3 is the best for delineating coniferous forests; mixed, deciduous stands and grasslands are best distinguished using TM4 data, while TM5 and TM7 bands can be used for delineating clearcuts with no vegetation cover and for discriminating mixed/deciduous stands from young spruce stands, grasslands and afforestation areas. The TM5/TM4 ratio is best for detecting and classifying damaged spruce stands. Thus, TM3, TM4, TM5 and TM7 were used for the analysis of forest conditions in the Sudety Mountains, and a specific colour composite (TM5/TM4, TM4/TM3 and TM7) proved to be especially useful.

4.1.3.2 Visual Image Interpretation

On the basis of this colour composite of the July 1984 TM data, the following classes of forest damage were distinguished (when compared with the 1984 aerial photography):

- **slightly damaged spruce stands** - on average 70 years old, characterised by I-II damage class for trees at a site (description of damage classification is presented in table 7), 703 stems per 1 ha, 7% of dead trees, 19% of dead and dying trees,

  heavily damaged spruce stands - on average 90 years old, characterised by II-IV damage class, 512 stems per 1 ha, 78% of dead trees, 90% of dead and dying trees,

- **dead stands**,
- **deciduous and mixed forests**,
- **young spruce stands**,
- **clear-cuts with vegetation cover**,
- **clear-cuts without vegetation cover (bare soil).**

Tab.7: Damage classification used to characterise individual trees within interpretation of CIR aerial photographs:

Damage class	% needle loss	State-of-health
I	0-10	Healthy
II	11-25	Initial damage
III	26-60	Moderate damage
IV	61-90	Heavy damage
V	91-100	Dying and dead

The comparison to the result of interpretation of the 1984 image with aerial photographs showed that the classes mentioned above were delineated correctly. Only one terrain cover type is mis-classified in the satellite image, namely mountain dwarf pine, which was classified as heavily damaged stands. This may result from similar spectral response of these two classes, since both can be characterised by a large amount of bare branch material. This mis-classification is not a serious limitation, however, as the dwarf pine covers only small areas.

Distinguishing between these classes has permitted determining the distribution of forest damage in the Sudety region. The area under study has 32 000 ha, some 23% of which is covered by slightly damaged spruce, 21% heavily damaged and 6% by dying and dead spruce. There are no healthy stands. Even young spruce trees, making up 12% of the area under study were slightly damaged. The area of deforestation, which has been excluded from timber production has an area of 7360 ha (23%). Practically one-fifth of the area studied had trees which had to be removed before attaining maturity.

Studies conducted at the Forest Research Institute in Warsaw reveal that loss of the nation's annual increment in timber volume in stands damaged by air pollution is as follows: physiological damage - 10%, slight damage - 25%, moderate damage - 50%, heavy damage - 75%. In assessing annual loss according to these data and according to the results of TM images analysis, four categories of forest can be distinguished in the Sudety Mountains.

If we take into account in these calculations the loss of increment of timber volume caused by too early removal of dying stands, the estimated loss of area increment in this 32 000 ha portion of the Sudety Mountains will be about 45 000 m^3 annually. This means an average loss in incremental volume of about 1.4 m^3/ha/yr, compared to 0.6 m^3 as the average value affecting Polish forests damaged by industrial emission of SO_2 (Ciolkosz and Zawila-Niedzwiecki, 1990).

These computations do not take into account the loss of increment among hardwoods and mixed forests, since it is more difficult to recognise a decline in the number of deciduous trees by the use of remotely sensed data in comparison with a similar decline in coniferous forests.

4.1.3.3 Automatical Classification of Damages

Visual interpretation of digitally prepared satellite data results in very precise recognition and delineation of ground elements but is rather difficult to carry out for large areas. Furthermore a result of visual interpretation cannot be automatically stored in the GIS database but must be digitised, which is a time-consuming operation. Therefore, further investigations of satellite images were performed digitally by using supervised classifications. The results of such classifications are not as precise as of visual or hybrid ones, but they are, however, still reliable. For such classification, the methodology proposed by the TWG was used. As the first step a separation of forested area was performed, thanks to the GIS database with a coverage representing state forests. Within woody area different classes were distinguished using CIR aerial photographs and forest inventory data. Special attention was paid to the defoliation of forest stands (assessed on the ground and on aerial photos) and deforestation (started by loose canopy closure and ended by broad openings).

During the supervised classification (maximum likelihood) procedures the following classes have been distinguished on the TM image, taken in 1984:

1. - 0-10% trees with needle loss>25% (needle loss of spruce with crown closure>60%) - this class has not been founded in the Sudety test site
2. - 11-33% trees with needle loss>25% (FOR1),
3. - 34-66% trees with needle loss>25% (FOR2),
4. - >66% trees with needle loss>25% (FOR3),
5. - openings - crown closure 41-60% - this class has not been founded in the Sudety test site,
6. - openings - crown closure 21-40% (CUTCR),
7. - openings - crown closure 0-20% (CUTSL),
8. - afforestations - coniferous thicket < 20 years old (AFF),
9. - mixed and deciduous stands (DEC).

Both pre- and post-classification accuracy assessments (table 8 and 9) prove a high precision - on the average of 94% and 83% respectively. The resulted images can be presented in different scales up to 1:25 000.

Applying the same approach, i.e. digital supervised classification using ground-truth data and results of aerial photo interpretation for training procedures, TM data acquired in August 1990 was used in order to determine changes in forest condition between 1984 and 1990. The results of the 1994 classification were digitally superimposed on a scanned topographical map and plotted in a 1:100,000 scale in Gauß-Krüger projection. The map is attached in the Annex of this report.

4.1.3.4 Change detection

The classifications of 1984 and 1990 were next compared digitally, using GIS facilities, in order to determine changes of forest condition, manifested by new clear-cutting. This comparison reveals a dramatic expansion of clear-cut areas over the six-year period.

A comparison of the satellite images with sketch maps of clear-cuts prepared on the basis of aerial photographs reveals similar locations of this class on both remote sensing based outputs. Slight discrepancies occur, especially on shaded northern slopes.

Due to the quantity of information it was decided to use the GIS database. It should be mentioned that GIS was not necessary for our analysis. Ratios of TM bands allowed the elimination of the slope effect. However the use of GIS permitted to perform multi-subject analysis concerning the environmental issues in the Sudety Mountains. The general scheme of the established GIS database contains spatial and relational sets:

1. The spatial database consists of the following files:

   a) digital terrain model (DEM) based on the scanned contour maps on the scale of 1:25000,

   b) forest condition 1984 - digitised from the maps elaborated on the base of CIR 1984 aerial photos, and containing the data on: impaired spruce stands, severely impaired spruce stands, dying stands, dead stands, hardwood and mixed stands, regenerations, openings (deforested areas), dwarf mountain pine, others,

   c) canopy closure - derived from aerial photos: stands with loose canopy closure,

   d) hydrography from topographic maps: rivers/streams, lakes,

   e) transportation lines from topographic maps: state roads, local roads, forest roads, railways,

   f) administrative units: forest districts, forest parcels, forest subparcels (test areas),

   g) satellite data.

2. Relational database consists of forest inventory and monitoring data.

The schemes of both spatial and relational databases permit to add any other information which will be needed during the future utilisation of the established data set for forest monitoring or management purposes. For the operational use of the GIS database, the following levels should also be taken under consideration: soils, geology, forest sites, industrial pollution data, as well as other data collected within different research projects carried out on the test site.

The analysis of all the collected data permitted to assess a spatial distribution of different categories of the analysed forest in the Sudety Mountains. This allowed to delineate three regions within the Sudety forested area, characterised by different degrees of forest decline. These are: the western area, covering Swieradow, Szklarska Poreba and northern part of Piechowice Forest Districts (18,270 ha); the southern area, comprising of Karkonosze National Park (5,557 ha); and the central area, covering Sniezka and southern part of Piechowice Forest Districts (7,813 ha).

The western area is characterised by the most serious damage, in which extensive forest loss occurred on ridges and upper slopes. Clear-cuttings were observed above 600 m above sea level. In higher regions above 750 m clear-cuts were extensive. Areas with change in forest canopy related to forest decline damage (both foliar loss and loss of trees) in 1984 represented 34% of the area forested in 1947 (clear-cuts - 26%, dead forest - 6%, open canopy - 2%). The southern region is characterised by similar changes, which covered 28% of the area forested in 1947 (clear-cuts - 12%, dead forest - 3%, open canopy - 12%). Changes exemplifying forest decline were observed within the whole region, above approximately 1000 m. The central area is covered with forest of the best quality, compared to the other areas (clear-cuts - 10%, open canopy - 1%, dead forest - 0.04%).

Because of the soil erosion risk, the understorey regenerations and only small clear cuts were the common practice on the territory under study. Now, due to decline processes one can observe a decrease in stand density and canopy closure as well as an increase of clear-cut areas. As a consequence, the extension of openings could be treated as a kind of forest change index. Analysis of stored data shows a large distribution of clear cuts, which are observed starting from 600 m a.s.l. and above 750 m.

The quantification of each classification of the satellite data gives a good opportunity to derive statistical data concerning areas of each class and to compare changes between 1984 and 1990.

Tab. 8: Results of TM based change-detection between 1984 and 1990 (in ha):

Name of class	1984	1990
Impaired spruces	2883	3137
Severely impaired spruces	4376	3057
Dying and dead stands	2771	2109
Mixed and young stands	3425	4411
Deforestations with vegetation	155	922
Bare soil	1480	733
Other (dwarf pine, roads, gravel pits...)	4544	5249
Total	19 634	19 634

The results indicates as follows:

- a continued expansion of the clear-cut areas and an increase in areas occupied by moderately damaged stands,
- a decrease in the area of heavily damaged and dying and dead stands, due to extensive clear-cutting activity,
- an increase of the area of young and mixed stands and open areas with vegetation due to the growth of grasses and afforestation activity on areas of previous clear-cuts,
- a decrease of bare open areas as a result of these afforestation activities,
- an increase of the "other" category as a result of constructing new and other facilities in order to perform forest activities on this mountainous region where access to many stands had been limited, as well as result of the rocks which had been previously covered by canopy.

4.1.4 Verification of the Classification Results

The accuracy of classification was assessed using computer facilities and by ground verification. Both pre- and post-classification accuracy assessments proved a high precision - on the average of 94% and 83% respectively.

Tab. 9: Pre-classification accuracy assessment (in %).

Class	FOR1	FOR2	FOR3	AFF	CUTCR	CUTSL	DEC
FOR1	96.0	0.0	0.6	0.0	0.0	0.0	0.0
FOR2	3.3	97.2	1.9	0.0	0.0	0.0	0.0
FOR3	0.7	2.1	96.7	0.0	0.0	0.0	0.0
AFF	0.0	0.7	0.0	84.8	3.2	0.0	7.7
CUTCR	0.0	0.0	0.0	10.9	96.2	4.7	0.4
CUTSL	0.0	0.0	0.8	0.0	0.0	95.3	0.0
DEC	0.0	0.0	0.0	4.3	0.6	0.0	91.9

Tab. 10: Post-classification accuracy assessment (%).

Class	FOR1	FOR2	FOR3	AFF	CUTCR	CUTSL	DEC
FOR1	88.1	11.2	0.3	0.0	0.0	0.0	0.0
FOR2	8.9	83.3	0.0	0.5	0.4	0.0	10.3
FOR3	3.0	4.4	99.7	1.4	0.0	0.3	0.0
AFF	0.0	0.9	0.0	63.5	5.6	0.3	6.3
CUTCR	0.0	0.0	0.0	3.4	93.3	28.7	2.6
CUTSL	0.0	0.0	0.0	0.0	0.0	70.7	0.0
DEC	0.0	0.2	0.0	31.2	0.7	0.0	80.8

4.2 Pilot Study in Fragile Mountain Ecosystems of the Czech Republic

4.2.1 Background of the National Project

In the Czech Republic, the classification of pollution caused damages to forests has a relatively long tradition. The Czech damage-classification system has been developed as a response to practical demands in the eve of the 1960´s and, with some fine adjustments, it is in the practical use until today. A damage classification based on remote sensed data has been investigated since 1980.

Airborne methods were found to be acceptable in small areas only because of their costs and technical problems (quality of photos, visual interpretation, former difficulties in availability of photos, etc.).

The satellite imagery as a basis for the classification of large areas is considered to be the best way since 1984. At present, maps showing the entire area of the republic, classified for the years 1984-85, 1986-88, 1990-92, and 1993-94, are available. They were provided in the context of a series of single projects carried out in co-operation between Lesprojekt, Forest Management Planning Institute, Brandýs n.L. and Stoklasa Tech., Prague.

The Czech contribution to the LAOE was carried out in selected areas of Krkonoše Mountains, Krušné Hory and Šumava Mountains. The work was funded by UNEP during 1994 -1995. Thanks to a fellowship granted by the National Air and Space Museum, Smithsonian Institution, Washington, D.C., USA, the forest ecologist responsible for the project has reached a good knowledge about possibilities and limitations of the satellite imagery with respect to forest damage classification. The long tradition and the experience in satellite data analysis of the involved firm Stoklasa Tech., enabled the generation of a special software for needle loss classification („classifier) in a short time.

4.2.2 Objectives

According to the letter of agreement signed by the Czech part (1994) under the UNEP project "Support to Policy and Guidelines for Sustainable

Management of Temperate Forest Ecosystems for the Conservation of Biodiversity" the project objectives have been specified as follows:

(1) classification of forest damage and its dynamics to fragile mountain forest ecosystems, and

(2) establishment of an integrated information system for the production of forest ecosystem damage assessment maps in selected test areas of the part of the Šumava, Krkonoše, and Krušné Hory.

Satellite based maps of the damage status in different years, provided by the program "Atlas of Damage to the Czech Forests", were analysed for the purpose of a classification of damage dynamics by Stoklasa Tech., Prague. The Atlas contains maps showing the damage intensity for entire area of the Czech Republic in following years: 1984-85, 1986-88, 1990-92, and 1993-94. The damages were classified according to the Czech classification system. Other methods of damage class definitions might be more convenient for analysing the dynamics of forest damages on large areas.

Within this framework the practicability of the standardised approach for forest damage assessment, recommended by the TWG had to be examined. Especially the classification schemes for single tree and stand wise assessment of damages differ with respect to other countries. This had to be considered during the selection of representative truing areas for the recommended satellite damage classes.

The products, deliverables, and expected results have been defined as:

(a) methodology development including standardisation aspects,
(b) preparation of test sites, including digitisation of maps, field verification, photo-interpretation, etc.,
(c) establishment of GIS including database,
(d) satellite image processing, integration to GIS,
(e) documentation in English and delivery of results for the harmonisation process at sub-regional level.

4.2.3 Remote Sensing Data and Ancillary Information

4.2.3.1 Remote Sensed Data

Satellite images

The project has been provided with the satellite images by

(1) the Ministry of Agriculture, Prague, and

(2) the NASA, Washington, D.C., USA, thanks to the activity of Prof. Barret N. Rock, University of New Hampshire, Durham, N.H., USA.

The NASA-granted files were not completely readable and unfortunately too old for the comparison with recent ground data on damages. The most actual images offered by the Ministry of Agriculture of the Czech Republic were used for the project.

Following Landsat Thematic Mapper- 5 images have been processed:

191/25, 23.7.1994 for Krkonoše Mountains,

192/25, 14.7.1994 for Krušné Hory, and

192/26, 28.6.1994 for Šumava Mountains.

Aerial photos

Only old sets of aerial photos were available and therefore not included in the investigations.

It was not feasible to carry out an actual flight campaign and to obtain ground truth data by extensive visual photo interpretation due to the limited time and financial funds. Therefore, the investigations had to rely on data collected by terrestrial assessments in field sample plots.

4.2.3.2 Auxiliary data

Stored data on forests

The field data on forests was provided by the Lesprojekt, Forest Management Planning Institute, Brandýs n.L..

The database contains periodical forest inventory data and information on recommended activities from the forest management plans (FMP). The mean area of an inventory unit is 2.30 ha. The inventory unit description offers information on stand composition, stocking density, site index (Schwappach´s „bonität"), dendrometric data by tree species, forest site type (vegetation climatic zone and soil properties), and health status of the stand. Concerning the damage caused by air pollution, the Czech classification system is used: the damage degree and the treat zone are recorded. Information on defoliation stage is not recorded.

The latest forest management plans for individual forest enterprises in the test areas were elaborated by the following dates:

Krkonoše
Forest enterprises of Harrachov, Vrchlabí, and Maršov - January 1, 1992.

Krušné hory
Forest enterprise Horní Blatná - January 1, 1992,
Forest enterprise Klášterec - January 1, 1989.

Šumava
Forest enterprise Kašperské Hory - January 1, 1994.

