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IMPLICATIONS OF CLIMATIC CHANGE ON LAND DEGRADATION IN THE MEDITERRANEAN

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F I R S T   D R A F T

N O T   T O   B E   C I T E D

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PART I, INTRODUCTION

This study presents an analyses of the impact of climatic change on land degradation in the Mediterranean region. The Mediterranean region is characterized by a seasonal climate and specific ecological and pedological conditions which make it particulary vulnerable for land degradation. The impact of CO_2-induced climatic change is potentially serious because of the low rates of primary production in the drier areas, the sensitivity of the soils to degradation and erosion and the high risk of drought and fire.

A vast body of information is available on various aspects of Mediterranean environments which can be used to assess the potential impacts of climatic change. However, very little is known about the response time of processes which are considered to alter the susceptibility of landscapes to climatic change. With respect to analogue information from past periods, prehistoric paleoclimatic records only provide coarse and speculative information on intermediate and long time scales. Historical climatic data allow more detailed study, but suffer from several other limitations. Furthermore, major temperature fluctuations in Europe in the past 1000 years (Medieval Warm Phase and Little Ice Age) involve statistically significant temperature deviations of no more than 0.5 - 1.0 °C. Statements about rainfall and its frequency and soil moisture in these periods (Lamb 1984) must be regarded speculative. It also remains questionable whether climatic data from the last century, which make it possible to compare warm and cool periods (see for example Berger 1984), give insight into future climatic response to a CO_2 increase.

Several direct relations between climatic parameters and erosion have been studied in varying depth. The findings are not conclusive because an enormous range of interplays, feedbacks and different types of response have been suggested by research. Because the impact of altered climatic conditions involves complex interactions between biotic and abiotic processes, many temperature and moisture dependent mechanisms have to be considered. Because of the many uncertainties concerning the processes involved, a discussion of the implications of climatic change must be limited to generalizations.

Two important aspects of data interpretation must be mentioned here. Firstly, various methods of investigating short term climatic trends lay emphasis on different types of time series, such as long term change, continuous variation, cyclical oscillation, abrupt transition etc. (c.f. Chorley et al. 1984), which create difficulties when trying to relate them to land degradation processes. Secondly, threshold conditions, which emerge from field data, involve factors varying widely in time and space. The response of a soil system to climate induced changes will consequently not be the same at different locations. Statistics and probability analyses offer opportunities for reliable predictions but sufficient data is not yet available for this to be done extensively.

The scope of this paper

Land degradation is a term used here to refer to the deterioration in the physical and chemical properties of the soil which occur as a result of environmental change and which result in soil erosion, problems of sedimentation and flooding, the loss of fertility and sometimes in salinization. Land degradation is thought primarily to be a result of human activities such as cultivation, deforestation and fire, but phases of land degradation are known to have occurred in the past during periods of environmental stress before modern man is likely to have had an effect on this phenomena. It should be pointed out that degradation can occur as geomorphological systems respond to internal changes so that erosion can occur periodically as intrinsic geomorphic thresholds are transgressed. In this way degradation can vary independently of present environmental conditions and it can reflect a pulsating delayed response to environmental changes which occurred perhaps hundreds of years ago (see for example Schumm 1977).

In this paper, firstly the soil system will be approached as an integrated component of the biotic environment and will be described as a body in which several key processes, in connection with land degradation, take place. Then these findings will be evaluated in terms of their significance for the prediction of land degradation upon changes in climate, whether approached qualitatively or by use of mathematical models.

The processes of land degradation considered here are for convenience separated under the headings of

1. soil erosion
2. river channel changes and sediment supply

which will be discussed further in part III.