Forest stand parameter values of the Forest Management Plans (FMP) were calculated for the entire stands. Variations within the stand are very common. The damage description in the FMP does not offer the latest information on the damage status. Therefore, the FMP data on damage was used as a secondary information only. According to the forest stand composition it was not necessary to assemble actual field data because the stands were relatively homogeneous in the focused regions.

The appropriate FMP information would be inevitable for image masking on the base of forest maps. Recent maps are not necessary for a correct masking of older stands.

Gathered data on forest

Ground truth data was collected from four series of sample plots successively. This data was used as a primary information.

For each of the sample plots, a sample plot record form has been filled out in the field that contains information thought to be decisive for satellite sensed reflection values.

The field form contains following information:

(a) identification number of the plot,
(b) date of the data collection,

(c) address - forest enterprise, compartment, forest stand, inventory unit,
(d) date of the FMP elaboration,
(e) longitude and latitude,
(f) elevation,
(g) slope aspect,
(h) slope gradient,
(i) stand composition,
(j) stand age,
(k) height,
(l) canopy closure,
(m) stocking density,
(n) understorey height,
(o) mean defoliation,
(p) shares of the defoliation by 0%, 1-20%, 21-40%, 41-50%, 51-60%, 61-80%, and 81- 100%,
(q) mean defoliation of the upper third of the crowns,
(r) other damage - top-breaks, needle eating insects, bark beetle, etc.,
(s) discoloration,
(t) understorey description,
(u) soil cover,
(v) site moisture,
(w) notes,
(x) Czech-system damage degree.

Special emphasis was given to information that would probably lead to a wrong damage interpretation in the satellite image. The separation of a damage exceeding 50% of defoliation was necessary for making it compatible with the Czech damage classification system.

Averages of the interval-assessed defoliation and an average of the three (o, q, and x) above mentioned mean assessments („combined defoliation index") were calculated in the office. The defoliation <26% class was derived mathematically as well.

All data on the forest status, including age and height, was assessed in the field. The information (c) and (d) was not found to be necessary and was not recorded.

Other data recorded in the field

The sample plots were recorded on a video recorder for documentation purposes. About 15 % of the plots were not recorded due to technical reasons (problem of batteries, day-time light conditions, etc.).
The Silva GPS (Global Positioning System) compass was tested in order to improve the accuracy of the geometrical registration.

Analogue forest maps

Analogue forest maps (scale 1:5,000 and 1:10,000) produced by the same dates as the individual FMP were provided by the Lesprojekt.

These cover all Czech forests except the military forests (±6%) and are stored in Lesprojekt, Brandýs n.L. The number of the individual map sheets is about 16,000. The maps are in a special projection system that has been transformed into Køovák´s (JTS-K) system.

4.2.3.3 Data Base Processing

Data format and standards

The ERDAS-software was not available in the Lesprojekt. The data was processed in the Topol, and MS Office and Works environments. A special software package was developed by the Stoklasa Tech., Prague.

FMP data

Selected FMP data, considered useful for the work, was included into the data base of the project. This was:
(a) unit address - forest enterprise, compartment, forest stand, inventory unit,
(b) area,
(c) mean age,
(d) composition,
(e) mean density,
(f) mean height,
(g) mean site index,
(h) damage degree - Czech system.
The database could be enlarged any time if necessary.

Training plots

The database includes following field information:

(a) plot identification number,
(b) date of the field form filling,
(i) forest stand composition (percentage of spruce, pine, dwarf pine, and hardwood),

(j) stand age,
(l) canopy closure,
(m) stand density,
(v) site humidity,
(o) assessed mean defoliation of spruce,
(q) assessed mean defoliation of the upper one third of the crowns,
(p) percent share of the single tree defoliation intervals (0 - 25%, 25-40%, 41-50%, 51-60%, 61-80%, 81-100%) and total share of trees defoliated by more than 25%,
(y) average of the interval-assessed defoliation,
(z) combined index of defoliation,
(x) Czech-system damage degree.

All 175 sample plots have been included into the database regardless whether they were suitable to be classified or not. As it can be seen, the data derived from the field information was included into this part of the data base as well.

Aerial photos

Aerial photos have not been included into the database.

Digitised forest maps

The digitised maps were stored in the TOPOL environment which is compatible with common formats. These cover the entire area of the Krkonoše Mts. and the former forest enterprise of Horní Blatná in the Krušné hory. The upper part of the Krkonoše Mts. was digitised automatically and it is in a form that differs from manually digitised other maps.

Satellite imagery

The images have been transformed into the Køovák´s (JTS-K) projection system, that is the base for unification of the topographic and other available maps in the Czech Republic, by the means of TOPOL.

The georeferenced satellite images as well as the scenes with the damage classifications were backed up on optical discs.

4.2.4 Damage Classification

4.2.4.1 Definition of a Classification Scheme

<u>Field truth classification</u>

Three independent assessments of defoliation were performed in the field in order to minimise subjective errors:

(a) mean foliage loss of all trees in sample plot,

(b) mean foliage loss of the upper one third of crown of all trees in sample plot, and

(c) percentage of trees defoliated by 0%, 1-20%, 21-40%, 41-50%, 51-60%, 61-80%, and by 81-100%. A 10% interval of tree defoliation is likely to be more appropriate for describing the single-tree damage distribution and calculating the mean foliage loss.

(d) average of the interval-assessed defoliation and
(e) averages of the (a), (b), and (d) defoliation have been calculated.

The method (c) was the most accurate for the assessment of the mean defoliation.
The method (e) did not improve the results.

<u>Classification of satellite data</u>

Three scales were used for damage classification on images:

a) Czech damage scale

b) TWG scale , and

c) 10% intervals of a forest stand (read here: a pixel area) mean defoliation.

The dynamics were classified as difference intervals between damage status in individual years.

Tab. 11: Czech damage classification system for Norway spruce.

Forest-stand damage degree	Description	Single-tree damage degree				
		S0	S1	>S1	>S2	5
		Maximum share of the single-tree damage classes from all trees in the stand, %				
0	not damaged	100	0	0	0	0
0/I	first symptoms of damage	99	20	0	0	0
I	slightly damaged			32 or 5		
II	moderate damaged			84 or 30		
IIIa	severely damaged				50	
IIIb	very severely damaged				70	
IVa	dying and dead stands				100	
IVb	depreciated wood					100

4.2.4.2 Methodology for the Definition of Representative Training Plots

Preparation of test sites

Four series of sample plots (175 altogether) were visited and described in detail.
Three methods identifying the position of the sample plot were tested:
(a) GPS,
(b) digitised maps integrated into satellite image, and
(c) transparent copies of the maps.

Transparent copies of maps have been used for testing a position identification possibility on the classified satellite images. This method (c) gives sufficient positioning accuracy in homogeneous stands which are large enough and when only the central part of the stand is considered to be the sample. In more complicated situations (rare reference points, small stands, small areas similarly damaged, etc.)., where a precise identification of pixels is important, the availability of digitised maps is quite inevitable. However, this method does not improve the positioning accuracy in large even-aged stands.
The method (a) resulted only in a rough position information with an accuracy of 18,5 m in the best case. Furthermore, the accuracy is unstable because of the US Secretary of Defence regulations of the satellite signal management.

In the field, the plots were registered in maps or in classified images (second series). The plot locations were fixed by digitising their precise position.

Gathering ground data

The sample plots were not marked in the field. Two of the three focused areas are in national parks where any disturbing activities are strictly prohibited. The demarcation in the field is not necessary if the plots location is done by other means (georeferencing, delineation in suitable forest maps and transmission to the satellite imagery, identification of pixels on the satellite image).
Four series of sample plots mentioned in the above paragraph have been recorded successively in the course of the study progress, 175 plots in total.

The first set of sample plots has been chosen in the Krkonoše Mts. on the base of specific satellite based maps produced by the Stoklasa Tech., Prague. The plots were selected in a way where forests were separated from other land use and different characteristics of reflection (in terms of the satellite recorded DN values) influenced by the site, slope, aspect and light conditions were represented. That approach has been felt inevitable for the collection of samples in order to cover the complete range of recorded reflection values in forests. Large sized and homogeneously classified stands were used as sample plots in this series.

A second set of sample plots was chosen in Krkonoše as well. The aim of this sampling was to define areas for the ground verification of the classification results.

A third set of sample plots was selected in Krušné Hory in order to cover the whole range of defoliation stages. This data has been used for the verification of a classification performed by a standard classifier.

A fourth set of sample plots was selected in Šumava Mountains for the purpose of verifying standard classification procedures.

Field-classification of the defoliation

Defoliation has been assessed by visual inspection of tree crown morphology that varies depending on the natural forest region (Plíva et Zlábek, 1986) and species ecotype.

The assessment of defoliation percentages was based on:

(1) the **experience** (local examples of trees with zero or near-to-zero defoliation showed by locally skilled foresters),

(2) the **manual** for forest damage assessment, published by Sanasilva (Sanasilva, 1990) used in the damage inventory in Switzerland, and

(3) a **photo-documentation** published in a Czech professional revue (Henzlík, 1989 a-f). The Czech classification system was assessed according to a currently used manual (Henzlík, 1991).

The one-man's eye method has been accepted: each plot has been assessed by the same assessor.

As mentioned above, the following assessments of defoliation of trees were provided within the sample plots:

(a) mean **crown defoliation** of spruce trees within the sample plot (D_m),

(b) **mean defoliation of the upper third of the crowns** ($D_{1/3}$), and

(c) percent portion of the **trees by defoliation classes** - in intervals of 0%, 1-20%, 21-40%, 41-50%, 51-60%, 61-80%, and 81-100% of needle loss - from all spruce trees in the stand.

The indicators (a) and (b) were derived by global assessments. In general, the requested assessment accuracy was ±5%. The dead trees- already without branches - were recorded separately and after that added to the class 81-100% of needle loss. The assessments also aimed to reach an accuracy of 5%.

An average defoliation was calculated on the base of the defoliation classes using following means of the class limits:

Tab. 12.: Mean defoliation of defoliation classes used in the field assessments.

Defoliation class (%)	0	1-25	26-40	41-50	51-60	61-80	81-100
Mean defoliation (rounded)	0	13	33	46	56	71	91

The averages of the interval-assessed defoliation were calculated as follows:

$$\overline{D} = \frac{0.n_0 + 13.n_{13} + 33.n_{33} + 46.n_{46} + 56.n_{56} + 71.n_{71} + 91.n_{91}}{100} \ (\%)$$

where n is the percent share of the defoliation class.

The combined defoliation index (D_i) was calculated as follows:

$$D_i = \frac{D_m + D_{1/3} + \overline{D}}{3} \ (\%).$$

The reason for such assessment combinations was to investigate the credibility and dependability of individual methods as well as a possibility for avoiding accidental mistakes and/or errors. The calculation of D_i resulted in no significant improvement in information quality and reliability. Therefore, it was neglected in the course of the further work.
The difference in defoliation of the upper third of crowns surprisingly did not affect the reflection DN value as much as expected and was neglected as well.
The mean defoliation assessed in intervals resulted in the most reliable characterisation of the damage.

4.2.5 Signature Analysis and Ancillary Information

4.2.5.1 Problems of Image Classification

In general, the reflection characteristics recorded by the Landsat TM depend on the amount and status of biomass within the area of a pixel (Lambert, 1993). Methods of biomass measurements are very labour-consuming and not convenient for the practical use. For classifications by the means of satellite remote sensing, these parameters can be substituted by defoliation assessments. However, mis-classifications might be caused by the variability of the distribution of single tree foliage losses within a given area or pixel.

The influence of the distribution of single-tree defoliation classes cannot be detected and eliminated by the means of image processing. However, the single-tree defoliation classes are not distributed regularly on a stand area. Furthermore, the resolution of an image element (pixel) is sufficiently small for showing differences which do not cause serious errors and can be used for a decision-making. This statement would not be true if the stand defoliation classes (mean defoliation) are defined in too wide ranges or if some single-tree defoliation classes are neglected in the stand damage classification.

4.2.5.2 Separation of Spruce Stands from other Species and Non-Forest

Areas up to 60 x 60 m in size and covered by crowns of trees older than 20-30 years with canopy closure more than ± 30% were easily separable. Registered forest land where such a coverage is missing or small isolated plots of forest land can not be detected by using satellite data only. Clearings and very young stands could be detected by the comparison of the recent and a thirty years old image. Non-conifers could be separated by masking the forest land, except in cases where the reflection values overlap with the ones of dwarf pine. It was impossible to separate Norway spruce from the other conifers. Any pre-stratification according to tree species and species mixture based only on the image data was impossible as well.

This limitation can be overcome by analysing the reflection values and selecting a sufficient series of sample plots with a convenient species composition (pure or quite pure spruce) as training areas. The plots had to cover the entire scale of reflection values of spruce stands. This way, any digitised auxiliary information - except of the sample plots - was not needed for the spectral signature classification.
The maps resulting from that approach show a more or less accurate classification of damages of spruce, but other forest stands will be misclassified. The reliability of the classification result must be interpreted particularly with the help of available analogue maps and numeric data. For a computerised interpretation (masking the inappropriate stands), it is inevitable to have a GIS data base containing maps and a minimum information on forest composition, age, and density.

4.2.5.3 Forest maps

The map digitisation was performed on the base of analogue forest maps (scale 1:5,000) by Lesprojekt´s regional branch offices, by the Ladap, Prague, and partly by the Help Service - Mapping, Prague. Two methods of map digitisation were tested:

(a) the automatic vectorisation of raster-scanned map matrices (Krkonoše - North, the upper part of the mountains, 18 map sheets on the scale 1:5,000; 12 km^2 each), and

(b) the manual digitisation (Krkonoše - South, Krušné hory) that gives a possibility to add line attributes.

The tests resulted in no significant advantages for the location of sample plots. For improving the classification of forest damages it was not practicable to digitise maps for large regions due to the limited time and budget. Therefore the missing digital layers were substituted by comparing the image with analogue forest maps and database information. Transparent copies of the maps - produced in the same scale as the image - was quite suitable for the correct interpretation of the classified image.

4.2.5.4 GIS Establishment

A GIS could well help when training plots are chosen in the field. The tests showed that the damage classification can be carried out without GIS. But a GIS with appropriate data layers is inevitable for the interpretation and presentation of the results (masking non-forest lands and stands composed of other tree species).

In this project the GIS was generated from the data base by Lesprojekt in collaboration with Stoklasa Tech. and Help Service - Mapping.
The GIS is in TOPOL-environment, based and set up on one server in the Lesprojekt´s network.

The GIS integrates following layers:

(a) manually digitised forest maps with line attributes (for example: borders of compartments, stand or inventory units, forest roads classified according to the size and quality, creeks, etc.) - Krkonoše-South and Krušné Hory,

(b)automatically digitised and manually corrected forest maps (delimitation of the inventory units only) - Krkonoše-North,

(c) manually digitised sample plots - all test regions,

(d) FMP selected data - all test regions,

(e) selected data from the sample plots - all test regions,

(f) analogue syntheses in raster format - all test regions,

(g) classified parts of satellite images - all test regions.

4.2.6 Classification and Map Production

Colour composites of the Landsat-TM bands 5, 4, 3 in R, G, B were processed for selected areas of Krkonoše, West Krušné Hory and a part of Šumava Mountains. The image classification has been processed by Stoklasa Tech., Prague using technologies owned by the firm.
A supervised maximum likelihood classification has been applied for the Krkonoše Mountains by using Stoklasa´s standard classification software "classifier". The standard classifier was specially designed for Norway spruce stands older than 20 years. The standard method includes an elimination of illumination affects (slope, aspect and gradient, fog) that is not based on a DEM.
Non-rectified standard classifiers have been used for the classification of Šumava Mountains and Krušné Hory.
It has to be mentioned that no masking or stratification was performed before the classification process, since this study was looking for the most operational method.

The definition of the training areas was performed on the sites of the above mentioned sample plots. Three different damage class definitions were applied: the harmonised damage class definition proposed by he TWG, the Czech classification system and 10% defoliation classes. Maps were produced for all of these class definitions in each of the test sites. All final damage maps were included into the report of the national project.

The classification results were analysed on all the sample plots where detailed ground truth information was available. The classification according to the 10% defoliation steps was proven to be the closest to the field truth and was judged as the most reliable for local forest management. The results according to the harmonised damage classes, recommended by the TWG, are valid for spruce stands older than approximately 20 - 25 years and a canopy closures above 30% only.

The stands with a low canopy density - proposed by the TWG as opening-up classes - were not separated here because of the spectral overlap of the reflection characteristics between the classes S3+ and D1, and C3- and D2, respectively. It can be assumed that the processing of images, taken in an appropriate phenological stage of the vegetation in the understorey, and the incorporation of a digital forest mask might reduce the mistakes in the final classification. Without having these prerequisites, the heavily defoliated stands with canopy closure below 30% could not reliably be detected and consequently were not classified (without exceptions).

A map in 1:100,000 scale of the forest damages in the Czech Krkonoše Mountains following the damage class definition of TWG is attached to this report.

4.2.7 Verification of the Classification Results

The verification of the results was performed by comparison of the ground truth data, gathered in the course of the classifier calibration, with the final damage classification.

A correlation between the assessment of the mean crown defoliation (D_m) and average of the interval-assessed defoliation was calculated (see Annex C, graph 1). The averages of the interval-assessed defoliation classes were compared with the assessed mean defoliation of the upper third of the crowns ($D_{1/3}$) and canopy closure (see Annex C, graph 2 and 3, respectively).

The comparison of the standard Stoklasa´s classifier results with the ground truth data, resulted in a mean quadratic error - STD - 9.5% in Krkonoše. After the adjustment of the classifier, the STD decreased to 6.7% (see Annex C, graphs 4 and 5).

The classification results for Krušné Hory and Šumava are shown in Appendix, graphs 6 and 7. No further adjustments of the classification could be performed due to the limited number of sample plots there. The comparatively worse closeness of the Krušné hory classification is probably caused by the recorded regeneration of the damaged trees. In Šumava, problems caused by the damages of bark beetles appeared.
The results of the three types of damage class definitions (LAOE , Czech system, and mean defoliation intervals by 10%) are shown in Annex C, graphs 15, 11 and 8.

The damage classes used for the LAOE (STD = ±0.7 of a damage class) overlap each other severely and a misclassification by two degrees can happen easily (see Annex C, graph 15).

The Czech classification system (STD = ±0,57 of the damage degree) shows comparatively greater dispersion, caused probably by the irregular size of the damage characteristic intervals (see Appendix, graph 11).

The mean defoliation (10% interval) of all test regions was classified with a STD = ±9.4%. The STD for the classification of the second set of sample plots in Krkonoše Mountains is just 6.7%. However, in Šumava and Krušné Hory, it decreased to 9,2% and 12%, respectively.

Correlation analyses between the reflection values and parameters like discoloration, site humidity, stand density, stand age, canopy closure and ground coverage type, elevation, and other information were not carried out due to the limited time and the small number of sample plots. Doubts exist whether this research would significantly improve the damage classification on the base of remote sensed data because it is uncertain which characteristics within Landsat TM spectral bands could help in separating these variances.

According to our study results, 20 to 75% of trees which are defoliated more than 25% are concentrated within the mean defoliation (of all trees) interval from 15 to 35% (see Appendix, graph 12). This makes it hard to separate individual damage classes because the spectral characteristics vary less than the assessed defoliation.

4.3 Forest Damage Assessment in Harz Mountains

4.3.1 Objective of the National Project

At first, forest damage inventories were carried out by field sampling methods, later on with colour infrared photos (BML 1984 and Hildebrandt 1984). The disadvantages of the former method are that forest decline symptoms due to dead trees are not taken into account and thus do not appear in the damage statistics; this results in a systematic underestimation of forest damages. In contrast to sampling methods satellite data allow a complete pixel-by-pixel covering assessment on the state of the vegetation integrating missing trees also. For the applicability of these methods it is necessary to define damage classes which correspond both to the requirements of satellite remote sensing and existing field methods of forest damage estimation. Therefore, in this investigation both, the separability of needle loss and deforestation symptoms will be taken into account.

As support for the satellite classification a Forest Information System (FIS) was established. The FIS consists of a digital elevation model (DEM) as well as digital forest stand maps and digital soil maps. Special attention was also given to the possibility of using these data for planning tasks, too. Because of the bad health-state of the forest, the forest administration of Lower Saxony plans to convert the widespread spruce monocultures into more stable deciduous and coniferous mixed forest stands or pure deciduous stands (Niedersächsische Landesforsten 1992). If put into practice these plans could be accompanied by investigations into how GIS-aided planning procedures can be used. The aim is to show in how far satellite classifications as component of the FIS is able to give information on the health-state of individual stands, i.e. the urgency of stand-conversions; however, the actual spectrum of the statements on further planning, which could be supported by such data, is much greater.

4.3.2 Description of Data and Processing

<u>Satellite Data</u>

Thematic Mapper data of the year 1991 was used for the forest damage inventory. The satellite images were geometrically corrected into the Gauss-Krüger co-ordinates using the pass point method. The RMS-Error of the geometrical correction amounts to 18m. For the evaluation of the satellite images the Image Processing System ERDAS was used.

Forest Information System (FIS)

A Forest Information System was established in order to support

- a distinctive mapping of forest disease supported by the integration of auxiliary information (Ekstrand 1993) and
- forest management planning

For digitising the maps and further processing of the vector-data the Geographical Information System Arc/Info was used.
The components of the FIS are illustrated in Table 13.

A. Digital forest maps

In order to integrate stand parameters such as tree age, tree species and stand structure, the forest management plans (70 map sheets consisting of over 15.000 planning units) of the complete Harz Mountains were digitised. Because of the insufficient geometrical accuracy of the forest survey (gaps and overlapping of neighbouring map sheets of up to 100 meters) each of the maps had to be geometrically corrected in Arc/Info using a rubber-sheet algorithm and of pass points derived from topographical maps. After the geometrical correction the digitised map sheets are merged together to one forest map containing the complete forest area of the Harz mountains.

As attribute data the digital stand description of the forestry administration could be used. The attribute data containing about 100 different stand parameters are prepared due to the requirements of satellite classifications and computer-aided forest management planning. By combining the attribute data and the digitised forest maps the planning units can be stratified according to single parameters or different combinations of the stand parameters. The result of stratification can for example be maps demonstrating the distribution of different age classes, tree species, tree heights or diameter classes.

Tab. 13: Components and information content of the Forest Information System

Components	Information Content
Digital forest maps scale 1:10.000 in vector-format	tree species, tree age, stand structure, timber volume, etc.. (more than 15.000 stands)
Digital soil maps scale 1:10.000 in vector-format	soil moisture, soil type, nutrient supply, soil depth etc.
Digital topographical maps scale 1:25.000, 1: 50.000 and 1:100.000 in raster-format	topographical features like streets, lakes, buildings, etc..
Digital elevation model in raster-format	slope, aspect, illumination, height zones of vegetation
Results of satellite classification in raster-format	crown closure and forest damage
Results of aerial photo interpretation in vector-format	crown closure, needle loss, vertical stand structure and other forest parameters

B. Digital soil maps

Digital soil maps are a central component of the Forest Information System. Together with the digital terrain model, forest management maps, and the forest damage classification, these maps will be used for feasibility studies of the Forest Information System according to forestry management planning. The soil maps were digitised by the Institute of Soil Science of Niedersachsen. The results of this investigation will not be discussed in this paper.

C. Digital topographical maps

Digital topographical raster maps were integrated in the Forest Information System in order to automate the process of geometrical correction of the digitised forest management maps. These maps were made available by the Surveying Administration of Niedersachsen.

D. Digital elavation model (DEM)

A digital elevation model is integrated into the FIS first to eliminate the negative influence of topographical parameters in the satellite image

(Schardt 1987) and secondly to derive information of growth conditions of the forests. A map of the height-zones was calculated using the topographical parameters elevation, slope and aspect from the DEM. The height-zones for the entire test area were integrated into the FIS on the geometrical level of stand units (the integration procedure is described in the chapter „Classification"). The DEM and the height-zone map were geometrically adapted and superimposed to the satellite data, too. The spatial differences between the DEM and the satellite data amount to about 15 meters due to the y- and x- axis and less than 5 meters due to the z- axis (height above sea-level) which is highly satisfactory for classification purposes on a scale of less than 1 : 50.000.

E. Remote Sensing data

The results of the satellite classification and the aerial photo interpretation are integrated into the forest information system, too. Herewith, important forest parameters were available which could not be derived from existing maps.

4.3.3 Classification of Forest Decline

4.3.3.1 Selection of Training Areas

Training areas are test sites used for the signature analyses and for defining the statistical characteristics of signatures of differently damaged stands. The characteristics are used as input for the computer-aided classification. The training areas were selected representatively for different illuminations, slope and aspect conditions, heights and natural age classes as well as for the different stages of damages. For the selection of training areas aerial photos were interpreted and field work was carried out.

Aerial photos

Aerial infrared photos on a scale of 1 : 6.000 and 1 : 7.000 were taken for small and representative areas of the Harz Mountains. They are used to estimate the crown density and the percentage distribution of the different needle loss classes. For the estimation of the crown density, a 1mm * 1mm grid (6m * 6m on the ground) was superimposed to the aerial photos. The relation between grid points covering a tree and those covering a gap between trees can be defined as the crown-cover percentage. The percentage of the different needle-loss classes was estimated by the interpretation of 3 trees per sample plot on a 30m * 30m grid. The interpretation was carried out using the AFL interpretation key (AFL, 1988).

Field work

Field work was done for altogether 300 training areas to evaluate stand parameters which cannot be derived from aerial photos such as ground vegetation and natural age classes of the stands.

4.3.3.2 Signature Analysis

The statistical analysis of the training areas was carried out by means of the statistical analysis system SAS. The results of the statistical analyses can be summarised as follows:

Influence of the crown density on the reflection of forest stands

From the results of the signature analysis it can be deduced that even slight differences of crown density have an enormous influence on the reflection of forest stands (Schardt 1990, Franklin 1986, Bodmer 1993). The reflection differences can mainly be seen in bands 4 (near infrared) and 5 (middle infrared).

The scattergram in figure 3 shows the mean grey values (y-axis) of training areas representing different crown cover percentages (x-axis) exemplary for the TM-band 4 (near infrared). All these stands belong to the same age and illumination class so that reflection differences are mainly caused by different crown cover percentages of the stands. In TM-band 4 decreasing grey values are associated with a decreasing crown cover percentage within the range from about 65% to 90%. A further reduction of crown density from about 65% to 10% leads to increasing grey values. This phenomena is due to the increasing influence of high - reflecting grass vegetation on the reflection of open stands.

In TM-band 5 (middle infrared) a slight reduction of grey values goes hand in hand with a reduction of crown density within the range from about 65% to 90%. Within the range from 65% to about 10% a significant

increase of grey values is associated with a decreasing crown closure as in band 4.
The high deviation of the mean values in band 4 and 5 of open stands (10% to 60% crown-cover percentage) is due to different types of ground vegetation.

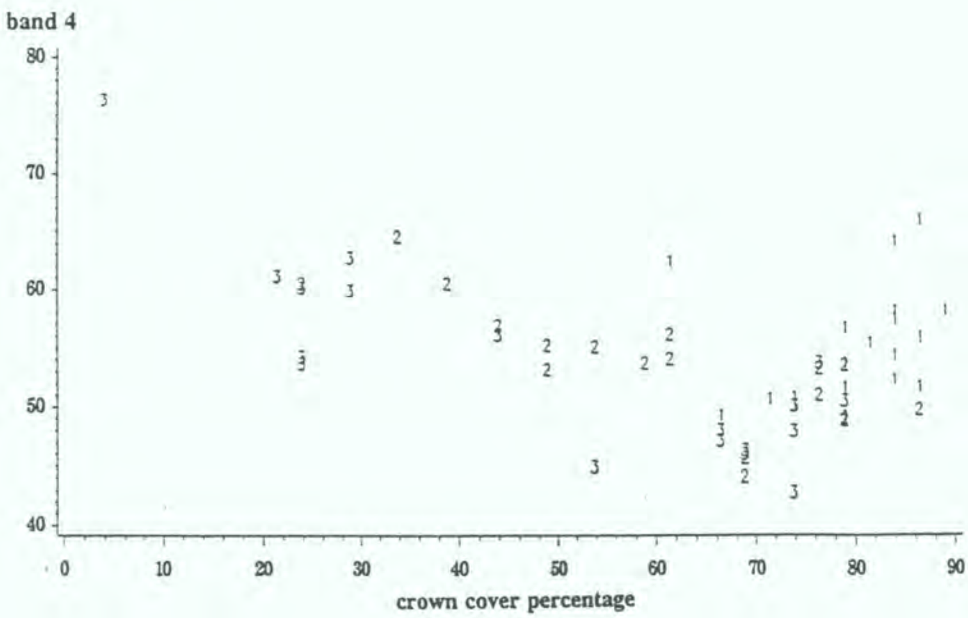

Fig. 2: Mean grey values (y-axis) of old spruce stands in dependence on crown density (x-axis) in TM-band 4 (1=no needle loss, 2=moderate needle loss, 3=severe needle loss)

Influence of needle-loss on the reflection of forest stands

An increasing percentage of needle-loss goes hand in hand with a significant increase in grey values in band 5 (middle infrared) and a slight decrease in grey values in band 4 (near infrared). This signature characteristic can be demonstrated by comparing training areas with different needle-loss symptoms belonging to the same crown cover category. The negative correlation of these two bands due to needle loss symptoms can be shown more clearly by the quotient of bands 4 and 5.

Nevertheless, comparing the signatures of dense stands which are characterised by severe needle-loss symptoms with those of open stands without needle-loss symptoms no clear separation is possible. From that it can be deduced that the reduction of crown closure and reduction of needles has a similar influence on the reflection of forest stands. Therefore, a satisfactory classification of needle loss without taking deforestation symptoms into account is to be seen as very critical.

Influence of ground vegetation

A decreasing canopy density leads to an increasing influence of ground vegetation on the reflection of forest stands. The typical reflection characteristic of forest stands can be modified strongly by different types and phenological stages of ground vegetation (Butera, 1986). Thus, a lower classification accuracy of deforestation and defoliation categories can be expected in stands with low stand densities. Therefore for stands with very low canopy density no assessment of different defoliation categories is possible. Detailed field information and knowledge about the reflection characteristic of the forest floor is necessary to estimate the influence of ground vegetation on the classification accuracy.

Influence of tree age and illumination on the classification of forest damage

Tree age has a similar influence on the signature of the bands TM4 and TM5 as defoliation and deforestation. Independent of the damage class they belong to older stands seem to be more damaged than younger stands. Forest stands on south and west slopes show a significantly higher reflection than those growing on north and east slopes.

However, taking the ratio band TM4/TM5 the signature differences caused by different tree age and illumination can be reduced, while maintaining signature differences resulting from different needle loss and deforestation stages.

4.3.3.3 Definition of Damage Classes

In this investigation three different damage classes and stand parameters respectively were developed and their practical applicability verified:

Stand density

The very important information about the stand density which indicates the stability of a stand was therefore classified in this investigation. Nevertheless auxiliary data such as digitised forest management plans or other maps providing information about the actual forest distribution are needed for a decision whether or not stand density has to be regarded as damage symptom, since low stand density may also be the result of silvicultural treatment of forest stands. In addition to that the problem of recognising damages caused by air pollution among clearcuts, windthrow areas or something similar cannot be solved if information on regular cutting operations and on disaster (storm, snow, ice, insect attacks etc.) is not available. In this investigation stand density was classified into 9 categories from 0 - 90%.

Needle loss

Satellite classifications of forest damage using Thematic Mapper data cannot give any information on the defoliation stages of single trees because from picture elements with a spatial resolution of 30m * 30m only an integrated information on approximately 10 to 50 trees can be derived. Because of the heterogeneous spatial distribution of defoliation stages most of the pixels integrate trees that belong to different defoliation classes. Therefore the stages were assigned to categories according to their respective portion of damaged trees within one pixel or stand.

Hence, in this investigation the needle loss categories were defined as the portion of trees belonging to the common needle loss classes S2 (25-60%), S3 (61-90%) and S4 (dead trees) in accordance to the common damage class definition established by the working group of aerial photo interpretation (AFL, 1988, or VDI, 1990):

- C0 = 0 - 10 % strongly damaged trees (S2-S4)
- C1 = 11 - 33 % strongly damaged trees (S2-S4)
- C2 = 34 - 66 % strongly damaged trees (S2-S4)
- C3 = 67 - 100% strongly damaged trees (S2-S4)

Using the damage class definitions described above the defoliation category of whole stands can be then calculated from its composition of differently classified pixel.

Other definitions classifying the damages of a stands suggested by Schmidtke (1987) and Neumann (1990) were investigated, too.

Reduction of green needle biomass

This class definition results from the needle loss caused by different stages of defoliation as well as from different stand density stages. Considering that reduced stand density also can be a result from silvicultural treatment, forest damage can be described only conditionally by this category. Also here, auxiliary data or information is necessary to interprete the classification result in a right way.

For the calculation of needle loss caused by the reduction of stand density the maximal crown cover percentage of young and middle old stands without any gap was assumed as 84% (Assmann, 1961). Only in very young stands (thickets and young pole timbers) a crown cover percentage of over 88% occurs. The maximal crown cover percentage for old stands was assumed as 75%. To consider different optimal crown cover percentages in dependence of tree age digital information has to be integrated into the process of classification. The information about tree age can be derived from the Forestry Information System.