Climatic changes indicated by global climate models

The 2* CO_2 predictions indicated by the two global climate models (BMO and GISS, Jung and Bach 1986), predict important and relatively uniform changes in climate for the Mediterranean region. Both models suggest a temperature increase in the order of 4 °C throughout the year. Precipitation predictions are different for the GISS and BMO models. The GISS model indicates a general precipitation increase for the Mediterranean region. This increase is more than compensated for by the increase in potential evapotranspiration. The data suggest that a very large increase in the soil moisture deficit will occur, particularly between the late summer and the early winter.

The BMO model predicts slightly lower increases in temperature but a decrease in precipitation. The predicted summer decreases are sometimes higher than the average precipitation in certain areas. The increase in potential evapotranspiration predicted by the BMO model is less than that predicted by GISS. Both models are in agreement concerning the prediction of very large increases in soil moisture deficit.

It should be stated that mean annual values of precipitation and evapotranspiration are of much less significance for the prognostication of a climatic impact on soil and vegetation than are mean monthly or mean weekly averages. Also, the effect of shifts in recurrence intervals and magnitude of extreme events are of major importance and must not be overlooked. At the best, the above mentioned climate models give predictions of monthly averages of temperature, precipitation and evapotranspiration for a large area of several hundreds of square kilometers. Unfortunately, these are the only kind of climatic data attainable. As an example, the forecasted changes in these parameters are given here for the Madrid region (see Table 1).

GISS and BMO models suggest an extension of the period with a rainfall deficit by 3 and 4 months respectively. Moreover, the difference between precipitation and evapotranspiration in the moist period from September until March is expected to decrease significantly. The BMO model calculates a period with rainfall deficits of eleven months and a decrease in the rainfall excess of 100% in the period November-February. GISS suggests a more modest decrease of about 30%.

To at least partly meet the disadvantages of the GCM's, use should be made of data having high spatial and temporal resolution, based on regional and seasonal information. Forthcoming instrumental-data-based scenarios (Wigley 1986) should be applied to those areas which are considered to be in various ways representative of recognizable Mediterranean sub-regions. For every such sub-region, climatological information, including extremes, variability etc., together with data about soil degradation and erosion, crop yield and management should be obtained. Only with this knowledge can the implications of future climatic change on land degradation be given on a regional scale.

		mean annual average	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Dec
ACTUAL	temp	14	6	5	7	10	13	16	21	24	23	20	14	9
	prec	444	48	39	34	43	48	47	27	11	15	32	53	47
	Epot	746	11	10	15	30	48	79	113	144	135	87	52	22
	Ep-p	426					0	32	86	133	120	55		
SCEN. 1	temp	+4	+4	+4	+4	+4	+4	+4	+4	+4	+4	+4	+4	+4
CHANGES	prec	+54				+6	+6	+6				+12	+12	+12
	Epot	+312	+8	+8	+14	+32	+32	+32	+32	+32	+32	+32	+32	+26
	Ep-p	656				25	38	64	118	165	152	75	19	
SCEN. 2	temp	+3	+2	+2	+2	+4	+4	+4	+3	+3	+3	+2½	+2½	+2½
CHANGES	prec	-198	-25	-25	-25	-12	-12	-12	-25	-11	-15	-12	-12	-12
	Epot	+234	+4	+4	+4	+32	+32	+32	+24	+24	+24	+20	+20	+14
	Ep-p	742			10	31	44	76	135	168	159	87	31	1

Table 1. Predicted climatic changes by GISS (scenario 1) and BMO (scenario 2) for the Madrid region in Spain at 660 m altitude.