The needle of the remaining trees can be defined by calculating the average needle loss of the stand wise damage classes C0 - C3. For this calculation it was assumed that the needle loss of the trees belonging to the damage classes S2, S3 and S4 is distributed normally.

4.3.4 Classification

The classification was carried out for all class definitions described above by a simple threshold method using the bands 4 and 5 (near and middle infrared) and the maximum likelihood method using the bands TM2,3,4 and TM5. In order to integrate illumination and tree age into the classification the entire Harz was stratified into two age and three illumination classes using the digital terrain model and the digitised forest management plans.

The classification results were integrated stand wise into the Forest Information System. For this purpose different steps of data processing were performed. In order to avoid overlapping errors at the stand boundaries the digital forest maps were buffered with a distance of +/- 30m which corresponds to the spatial resolution of the Thematic Mapper data. In a second step the buffered forest maps were converted into raster-format. In doing that individual grey values (from 1-16.000) were allocated to each of the stands. In a third step the classification result was masked by the rastered forest maps. This masking procedure results in an ASCII-table which provides different statistical parameters such as mean value, standard deviation or median value of the classified forest parameters (class values) for each stand. In a last step the ASCII-table was linked to the attribute table in Arc/Info and used as an additional parameter of the digital forest maps.

4.3.5 Verification of the Classification Result

For the examination of the classification accuracy an aerial photo interpretation for three representative areas of the Harz was carried out:

1. Region of the lower Harz Mountains showing only slight damages and dense stands.
2. Sub-montainous region showing moderate and severe needle loss symptoms and more or less dense stands
3. Ackerbruchberg - region with very severe needle loss and deforestation symptoms

The comparison of the classification results with the results of the aerial photo interpretation shows the following correspondences.

Stand density categories can be classified in intervals of 10% with an average accuracy of over 90%. The negative influence of ground vegetation on the classification of stand density is not as high as expected. Figure 5 shows the satisfactory correspondence of the aerial photo interpretation (y-axis) and the satellite classification (x-axis). In this figure each cross represents the mean crown closure percentage of a verification stand. The accuracy of the classification of 4 needle loss categories (C0-C3) is very low and amounts to not more than 65%. This is due to the high influence of stand density on the signature masking the signature differences caused by different needle loss symptoms. The classification of needle loss in stands with low density is even impossible. The classification of the category resulting both from stand density and needle loss of remaining trees provides satisfactory results. 5 classes could be classified with an accuracy of about 85%.

The threshold and the maximum likelihood method provides similar results for the classification of dense stands. Because of the abnormal grey level distribution of open stands the maximum likelihood method provides lower accuracies.

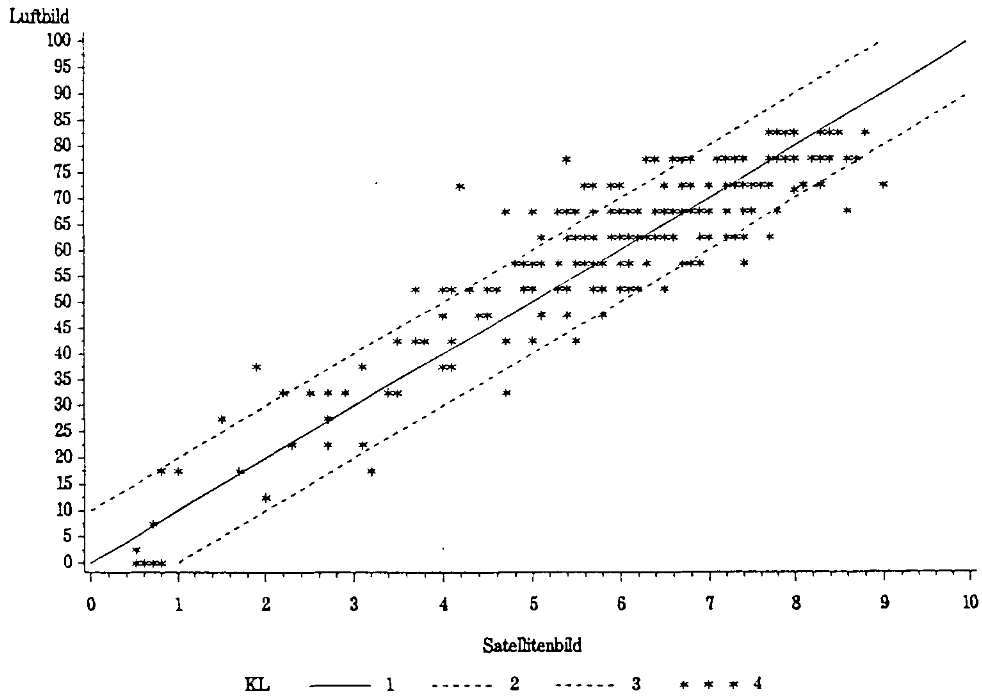

Fig. 3: Comparison of the aerial photo interpretation and the classification for crown closure

4.4 Development of a Forest Monitoring System in Fichtel- and Ore Mountains

4.4.1 Objectives of the National Project

The objective of the German research project in the Fichtelgebirge and the Erzgebirge was the development of remote sensing methods for classifying forest condition focused on Norway spruce. Satellite data with different radiometric and geometric resolutions on the ground as well as high and low altitude aerial photography was investigated in order to exploit different levels and scales of planning. The interpretation and the project implementation was managed within a GIS system. The remote sensing data was combined with different categories of ancillary data, ranking from regular forest inventories, management plans, ground truth data and other thematic data from digitised maps.

Specifically, the objectives which are of relevance for the LAOE can be summarised as follows:

- to develop a forest monitoring concept for local and regional planning based on remote sensing and GIS,
- to evaluate the operationality of different sensor data for damage assessment,
- to develop a Forest Information System (FIS) in which results of remote sensing analysis can be combined with traditional forest management and other relevant spatial data,
- to utilise existing spatial information on the forests by GIS techniques for the analysis of the remote sensing data
- to test the transferability of the damage classification results to other regions.

A focal point in the national project was the development of a classification scheme for spruce damage classes. Since the project started in 1993, the discussions and the results of the TWG within the LAOE could be fully adopted without any additional effort and funding. With this approach a monitoring concept for damage assessment on large scale was established and can be used as an instrument for forest and land-use planning in future.

4.4.2 Description of Data and Processing

Satellite Data

The entire area of investigation is 160 x 110 km in size. The acquisition of two Landsat TM scenes, path/row 193/25 and 192/25 from 02.07.1993 and 09.08.1992, respectively, was necessary for a complete coverage. Both scenes were handled separately: they were rectified on the base of topographic maps 1:25,000 of Bavaria and Saxony, and were referred to the Gauss Krüger co-ordinate system.

Additional Landsat TM scenes from 1990, 1987,1986, 1984 and MSS scenes from 1990, 1981,1980 and 1972 were acquired and processed mainly for the purpose of a change detection, which was not the objective of the LAOE. Only the most recent scenes of Landsat TM and one MSS scene of 1972 was necessary for the LAOE. The historical scene was used for the improvement of the classification of spectrally ambiguous classes like clearings, thickets and deciduous forests.

Within the national project three SPOT-XS scenes of 1993 and a multi-seasonal data set of three ERS-1 scenes of 1992 were investigated.

The damage classification was performed by applying a supervised maximum likelihood classifier. It was already discussed within the TWG that the classification of forest classes requires the incorporation of a forest/non-forest mask in order to avoid mis-classifications. The forest mask can be derived either from a digital topographic map or by multi-temporal classification of satellite data. Due to the large size of the test area and the high number of required maps, the forest mask was processed from satellite data only. Therefore an approach was chosen where automatical classification was combined with ensuing visual interpretation.

Hardcopies in 1:50,000 scale from colour composites of the TM-bands 4, 5, 3 in R, G, B were produced for supporting the field checks and the signature interpretation. The filmwriting was performed with a high-quality laser- filmwriter.

The ERDAS software and a special GAF tailor made software was used for image processing. The signature analysis was carried out in combination with the GIS software ARC/Info.

Aerial photography

The determination of stand wise damage classes by assembling single tree damage assessments can be carried out best by visual interpretation of colour infrared aerial photography (CIR). In meantime a standardised interpretation key on the basis of single tree assessment, developed and published by the "Working Group for Aerial Photo Interpretation in Forestry" (Arbeitsgruppe Forstlicher Luftbildinterpreten - AFL, 1988), is applied in various countries with giving reliable results. Therefore, CIR photo interpretation was considered to play an important role in the definition of training areas of the harmonised damage classes in the satellite classification as well as for the verification of the classification results.

In order to minimise the cost and the effort for the time consuming photo interpretation it was necessary to perform the flight campaign on restricted areas only and to investigate the photography by an area frame sampling approach. Representative test areas had to be selected for the planning of the flight campaign and the terrestrial surveys. Three test areas are located in the Erzgebirge, named "Keilberg", "Marienberg" and "Altenberg", referring to geographic marks. The fourth one covers the central part of the Fichtelgebirge.
For these test sites (mean size about 14 x 16 km) the CIR photo mission at scale of 1 : 7.000 was carried out by DLR in 1993.

In each of these test areas a further sub-sampling was performed. Up to ten area frames were selected, each corresponding to one CIR image (scale 1:7,000). These area frames represent the variability of the forest cover condition, elevation, exposition and other relevant factors. They can be seen as the main training areas (ground truth) for the satellite data classification (Reuther and Akgöz 1995).

Geographic Information Systems (GIS)

One of the main aims of the project was to set up a Forest Information System (FIS) for further forest management purposes. Beside the digital integration of forest maps, topographic information, digital terrain models and other auxiliary data, as well as the satellite classification results, this tool will be able to support forest management and other spatially relevant decisions concerning forest and environment.

A broad data base was built up comprising of the following thematic contents:

- forest management plans
- stratification of forest stands in selected CIR photos
- stand site maps
- forest function maps
- forest inventory data
- infrastructure elements
- digital elavation model (DEM)
- geological, pedological, climatic and hydrological maps
- administration boundaries
- satellite data: original data and classification results

In the context of the satellite data analysis, selected parts of this data base were used for supporting the classification of forest condition.

4.4.3 Classification of Forest Condition

4.4.3.1 Definition of Representative Training Areas for the Damage Classes

<u>CIR photo interpretation for ground truth assessment</u>

In order to obtain a reliable and objective base for the satellite classification a detailed interpretation of CIR photos was carried out in the selected area frames of the 4 test areas. In total 40 test sites - each covering the central area of one CIR photo - were chosen under consideration of covering the full range of different forest conditions, management types and topographic aspects. The selection of these test sites are supposed to be representative for the variability of the forests in the investigation area.

Within the selected test sites a stratification of homogenous forest stands in terms of tree composition, stand age and crown density was carried out by stereoscopic interpretation. The following table shows the stratification criteria.

Tab. 14: Criteria for forest stratification

Spruce	Tree composition	Stand age	Canopy density
	spruce 90 - 100 %	old timber	> 90 %
	spruce 50 - 90 %	timber	75 - 90 %
	spruce 10 - 50 %	pole timber	60 - 75 %
		thicket	40 - 60 %
		culture	20 - 40 %
			0 - 20 %
Deciduous			
Clearings			

The purpose of the stratification was to obtain homogeneous reference units for which a description of the damage situation could be assigned to.

This stratification approach, performed from the bird's-eye view by using aerial photography , is best adopted to the appearance of different forest types as seen from the satellite perspective. In total more than 900 stands were delineated and described in their appearance and composition.

The distribution of AFL damage classes was assessed in more than 400 strata. The frequency of needle loss classes was obtained by sampling of at least 40 trees by applying a systematic grid and interpreting the single tree damage classes.

The strata were digitised and the needle loss assessment results were integrated into the data base.

4.4.3.2 Signature Analysis

The signature analysis was supported by GIS selections according to different stand parameters and forest conditions. Training areas were defined by generating several GIS masks and signature extraction from the Landsat TM data set for the different crown density classes, the different natural age classes, species composition and stand wise damage classes. The separability of these classes was tested by self classification tests. The findings are summarised below:

Forest and non-forest land

In order to separate damaged areas with severe or total deforestation from non-forested land (e.g. grassland), knowledge on the extent of the forested area is necessary. This information can be taken from existing maps (forest maps, topographical maps) providing that they are up-to-date, or alternatively from a multi-temporal satellite data set, as it was performed in this study.

Species type

The current status of satellite remote sensing allows a proper classification of damage only for spruce. The satellite remote sensing method cannot be applied to mixed spruce stands or other stand types, a pre-stratification of the target area is therefore required. Digitised forest maps are most suitable for this purpose but were not available for the entire area. In this project a separation of deciduous and mixed stands was achieved by analysing the satellite data and applying automatical classification in combination with visual interpretation.

Stand density

The spectral signatures of forests are influenced by ground reflectance and its vegetation, depending on the stand density and crown closure. This influence increases with decreasing canopy density. Consequently, a deterioration of the damage classification can be expected. Finally, where stands show an extremely low density the differentiation of damage classes is no longer feasible. Most evidently in strongly opened stands, the identification of forest in satellite data becomes problematic. The figure below shows that the spectral signals of the TM bands are influenced by the crown cover classes:

A significant difference exists in the reflection values of above and below 60% crown cover. This indicates that crown cover classes can be separated by digital classification and be considered as an additional damage symptom.

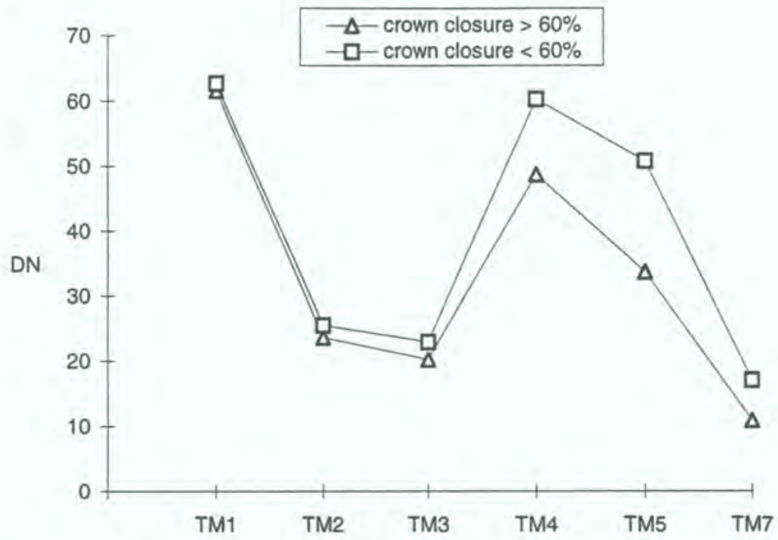

Fig.4: Mean grey values of crown density classes of the TM bands

Topography

In areas with pronounced topography, considerable differences in illumination occur and have to be taken into account. Here modelling and subsequent correction of the disturbing effects using digital elevation models (DEM) is the most appropriate method. Unfortunately, the availability, resolution and costs of a DEM for the entire investigation area ruled out this kind of application. Mis-classifications caused by topographical effects were minimised by using the synergetic effects of TM bands 4 and 5. A ratio transformation of the bands 4/5 were incorporated into the damage classification of the coniferous stands. Classification errors of the other classes due to topography were compensated by the application of a combination of automatical classification and visual interpretation.

Stand age

Young trees show usually a higher spectral response than old trees, independently of forest decline. Thus variable age classes cause significant spectral differences and may result in false damage assessment .

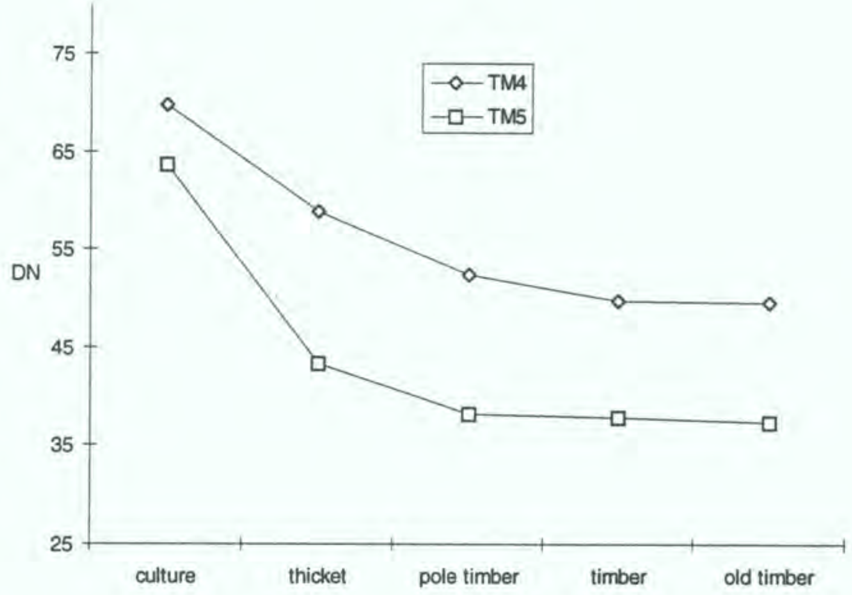

Fig. 5: Mean gray values of TM bands 4 and 5 in dependence of natural age classes

A pre-stratification according age classes before the damage classification was thought to be not necessary, because both parameters are highly correlated in the Fichtel- and Erzgebirge.

Needle loss

The signatures of the needle loss classes as recommended by the TWG were analysed intensively. The definition of representative training areas for the stand wise needle loss classes was based on the results of the aerial photo interpretation. In each of the 40 test areas the forest strata were characterised by the distribution of the AFL damage classes of individual trees. This frequency of damage classes could easily be transformed into the stand wise damage classes C0, C1, C2 and C3. A set of training areas could be defined by GIS-selections according to the harmonised class definitions. With GIS overlay procedures the signatures could be extracted from the TM data.

The signature curves in figure 6 show the mean grey values of the classes C0 - C3 in the TM bands for stands with crown closure above 60%. The most evident seperability is given in the infrared spectrum of the TM bands 4 and 5.

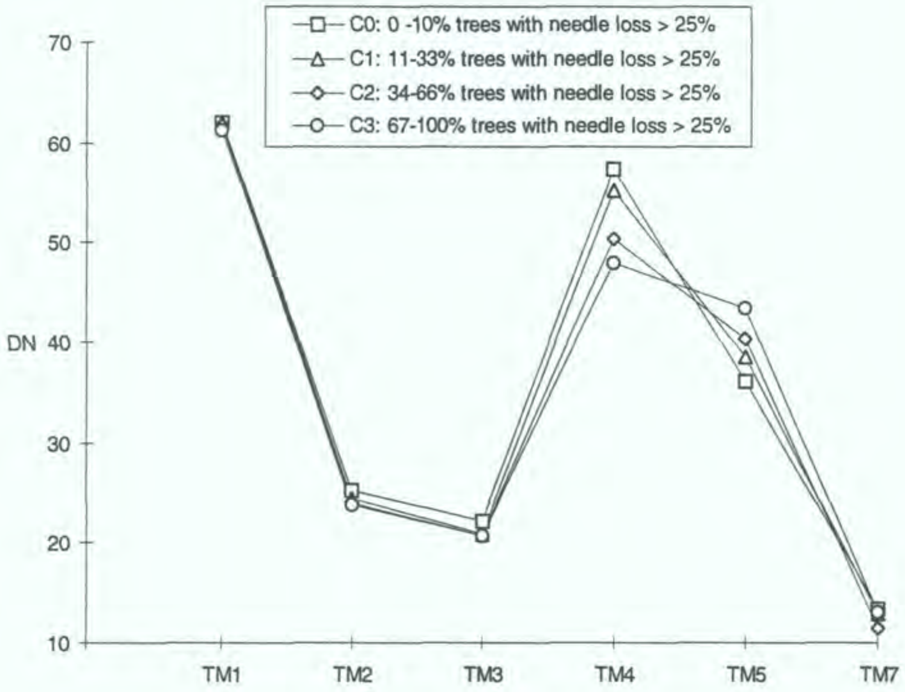

Fig. 6: Mean grey values of needle loss classes C0-C3 of the TM bands

The grey values of TM 4 are decreasing with increasing needle loss. The spectral curve of TM 5 shows a reverse behaviour. Due to the negative correlation of the needle loss signatures in these bands, the differences became more significant in the ratio transformation. Therefore, the ratio of the TM bands 4/5 was incorporated into the classification.

A comparison of signatures between increasing needle loss and decreasing crown density shows a contrary tendency. This means that needle loss symptoms cannot be separated in stands with low crown density. A separation of opening-up classes with a crown closure below 60% from needle loss classes is mandatory for a proper damage classification.

4.4.3.3 Classification and Map Production

As mentioned above multi-temporal satellite data sets were used to get a satisfying forest / non-forest mask. Within this first classification step general landuse classes like coniferous and deciduous forest as well as settlements, water, agriculture, etc. were separated. Due to signature overlap of some classes (e.g. clearings/culture with agriculture, or in general settlements) this first classification result was edited by visual interpretation on screen with the help of topographic maps.

Inside the forest mask a maximum likelihood classification was applied by using the training areas for deforestation and needle loss classes resulting from the CIR interpretation.

The visible TM bands were not used for the classification because of the very low information content inside the forests, and the varying atmospheric influence. Therefore only the infrared bands TM 4, TM 5 and TM 7 were used. In order to minimise illumination influences the band ratio of TM channels 4 / 5 was included.

Due to low information about the forested areas, e.g. in Bohemia or Thuringia, the areas with coniferous trees outside of the growth districts of Fichtelgebirge and Erzgebirge were not classified furthermore into damage classes, but were displayed as an own class, labelled "coniferous outside of investigation area".

The following classes were classified in total:

Needle loss and opening-up classes of spruce from pole timber to old timber

- needle loss of spruce with crown closure > 60%
  0 - 10 % trees with needle loss > 25 %
  11 - 33 % trees with needle loss > 25 %
  34 - 66 % trees with needle loss > 25 %
  67 - 100 % trees with needle loss > 25 %

- opening-up classes
  crown closure 41 - 60 %
  crown closure 21 - 40 %
  crown closure 0 - 20 %

Other forest types:

- deciduous
- clearings, cultures and thickets
- coniferous outside of investigation area

Non-Forest:

- agriculture
- settlements
- water
- swamps
- others (mining area, rocks)
- highways

The final classification result, showing the forest damage classes, as well as deciduous forests, clearings, cultures and thickets, and also the surrounding general landuse together with topographic information like city names, state boundaries and the Gauss Krüger co-ordinate grid, was printed at scale of 1:200.000. Inside the national project it is planned to print maps on forest district level at scale of 1:50.000.

4.4.4 Verification

The verification of the harmonised damage classes was performed by establishing confusion matrices of sampled ground truth data, derived from CIR aerial photography, and the corresponding satellite classification results. The national project was still in process when the LAOE report was finalised. Therefore, the verification results were not yet complete at this stage and only tentative figures could be given. The best discrimination could be obtained with the general land cover and forest classification. Opening-up classes, deciduous stands, mixed stands and clearings could be classified with an accuracy of more than 90%. This is due to the fact that the classification could be improved by visual image interpretation.

Tab. 15: Confusion matrix for opening-up classes

	Crown closure 0-20%	Crown closure 21-40%	Crown closure 41-60%	Σ
Crown closure 0-20%	84.9	15.1	0	100
Crown closure 21-40%	8.4	90.3	1.3	100
Crown closure 41-60%	0	7.5	92.5	100

Tab. 16: Confusion matrix for needle loss classes C0: 0-11% trees with AFL-classes S2-S4, C1:11-33% trees with AFL-classes S2-S4, C2: 34-66% trees with AFL-classes S2-S4, C3: more than 66% trees with AFL classes S2-S4

	C 0	C 1	C 2	C 3	Σ
C 0	80.3	11.4	5.2	3.1	100
C 1	14.2	68.8	14.3	2.7	100
C 2	10.4	23.2	47.6	18.8	100
C 3	4.2	3.6	20.3	71.9	100

The accuracy of the needle loss categories is relatively low. Especially the category C2 is spreading into C1 and C3. A grouping of C0/C1 and C2/C3 increases the accuracy and is much better suited to characterise a large region in terms of damage concentrations.

5 Discussion of the Results

The final image classifications and the presentation of its results was performed by following the common methodology approved by the Advisory Board of the Large Area Operational Experiment for Forest Damage Monitoring in Europe using Satellite Remote Sensing. This methodology was based on the suggestions of the TWG.

The results of the forest damage classifications were printed on coloured maps in scale of 1:100,000 (Polish Sudety Mountains, Krusne Hory, Harz) and 1:200,000 (Fichtel- and Erzgebirge). They are attached in the Annex of this report. The digital cartography including the harmonisation of the map layout was performed by GAF in Munich.

The potential value of such regional forest damage maps, derived by satellite remote sensing, is closely tied to the questions of thematic accuracy, geometric and temporal resolution. The detailed examination of these points in the frame of the LAOE and the discussion of the theoretical and technical constraints, combined with the actual examples from the test areas, give answers in a semi-quantitative to quantitative manner. Although the conditions in the test sites were differing in terms of forest condition and availability of auxiliary data, the particular projects could apply the harmonised classification scheme for forest damages and were able to produce standardised comparable maps.

The feasibility of the harmonised approach for forest damage mapping has to be judged in the light of benefit versus cost and is generally seen positive by the study team. The costs for the applied method of forest damage mapping by satellite remote sensing as demonstrated in the LAOE are generally less than for terrestrial or aerial photography surveys. The results of the particular projects are discussed below.

5.1 Necessity of Ancillary Information

The investigations in pilot studies showed that the integration of a DEM and forest stand parameters derived from digital forest maps (e.g. tree age) increased the classification accuracy only slightly.

The digitisation of forest maps is very time consuming. Digitising large amounts of these data just for the purpose of optimising satellite classification is not advisable and thus not feasible for small scale classifications.

The thematic information of forest maps should only be integrated into the classification process if it is already available in digital format.

It can be concluded from the study results that the integration of additional information is necessary in order to separate forest (open stands <20% crown closure) from non-forest. This can be derived either by using the digital forest layer of topographic maps or by classifying a forest mask through multi-temporal classification of Landsat TM data. Multi-temporal classification has the advantage that critical forest classes which are easily mixed up with non-forest classes - like deciduous forest, clearings, cultures and thickets can be detected with an accuracy of over 90%. Without these additional data the harmonised damage classes developed in this project cannot be met by the classification.

5.2 Damage Classification

Due to the high spectral response of ground vegetation in open forest stands, opening-up classes have to be considered in a stand wise damage class definition.

The stand wise definition of needle loss symptoms as defined by Förster (1989) fits very well into the dynamic of forest damage. This could for example be tested by using the results of a former stand wise forest damage inventory performed by the Forest Research Organisation of Niedersachsen.

It was a major assumption in the LAOE that the damage class definition should be based on conventional definitions in order to be accepted by the forest administration. The class definition should not be adapted to one test site only.

The damage class definition applied in the LAOE was proven to be flexible enough to characterise the different damage situations among the test sites.

5.3 Signature analysis

All the pilot studies stated that the influence of stand density on the spectral signature of Landsat TM data is high.

The influence of different needle loss symptoms on the spectral signal is generally lower and is masked by the influence of varying stand densities.

The influence of tree age and illumination is significant in each band. But by using synergetic effects of band 4 and 5 this influence can be reduced.

The separation of different needle loss categories is not possible in stands with crown closure below 60%. Crown closure below 60% is mostly caused by forest damage and exceptionally a result of regular forest management. Therefore, the damage class definition used in the LAOE is very suitable for describing the whole range of damage symptoms (opening up and needle loss).

5.4 Evaluation of the Classification Accuracy

The verification of the results was carried out with differing methods among the projects. Terrestrial ground data and aerial photo interpretation was used for the assessment of accuracy. In the Harz project for example the accuracy of the classification of the 4 stand wise needle loss classes is about 70%. Here, only the combination of the classes C0,1 and C2,3 gave a satisfying accuracy of 84%. In the other test sites the average accuracy of the needle loss classes was above 89%.

The classification of the three opening up classes can be performed with an accuracy of over 90%.

Even though the accuracy of needle loss classes is varying, such classification results can be used as a first phase of small scale inventories. Additional investigations by the means of aerial photos or field measurements can be performed in order to obtain more detailed information on the level of forest damage. The satellite classification can provide information for the selection of areas, in which those detailed inventories have to be carried out.

The classification of opening up classes provide very useful information on the stability of the stands. This parameter was neglected by most of the former forest damage inventories based on aerial photos or field measurements.

Needle loss classes and opening up classes combined in one classification scheme provide very important information of forest damage on a small scale. This information cannot be derived from conventional inventory methods for very large areas. The main advantage of satellite remote sensing is to be seen in the pixel by pixel assessment of the damages.

The integration of the classification results into small scale GIS and the combination with auxiliary data allows investigations on the causes of damages.

The digital format and the large area coverage of the classification results can easily be integrated into other international projects (e.g. the "International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests" (ICP-Forest) or the "European Forest Information from Remote Sensing" (FIRS) Project).

Investigations on the damages of pine and beech have to be carried out in the nearest future to establish a complex classification system. Classification of damages of mixed forest stands is not possible and therefore not worthwhile to investigate. This will be a gap in forest damage assessment by satellite remote sensing.

5.5 Collection of Ground Truth

It has been shown that the methodology of the definition of representative traing areas for the damage classes is the most crucial point influencing the classification result.

It is necessary to collect the ground truth data in such a manner that the stands or training areas can be directly categorised into the harmonised damage classes. Harmonisation must already be started by collecting the ground truth data.

The interpretation of aerial photos is best suited for a precise definition of the ground truth. The verification areas have to be defined with the same procedure.

6 Conclusions and Recommendations

Recent and realistic forest damage maps with harmonised forest damage classes did not exist at regional scales until now. This project has demonstrated the value of satellite based remote sensing data for forest monitoring, in particular for assessing forest damage areas, where rapid changes in stand conditions occur.

The satellite based remote sensed data is usable for forest health status detection. It has been demonstrated in all the individual investigations of the LAOE that the reflected radiation recorded by the sensor of Landsat-TM is affected by changes of forest health status. Satellite remote sensing has been proven as an appropriate tool for monitoring forest condition by measuring the spectral characteristics associated with changes in vegetation health and destruction of forest canopy.

The digital data sets and maps elaborated in the course of the LAOE can serve as basis for future change detection studies and for the installation of a long-term monitoring system. The results of the project are comparable among the countries and provide planners at national and regional level with relevant data for their decisions. Especially valuable is the ability to control the effects of already initiated counter measures against the enormous pollution problems.

With the remote sensing methodology developed in this project it is generally possible to complement terrestrial and aerial photography damage assessments. In the Czech Republic the method is also used operationally for providing foresters with information they need on local level.

The advantages of using satellite data include:

- large area coverage that allows mapping of the spatial extent of forest damages,
- spectral resolution of the sensor improves the measurement capabilities for assessing the health status of vegetation,
- archived data sets allow change-over-time studies of forest stand conditions.

The remote sensing methodology developed in the project should be brought to the consideration of all European bodies dealing with the assessment of forest condition, as a complement to current methodologies.

The methodology should be brought to the attention of the bodies monitoring the implementation of and in compliance with the Convention on Biological Diversity as well as the UNCED Forest Principles, as a complement to current methodologies.

The results of the project should be brought to the attention of the governments of Central and Eastern Europe, the process of Ministerial Conferences on the Protection of Forests in Europe, the task force for the implementation of the Pan-European Biological and Landscape Diversity Strategy, the CSD International Panel on Forests and the scientific community dealing with global change.

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Annex A

Ground Spectral Measurements in the Polish Sudety Mountains (Rock et al., 1992)

During July 1991, researchers from the University of New Hampshire conducted field assessment activities at several stands within Surety test site. These activities were focused on collection of branch and needle samples in order to characterise the spectral reflectance properties associated with increasing levels of visual symptoms (chlorosis and foliar loss) of forest damage occurring at these sites (Rock at al., 1992).

A total number of five trees was selected and marked at each of the six study sites located on north-facing slopes along an elevation gradient (534-953 m). Branch samples were collected from mid canopy on the east-facing portion of each tree. North-facing slopes and east-facing portion of tree canopies were selected so that each collection would represent the most protected foliage and branch material from a given site.

The reflectance data acquired at three sites, selected to represent low elevation (534 m), moderate elevation (640 -below the 700 m upper-limit for healthy forest stands) and high elevation (945 m), very clearly indicate differences in level of health. At all sites, first-, second-, and third-year needle were spectrally characterised (Rock at al., 1992).

The average reflectance curve for first-year needles from the low-elevation site appear to represent the spectral properties of healthy needles - strong green peak in the visible, high reflectance in the near infrared (0.7-1.4 µm) spectral region (referred to as the NIR plateau), and low reflectance at 1.70 µm - while the curve for the first-year needles from the high-elevation site represents spectral properties of damage (weaker green peak and lower NIR reflectance). The curve for the first year needles from the mid-elevation site represents an intermediate condition.

In addition, the first-year needles at each of the sites have a shape in both the visible (0.4-0.7 µm) and the near infrared (0.7-1.4 µm) portions that is different from the same spectral regions in second- and third-year needles. The green peak is most pronounced in first-year needles as compared to second- and third-year needles, and the shape of the NIR plateau (sloping down towards longer wavelengths) in first-year needles at all sites is clearly different from the nearly flat NIR plateau exhibited by second- and third-year needles at all sites.