Problems specific to Mediterranean regions

Mediterranean environments are characterized by hot dry summers and by mild moist winters. With respect to agricultural production in the Mediterranean three climatic aspects are important (Rosini 1984): a marked tendency to water shortage during the whole year, high solar radiation and the occurrence of extreme weather phenomena (e. g. heavy rainstorms and hail). Today agriculture is already facing problems through the effect high short term variability of climate has on plant growth. In the drier Mediterranean areas of north Africa and southern Spain the winter rains are less reliable and the climate can sometimes be described as semi-arid. Due to climatic change, the area of unreliable rainfall might become more extensive and shift northwards. This is important because water is the main limiting factor to plant growth and because net primary production is related to the amount of precipitation during the growing season. Because, in general, the Mediterranean vegetation is adapted to summer drought, which extends to several months, and to the marginal moist periods between summer and winter these two aspects of climatic rank above mean annual values in importance. It is therefore erroneous to consider mean annual values adequate for evaluating the impact of climatic change. Furthermore, an increasing overlap of the growing season and period of drought (see previous paragraph) will greatly affect Mediterranean agriculture, especially when thresholds are involved, such as a sustained experienced permanent wilting point. The Mediterranean environment is, therefore, potentially vulnerable to an increase in aridity. For aridity to increase it is not necessary that the yearly amount of precipitation decrease. Increasing aridity could be caused by 1) higher evapotranspiration, 2) by a change in the frequency and magnitude of rainfall events and 3) by processes of soil degradation which lower the ability of soil to retain water.

The Mediterranean area cannot be regarded as an in itself homogeneous climatic or climomorphic region. A relatively wide range of marked climatic zones exists between moist and dry. In southwestern Australia for example a distinction is made between moderate, dry, extra dry and semi desert Mediterranean environments (Beard 1983).

The global climate models suggest that in general the potential evapotranspiration will increase to cause a significant increase in soil moisture deficits. This general trend should be superimposed upon local environments but to really evaluate the environmental impact of these changes much more detailed information about the weather patterns and local climates predicted is required. The relationship of a number of specific environmental processes to, for example, temperature and precipitation is in many cases well understood. To be able to apply such relationships more information about local weather conditions should be available, as for example is demonstrated by Garcia (1984) for an agricultural area in south-eastern Spain. The bioclimatic response at any location could be influenced by local winds, dew, sunshine and temperature inversions.

The vulnerability of the Mediterranean environments to aridity takes on many forms. The implications of increasing aridity are many and these pose many problems which can be traced back to altered vegetational structures, to the lower rates of organic matter production or higher decomposition in the soil and to changes in the salt and water balances. A major chain of problems is associated with the probable deterioration in soil structure and the effect this will have on the partitioning of rainfall between infiltration and runoff. In rivers, low flows may become inadequate to dilute effluents, which may cause pollution, and higher salinity will become a problem with special significance to irrigation. The last problem of salinity will be intensified in shallow coastal aquifers where a sea level rise (+/- 40 cm) is predicted.

On the basis of present knowledge and also because of the diversity of Mediterranean landscapes and climatic conditions, in the framework of this study, it is not possible to deal with spatial variability at a local scale. Before this can be done much research will be required in the near future. With respect to existing knowledge, much less information seems to be available for the European Mediterranean area than for areas with mediterranean climates in Australia and South Africa.

In conclusion, most problems arising from climatic impact are likely to be associated with various aspects of increased aridity. Therefore, this aspect is regarded as the force behind imposed alterations of soil characteristics and hydrological behaviour.

PART II, THE SENSITIVITY AND VULNERABILITY OF MEDITERRANEAN SOILS TO CHANGES IN CLIMATE

I Introduction

In this section the possible impact of climate change on the soil system and its significance for hydrology is discussed. Attention is given to key parameters relevant to land degradation and to those processes sensitive to climatic change. Finally, some remarks about the effect of forest fires and the importance of the desertification process in Europe are made.

II The soil system

Introduction

For the purpose of this study, at a high level a distinction should be made between arable soils and soils under a (semi) permanent forest or shrub cover. This is especially important with respect to organic matter dynamics, element concentrations and tillage. It is also useful to limit considerations to those aspects of soils which are likely to be influenced by relatively small changes in precipitation or temperature. The soil contains elements which vary in age from a few weeks (e.g. nutrient concentrations) to tens of thousands of years (e.g. calcic and oxic horizons). Many soil characteristics, therefore, reflect the operation of soil forming processes under a wide range of former climatic conditions and because these conditions differed much more from the present climate than the climate predicted for a doubling of the CO_2 concentration, these characteristics are not expected to be influenced to a degree which requires consideration.

A great diversity of soil types is found in the Mediterranean region. This reflects differences in the major soil forming factors, two of which are climate and parent material. The climatic changes associated with an increase in CO_2 are comparable to differences in climate which occur locally as a result, for example, of relief and exposure. Unless threshold factors are involved it is not thought likely that CO_2 induced climatic changes will result in major shift in the boundaries between the main soil types. The soil may be considered as an open system, which responds to a number of dynamic processes. These processes are driven by the inputs of material and energy. The processes which are likely to be influenced by the predicted climatic change are those involving:

1. the input and output of water, gasses and soluble salts
2. the input and output of calcium carbonate
3. the input, decomposition and output of organic matter.

The changes in these processes might not be very significant for the long term morphological evolution of the soil but they are undoubtedly important with respect to (soil) ecology and land use. This is particularly the case when small changes in climate lead to the occurrence or intensification of certain pedological processes. For example, the response of soil aggregates to wetting by rainfall is extremely sensitive to the chemistry of the soil solution and to microbiological activity. Slight changes brought about, for example, by longer dry seasons or changing atmospheric deposition may lead to changes in the soil structure occurring which dramatically alter the hydrology and nutrient balance of the soil.

Processes sensitive to climatic change

The envisaged changes in climate are likely to have the greatest short term (50 years) impact through the effect they have on:

1. the salt balance and salt composition of the soil
2. the chemical precipitation of Ca/Mg carbonates in the soil
3. processes associated with the supply and breakdown of organic matter.

1 The salt balance of the soil

In this section the effect of increasing aridity on the salt balance of soils and implications of this for soil stability will be discussed. Shainberg and Letey (1984) summarize the problems faced when trying to point out the relations between saline and sodic conditions and soil response, as the inability to indicate threshold values of, for example, exchangeable sodium percentages (ESP) and other cations, the effect of clay content and clay mineralogy and the sensitivity and continuity of certain processes in terms of their response to exchangeable sodium (e. g. clay swelling and clay dispersion).

The transport and distribution of salts within a landscape and in a soil profile reflect the water balance, groundwater levels and transport in throughflow. Therefore, precipitation and evapotranspiration together with soil profile characteristics are important in this respect. The general level of water soluble salt concentrations in the soil is also partly influenced by atmospheric inputs which will be sensitive to climatic change.

In general a restricted number of quantifiable interrelationships between soil and soil solution chemistry and soil physical properties are important. Focussing on the interactions between the solid and the liquid phase of the soil a few general statements can be made. Firstly, the salt concentration in the soil solution is inversely proportional to the thickness of the water layers on clay particles and therefore influences the bonds between these particles. As a result, a change in electrolyte concentration may cause flocculation (if increased) or dispersion (if decreased) of soil particles and the threshold is referred to as the flocculation value. Also with Na as the predominant cation on the external surfaces of clay particles, the water layer is relatively thick, according to the Boltzmann equation, and the sensitivity to dispersion far exceeds that of for example Ca clays. Since sodium affects soil physical properties, the exchangeable sodium percentage (ESP) of a soil is an important criterion for evaluating soil stability and erodibility in semi arid regions. High ESP values not only cause a loss of aggregate stability but can also lead to decreasing hydraulic conductivity. Montmorillonitic soils, for example, tend to show a considerable increase in water retention and swelling capacity with increasing ESP. Illitic soils become particularly dispersive. General relations between salt concentration and ESP are visualized in Figure 1 (taken from Bolt and Bruggenwert 1982), which shows that high ESP and low water salinity destabilize soil aggregates. Destabilised soil aggregates break down to form surface seals or crusts.