A strong green peak is related to the bright green colour characteristic for young, first-year needles (approximately two months old in mid-July), while the weak green peaks seen for second-and third-year needles indicates a dull-green colour. The change in slope and shape of the NIR plateau is likely related to the amount of water in foliage, since a strong water-absorption band occurs at approximately 1.45 μm, at the long-wavelength end of the NIR plateau. First-year needles were still succulent and flexible (non-lignified) in mid-July at all sites studied. The increase in reflectance at approximately 1.35 μm in both second- and third-year needles at any elevation is likely due to needle dryness.

The very low reflectance of all age classes of needles collected from the upper-elevation site is indicator of heavy cellular damage and low biomass (Rock et al., 1986, 1988). This is especially surprising for the firs-year needles, but also for the second- and third-year needles (NIR reflectance of 20% or less). The downward slope of the NIR plateau toward the short wavelengths exhibited by curves for the second- and third-year needles suggests senescence and dryness in these needles.

The wavelength position of the red edge inflection point (REIP) has been shown to be strongly correlated with chlorophyll concentration. Normal level of chlorophyll in healthy needles result in a REIP located between approximately 0.720-0.725 μm (Rock at al., 1988; Moss and Rock, 1991). As the chlorophyll concentration decrease due to stress, the REIP shifts to shorter wavelengths. This shifting of the red edge toward the blue end of the spectrum has been referred to as the "blue shift" (Horler et al., 1983; Rock et al., 1986). A blue shift of a few nanometers (5-10 nm) is typical of initial forest decline damage, expressed visually as mild chlorosis. In heavily chlorotic needles, a shift of 15-20 nm is characteristic (Rock et al., 1986, 1988).

A pronounced blue shift of the REIP is seen with increasing needle age at low site, as well as with all age classes of needles from the high site. Although chlorophyll concentration were not determined in this pilot study, the REIP values indicate a dramatic loss of chlorophyll with increasing needle age and with elevation. It is significant to note that none of the average REIP values are in "normal" or healthy range (0.720-0.725 μm), even for first-year needles at the low site, and that the REIP values for all age classes of needles at the upper site indicate very low chlorophyll values.

Spectral ratios are also very significant. These ratios were designed to mimic reflectance values acquired by TM bands 3, 4 and 5. TM4/TM3 is called biomass ratio, while TM5/TM4 - damage assessment ratio, also referred to as the Moisture Stress Index (Rock et al., 1986).

The biomass ratio values clearly indicate a dramatic loss of foliar biomass (decreasing ratio value) with increasing needle age class at all sites. This is true, even at low-elevation site, and is not typical of healthy spruce. With increasing elevation even the first-year needles show evidence of decreasing biomass.

As far as damage assessment/moisture stress ratio is concerned, increasing values are indicative of increasing levels of both dryness and damage. A dramatic increase in damage/dryness is suggested by these values with increasing needle age at given site, and increasing elevation. Based on the works at University of New Hampshire correlating plant moisture stress with TM5/TM4 ratios, ratio value above 0.5 is indicative of foliar water loss, while values above 0.7 are typical of dead foliage.

Annex B

Regressionfunctions between Stand Parameters and Spectral Responses Recorded by TM Scanner in the Polish Sudety Mountains

N-aspects:

(1) Df=-5.99TM1 + 6.82TM3 + 0.64TM4 - 1.24TM5 + 0.35Age — $R^2a=0.96$

(2) Dc=-2.23TM1 + 2.58TM3 + 0.06Age — $R^2a=0.87$

(3) Dm=-0.18TM1 + 0.24TM3 + 0.02Age — $R^2a=0.95$

NE-aspects:

(4) Df=-5.34TM1 + 10.3TM2 - 5.41TM3 - 0.26TM4 — $R^2a=0.94$

(5) Dc=-2.40TM1 + 2.55TM2 - 0.13TM4 — $R^2a=0.77$

(6) Dm=-0.29TM1 + 0.59TM2 - 0.36TM3 - 0.01TM4 — $R^2a=0.94$

E-aspects:

(7) Df=-5.56TM1 + 5.87TM2 - 0.27TM4 + 0.21Age — $R^2a=0.88$

(8) Dc=-1.93TM1 + 2.67TM3 - 0.22TM5 + 0.05Age — $R^2a=0.55$

(9) Dm=-0.28TM1 + 0.28TM2 - 0.01TM4 + 0.01Age — $R^2a=0.90$

SE-aspects:

(10)Df=17.14TM2 - 21.92TM3 - 1.07TM4 + 5.10TM7 — $R^2a=0.90$

(11)Dc=-1.18TM1 - 1.93TM3 - 0.15TM4 + 0.09Age — $R^2a=0.51$

(12)Dm= 0.61TM2 - 0.73TM3 - 0.06TM4 + 0.11TM5 — $R^2a=0.91$

S-aspects:

(13)Df=-5.19TM1 + 6.38TM2 - 0.46TM5 — $R^2a=0.97$

(14)Dc=-1.98TM1 + 2.37TM2 - 0.32TM5 — $R^2a=0.83$

(15)Dm=-0.31TM1 + 0.36TM2 - 0.01TM4 — $R^2a=0.97$

SW-aspects:

(16)Df=17.41TM2 - 20.91TM3 - 1.12TM4+2.85TM7+ 0.24Age — $R^2a=0.91$

(17)Dc=-1.88TM1 + 2.48TM2 - 0.23TM4 — $R^2a=0.77$

(18)Dm= 0.90TM2 - 1.13TM3 - 0.05TM4+0.17TM7+ 0.01Age — $R^2a=0.95$

W-aspects:

(19)Df=-8.33TM1 + 7.74TM2 — $R^2a=0.93$

(20)Dc=-8.22TM1 + 9.53TM3 — $R^2a=0.53$

(21)Dm=-0.42TM1 + 0.44TM2 - 0.01TM4 — $R^2a=0.96$

NW-aspects:

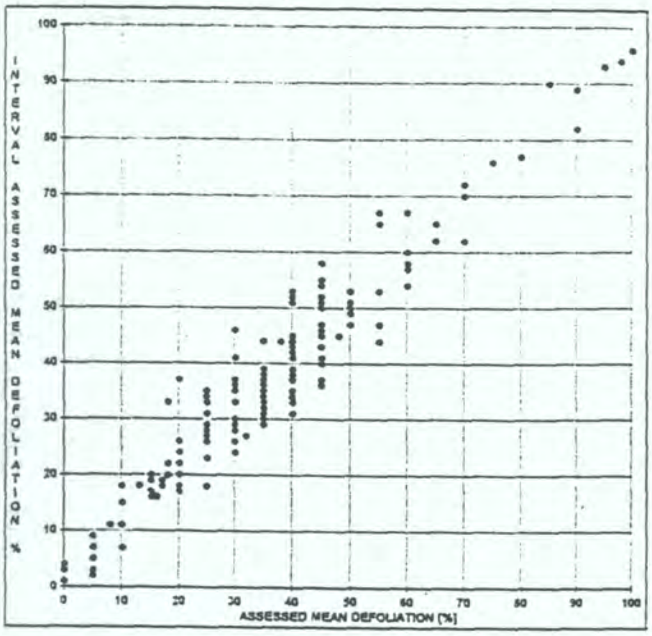
(22)Df=-8.68TM1 + 9.23TM2 - 1.81TM5 + 0.28Age — $R^2a=0.94$

(23)Dc= 0.58TM4 - 1.97TM5 + 2.40TM7 — $R^2a=0.78$

(24)Dm= 0.06TM4 - 0.13TM5 + 0.02Age — $R^2a=0.95$

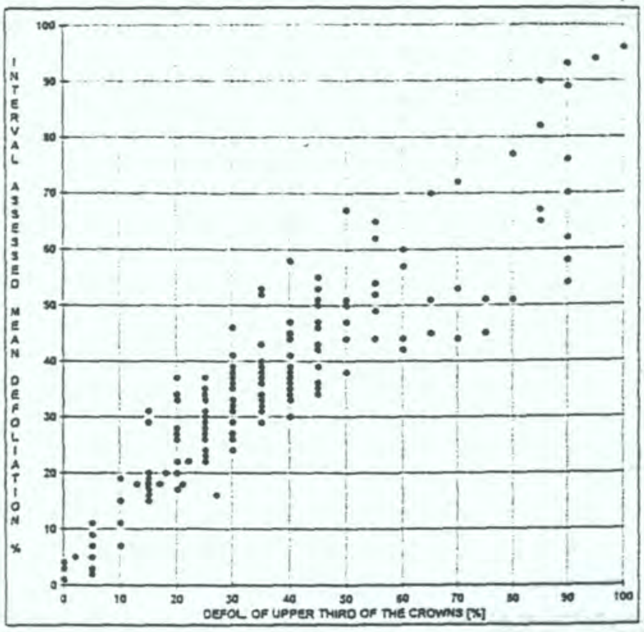
Annex C Statistics of the Czech Project

GRAPH 1. CORRELATION BETWEEN FIELD ASSESSMENTS OF DEFOLIATION
Norway spruce



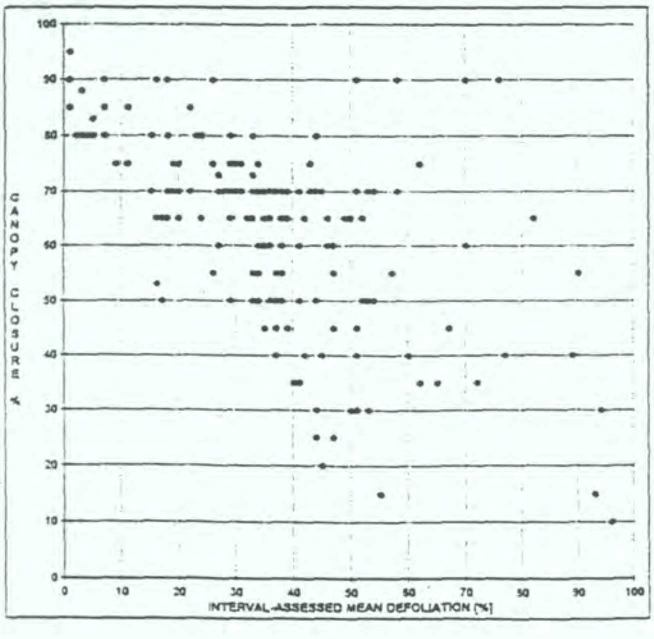
In the field, defoliation has been assessed by visual inspection of the crown morphology. An objective of using various methods of mean defoliation assessment was to test possibility how to avoid mistakes. Mean defoliation (x-axis) is one-step global assessment of % defoliation of all trees. Interval-assessed mean defoliation (y-axis) is an average calculated on the basis of estimated shares of trees defoliated by 20% intervals of needle loss.

GRAPH 2. CORRELATION BETWEEN FIELD ASSESSMENTS OF A DEFOLIATION OF ENTIRE CROWNS AND A DEFOLIATION OF THE UPPER THIRD OF CROWNS
Norway spruce



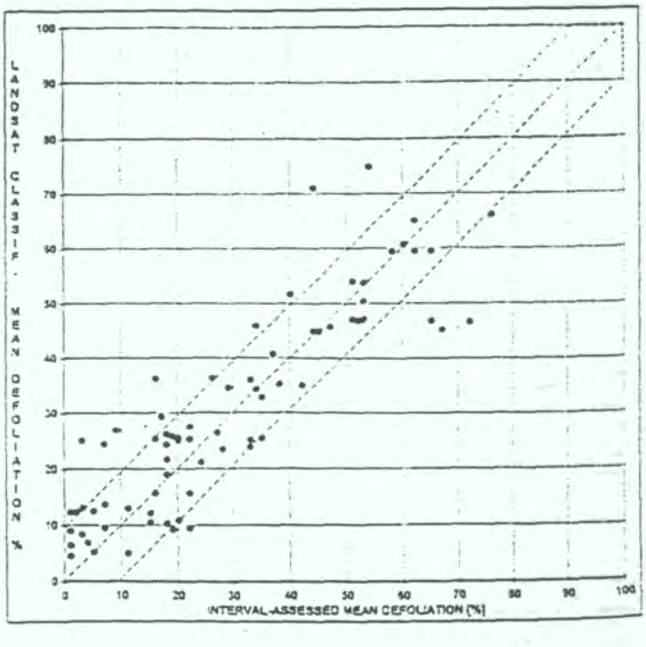
Differences between the mean defoliation of entire crowns and the mean defoliation of the upper third of crowns varies more in severely damaged stands.

GRAPH 3. CORRELATION BETWEEN FIELD ASSESSMENTS OF MEAN DEFOLIATION AND OF CANOPY CLOSURE
Norway spruce



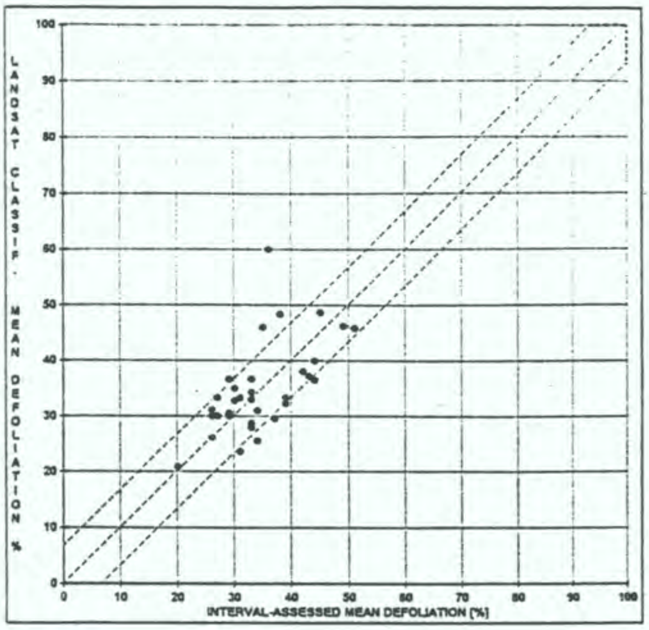
Crown coverage (canopy closure) does not strictly depend on defoliation stage. Sparse stands (closure <51%) are defoliated by from 16 to 95% and dense stands (closure > 60%) by from 2 to 84% here.

GRAPH 4. CORRELATION BETWEEN FIELD ASSESSED MEAN DEFOLIATION AND SATELLITE IMAGERY CLASSIFICATION
Standard calibrated classifier, Krkonoše Mountains
Norway spruce, age > 20 years



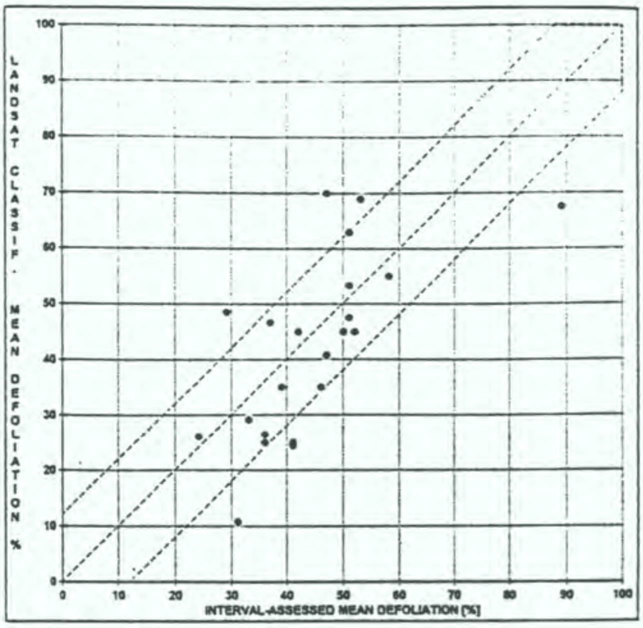
Standard deviation of the image classification using a standard calibrated Stoklasa's classifier was 9.5%

GRAPH 5. CORRELATION BETWEEN FIELD ASSESSED MEAN DEFOLIATION AND SATELLITE IMAGERY CLASSIFICATION
Standard calibrated classifier. Krkonoše Mountains
Norway spruce, age > 20 years



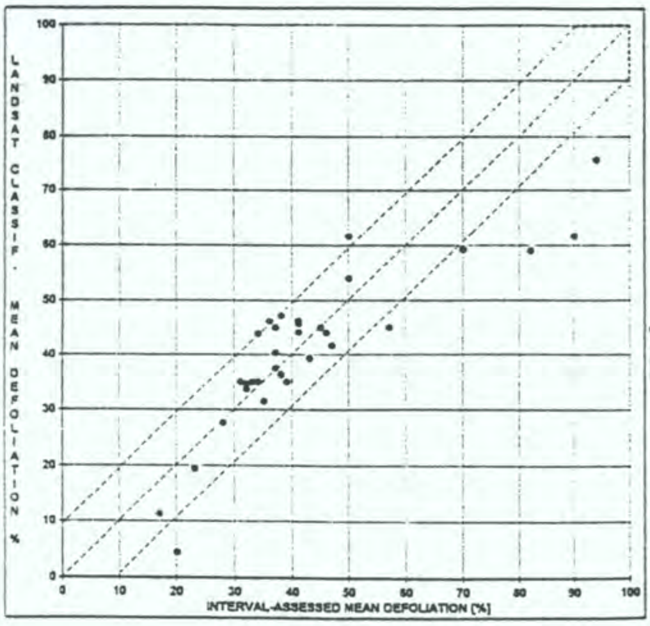
Correlation between field assessed mean defoliation and the mean defoliation classified using a standard calibrated Stoklasa's classifier has been verified on the second set of sample plots. Standard deviation was 6,7%.

GRAPH 6. CORRELATION BETWEEN FIELD ASSESSED MEAN DEFOLIATION AND SATELLITE IMAGERY CLASSIFICATION
Standard non calibrated classifier. Krušné hory Mountains
Norway spruce, age > 20 years



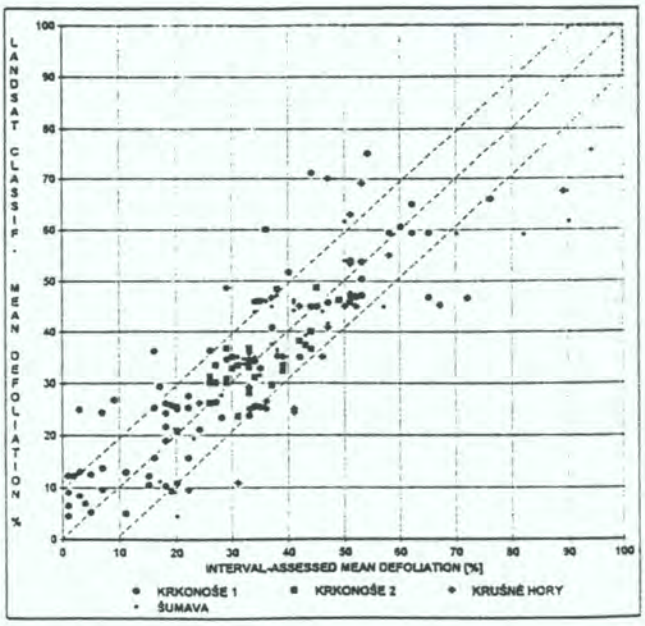
The Landsat image has been classified using a standard non calibrated Stoklasa's classifier. The closeness (standard deviation = 12%) is probably affected by a regeneration of trees.

GRAPH 7. CORRELATION BETWEEN FIELD ASSESSED MEAN DEFOLIATION AND SATELLITE IMAGERY CLASSIFICATION
Standard non calibrated classifier. Šumava Mountains
Norway spruce, age > 20 years



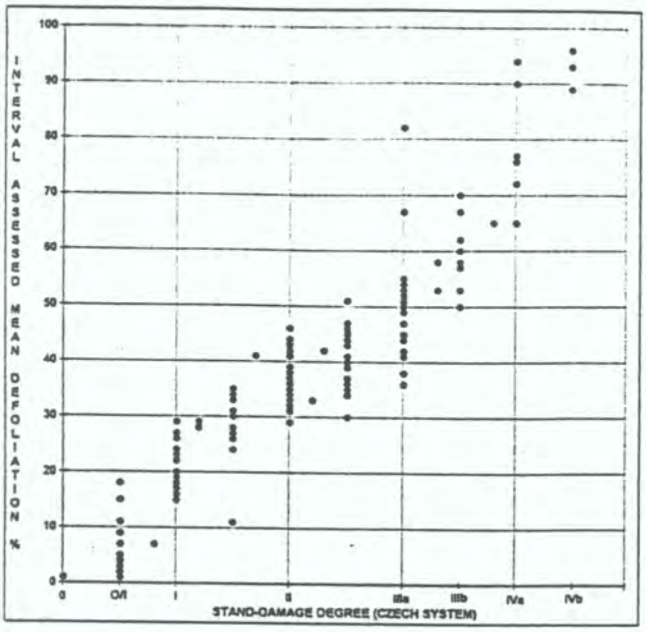
The Landsat image has been classified using a standard non calibrated Stoklasa's classifier. Classification results were verified on the fourth set of sample plots with the standard deviation of 9.2%. The classification accuracy is probably affected by the damage caused by barkbeetle.

GRAPH 8. CORRELATION BETWEEN FIELD ASSESSED MEAN DEFOLIATION AND SATELLITE IMAGERY CLASSIFICATION
All test regions
Norway spruce, age > 20 years



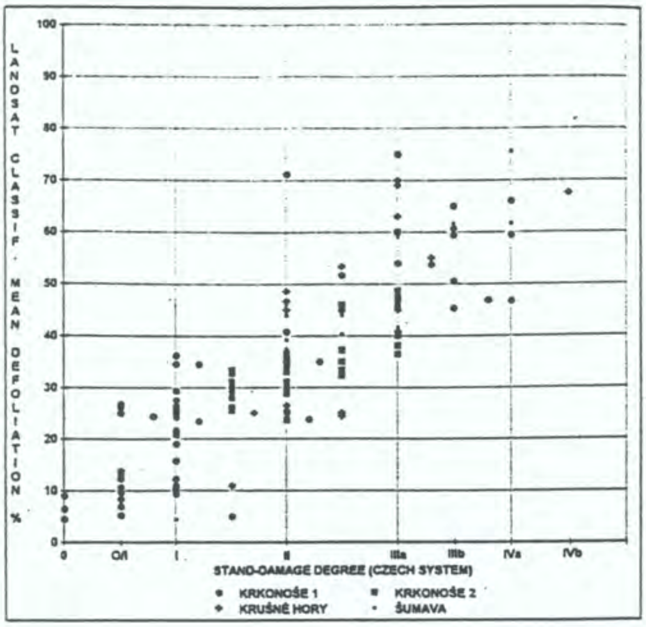
Results of all the image classifications are shown in the above graph. Standard deviation was 9.4%.

GRAPH 9. ASSESSED MEAN DEFOLIATION AND THE CZECH SYSTEM OF DAMAGE CLASSIFICATION
All test regions
Norway spruce



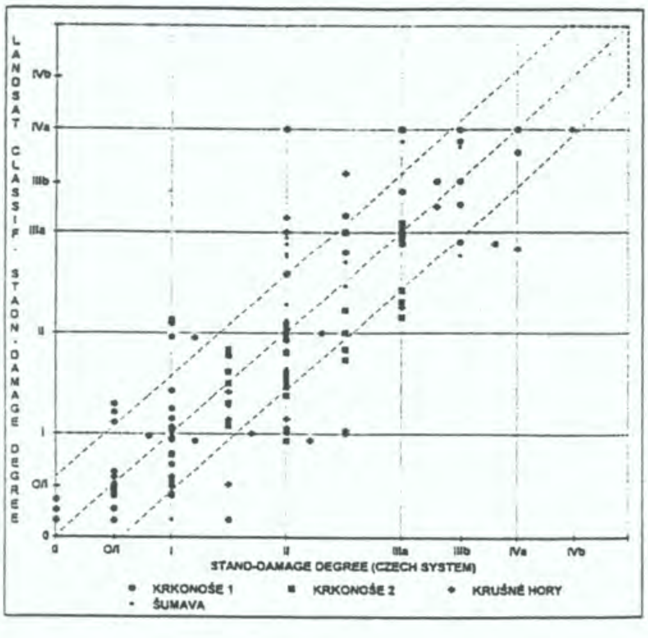
This graph shows a relationship between the mean defoliation of a stand (as assessed in the field) and the stand-damage degree by the Czech damage classification system also assessed in the field.

GRAPH 10. STAND-DAMAGE DEGREE BY THE CZECH SYSTEM AND SATELLITE IMAGERY CLASSIFICATION OF MEAN DEFOLIATION
All test regions
Norway spruce, age > 20 years



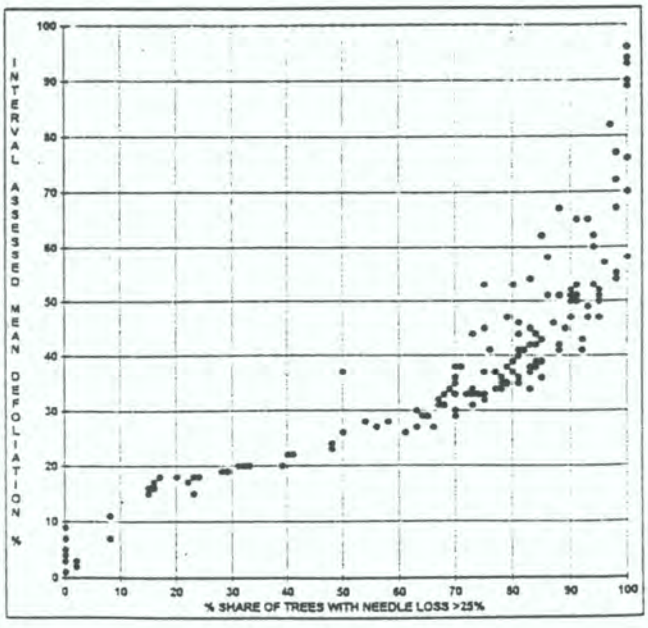
Large intervals in a damage degree definition (Czech system) cause increment in dispersion of the image classification results.

GRAPH 11. CORRELATION BETWEEN THE FIELD ASSESSED AND SATELLITE IMAGERY CLASSIFIED STAND-DAMAGE DEGREE BY THE CZECH SYSTEM
All test regions
Norway spruce, age > 20 years



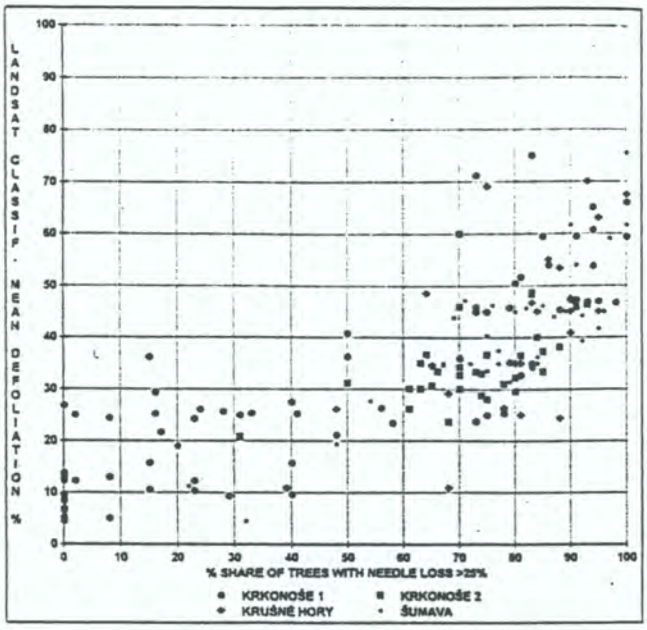
In Krkonoše Mountains, the standard calibrated classifier of the stand-damage degree was used. In Šumava and Krušné hory, standard non calibrated classifiers of the stand-damage degree were applied. Results can be compared on the above graph. A standard deviation of classification is 0,57 of a damage degree.

GRAPH 12. SHARE OF TREES WITH NEEDLE LOSS > 25% AND MEAN DEFOLIATION OF A STAND
All test regions
Norway spruce



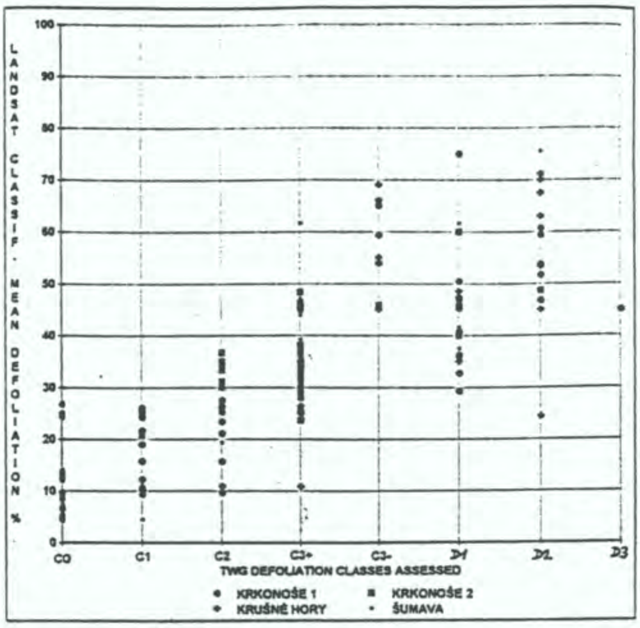
If slightly defoliated trees are neglected by the damage classification system definition, a possibility to separate the less damaged stands - needed for practical uses - is reduced. On the other hand, accuracy of higher defoliation classes identification could increase. Detection of severe damaged localities would be easier.

GRAPH 13. SHARE OF TREES WITH NEEDLE LOSS > 25% AND SATELLITE IMAGERY CLASSIFICATION OF MEAN DEFOLIATION
All test regions
Norway spruce, age > 20 years



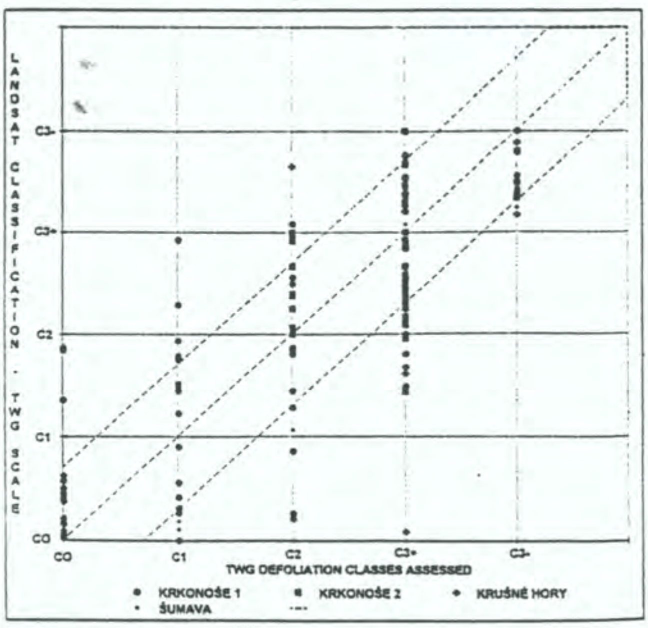
As it is shown in the above graph, a detection of the TWG classes will be very difficult because its mean defoliations, decisive for the satellite sensed DN value of reflexion, mutualy overlap (all the classes overlap in the mean defoliation from 20 to 30%).

GRAPH 14. TWG DEFOLIATION CLASSES ASSESSED IN THE FIELD AND SATELLITE IMAGERY CLASSIFICATION OF MEAN DEFOLIATION.
All test regions
Norway spruce, age > 20 years



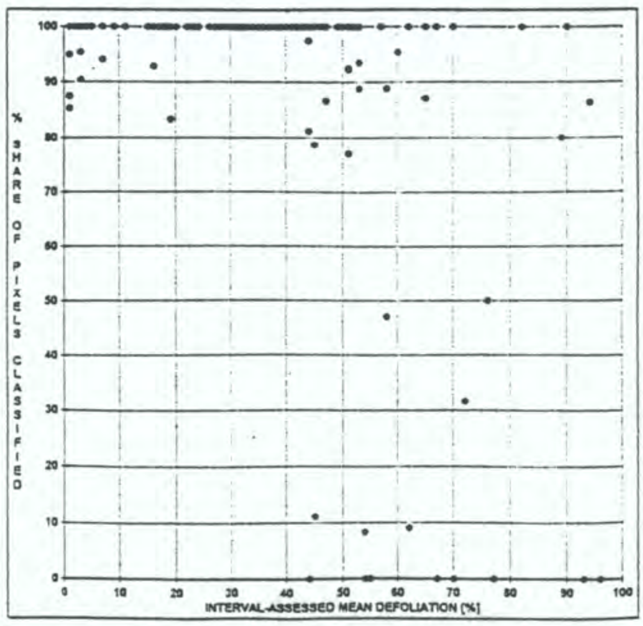
As it is shown in the above graph, it was impossible to separate „deforestation" classes by the TWG scale from the severe damaged stands because of the overlapping of the mean defoliation. Concerning the mean defoliation, differences between the defoliation TWG classes are also very small.

GRAPH 15. CORRELATION BETWEEN THE FIELD ASSESSED AND SATELLITE IMAGERY CLASSIFIED DAMAGE BY THE TWG SCALE.
All test regions
Norway spruce, age > 20 years

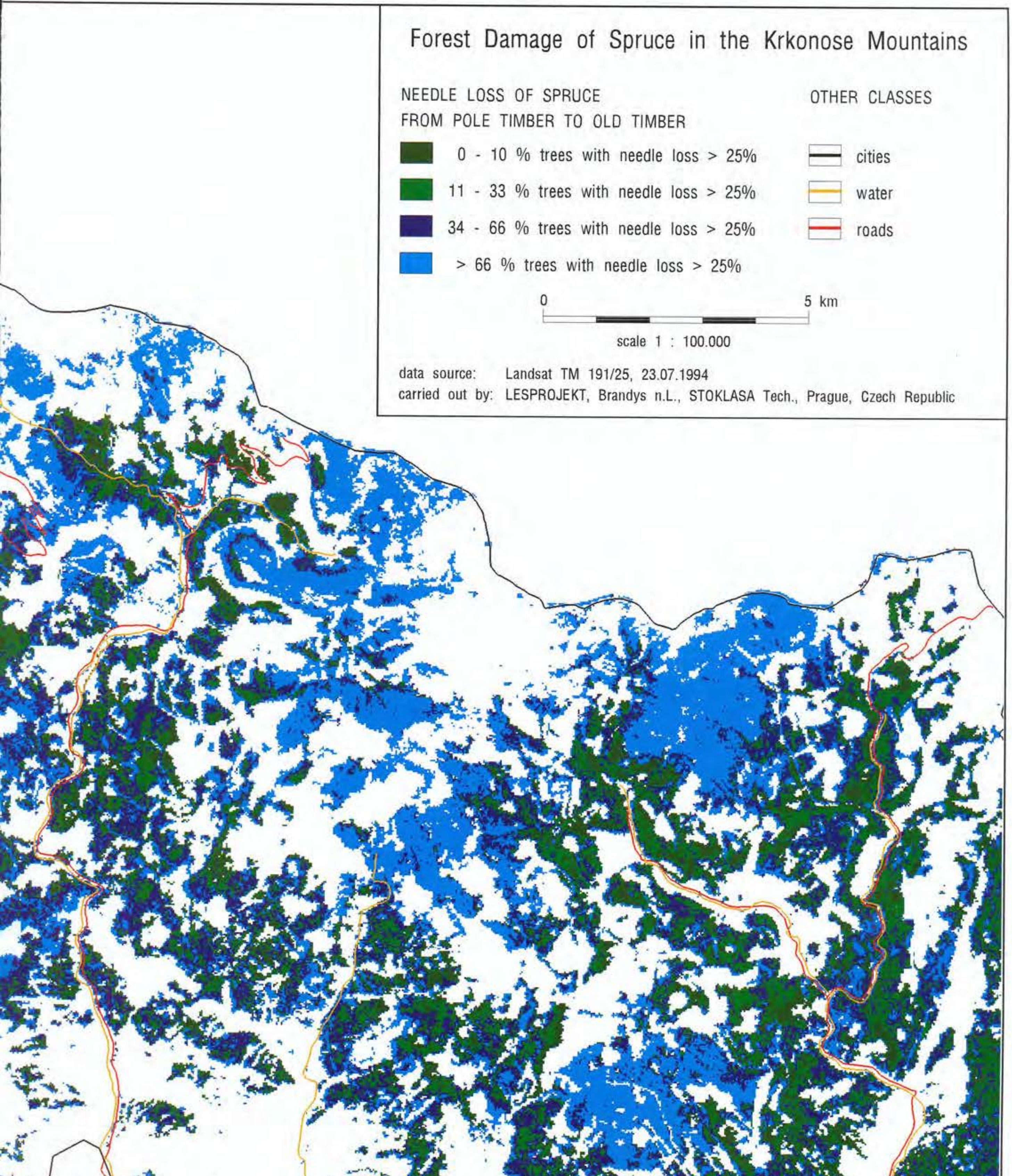


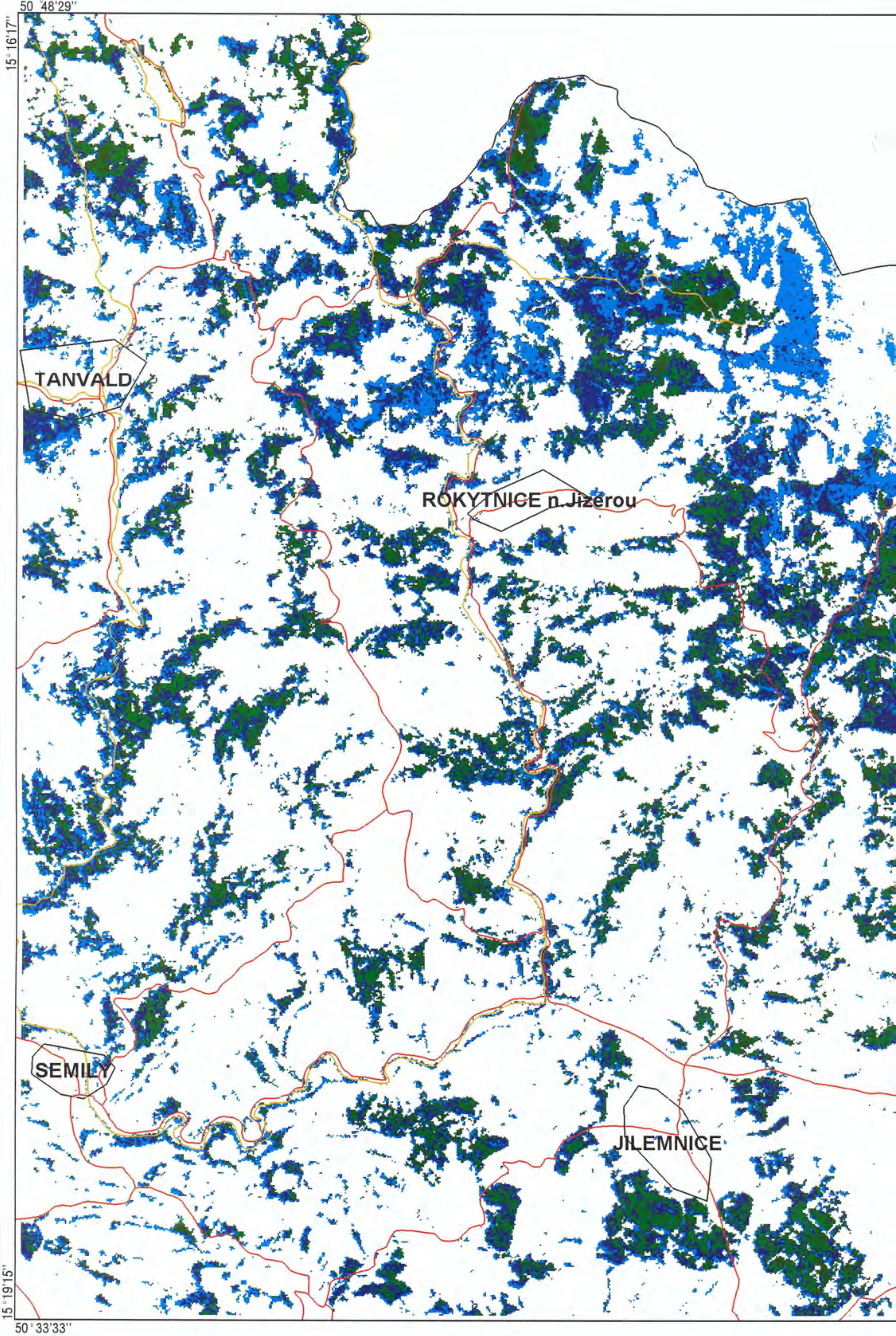
When the damage is classified regardless to the deforestation classes, a standard deviation of the output is 0.7 of a damage class.

GRAPH 16. CLASSIFICATION OF PIXELS ON A SAMPLE PLOT AREA
All test regions
Norway spruce, age > 20 years



With decreasing homogeneity in more defoliated stands, the % share of pixels that fit the classifier parameters also decreases. In the excluded plots (0= of pixels possible to be classified), mostly the dwarf pine prevailed. The plots with defoliation between 40 and 100% that were not classified are composed of dead trees often with a small number of branches resting on the stem.


Forest Damage of Spruce in the Krkonose Mountains
NEEDLE LOSS OF SPRUCE
FROM POLE TIMBER TO OLD TIMBER
0 - 10 % trees with needle loss > 25%
11 - 33 % trees with needle loss > 25%
34 - 66 % trees with needle loss > 25%
> 66 % trees with needle loss > 25%
OTHER CLASSES
cities
water
roads
0
5 km
scale 1 : 100.000
data source: Landsat TM 191/25, 23.07.1994
carried out by: LESPROJEKT, Brandys n.L., STOKLASA Tech., Prague, Czech Republic
VRCHLABÍ
SVOBODA n.Úpou
15°51'21"
50°36'02"


50°48'29''
15°16'17''
TANVALD
ROKYTNICE n.Jizerou
SEMILY
JILEMNICE
15°19'15''
50°33'33''

Forest Damage of Spruce in the Western Sudety Mountains

NEEDLE LOSS AND OPENING-UP CLASSES OF SPRUCE FROM POLE TIMBER TO OLD TIMBER

needle loss of spruce with crown closure > 60%

- 0 - 10 % trees with needle loss > 25%
- 11 - 33 % trees with needle loss > 25%
- 34 - 66 % trees with needle loss > 25%
- > 66 % trees with needle loss > 25%

opening-up classes

- crown closure 41 - 60 %
- crown closure 21 - 40 %
- crown closure 0 - 20 %

OTHER FOREST TYPES

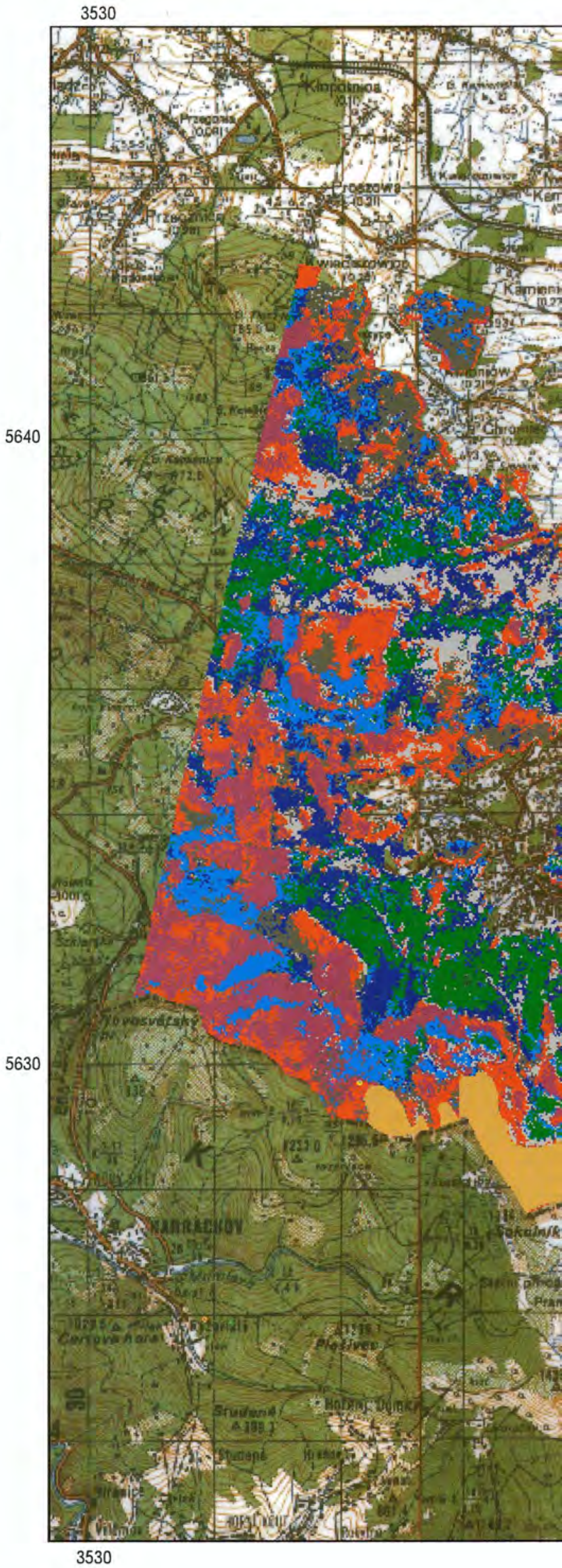
- afforestations (coniferous thicket <20 years old)
- mixed stands
- dwarf mountain pine

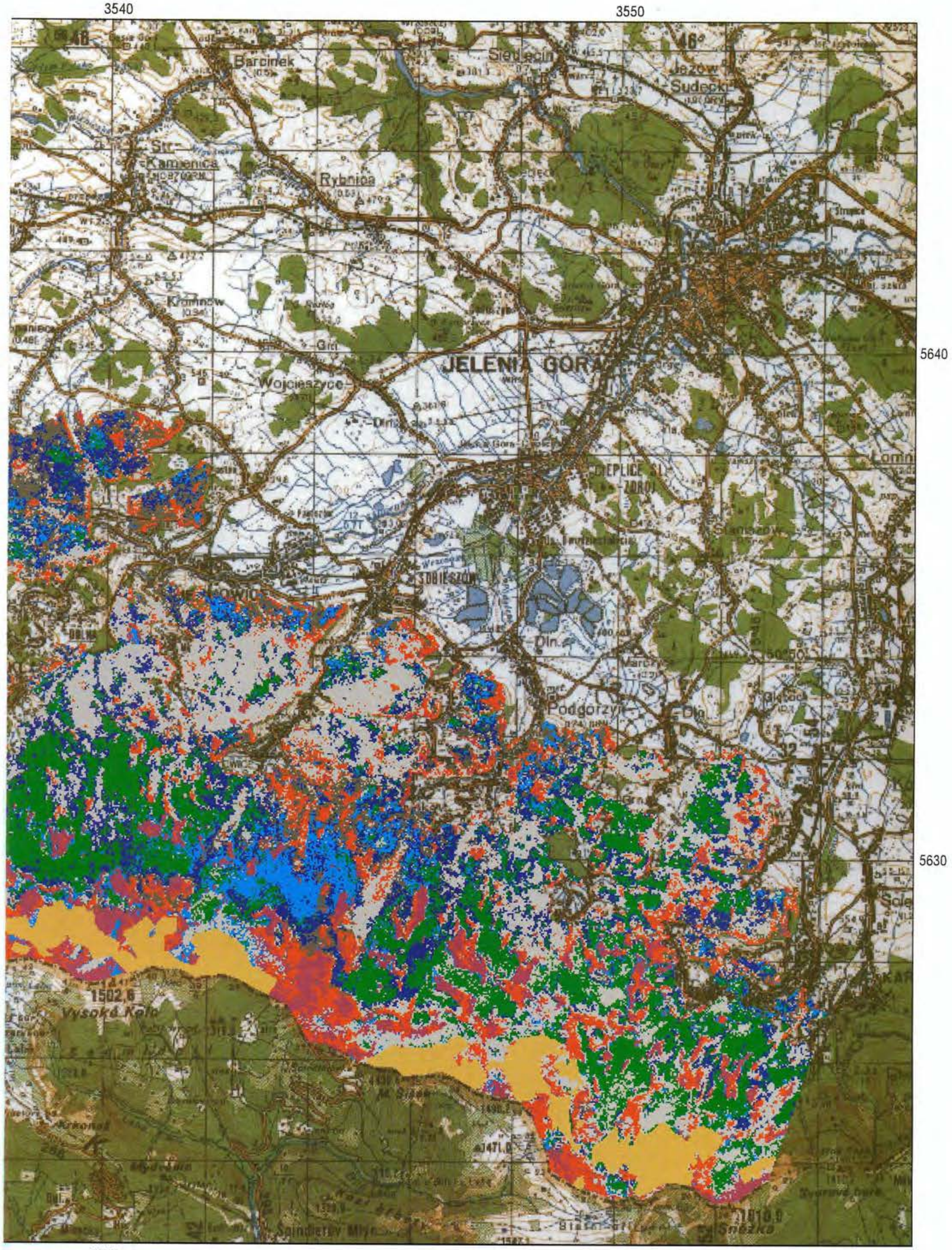
0 5 km

scale 1 : 100.000
projection: Gauss Krüger

data sources:
Landsat TM 191/25 29.08.1990
Topographic Map 1:100.000

carried out by:
Institute of Geodesy and Cartography, Warsaw, Poland




3540
3550
5640
5630
Barcinek
Siedlęcin
Jeżów
Sudecki
Rybnica
JELENIA GÓRA
Wojcieszyce
SOBIESZÓW
Podgórzyn
1502,6
Vysoké Kolo
Sněžka