When soil surfaces are sealed by crusts the infiltration capacity becomes reduced and overland flow occurs after lower threshold amounts of rainfall than before (see Figure 2, from Imeson 1983). Two other processes that cause sealing are slaking, caused by sudden wetting and mechanical destruction of aggregates by raindrop impact. These are both more effective when ESP values are high (Agassi et al. 1985).

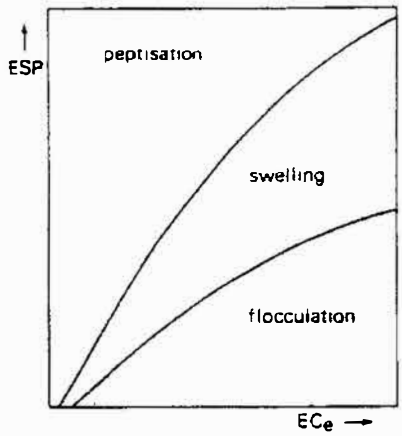


Figure 1. The influence of electrical conductivity (EC) and exchangeable sodium percent (ESP) on peptisation and flocculation thresholds (from Bolt and Bruggenwert 1982)

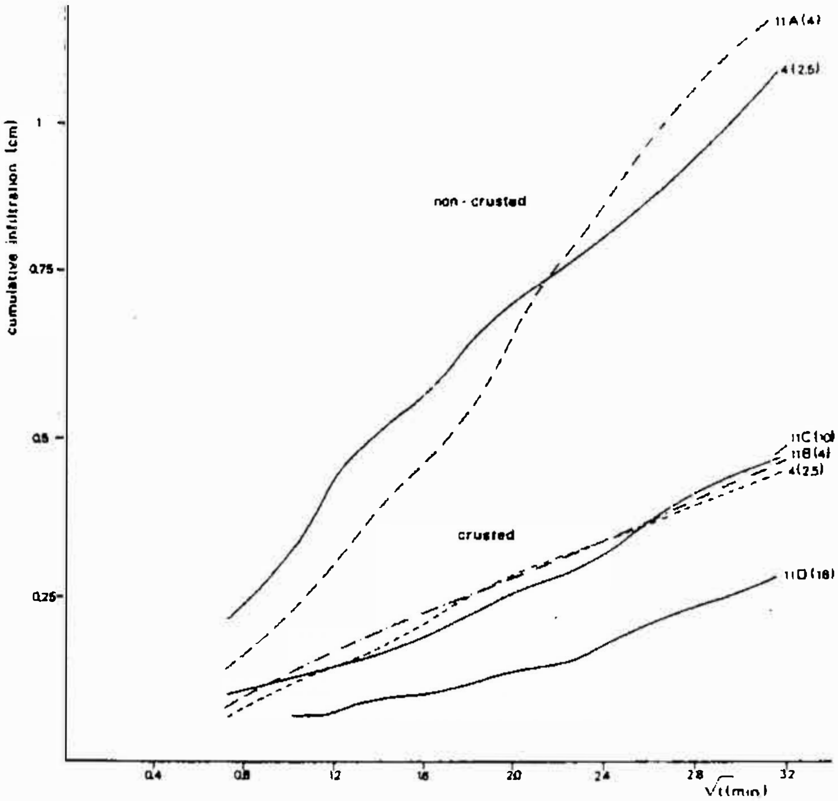


Figure 2. Effect of the presence of a surface crust on cumulative infiltration near Beni Boufrah, Morocco (from Imeson 1983).

To illustrate the high sensitivity to changes in salt concentration of the soil properties which regulate the infiltration process, results from research by Shainberg and associates in Israel are shown in Figure 3. The importance of antecedent soil moisture content with respect to surface response to rainfall has become clear from a study by Ben-Hur et al. (1985). They show that surficial crusts become more permeable upon drying due to structure development and cracking, but they also become more sensitive to destruction by raindrop impact.

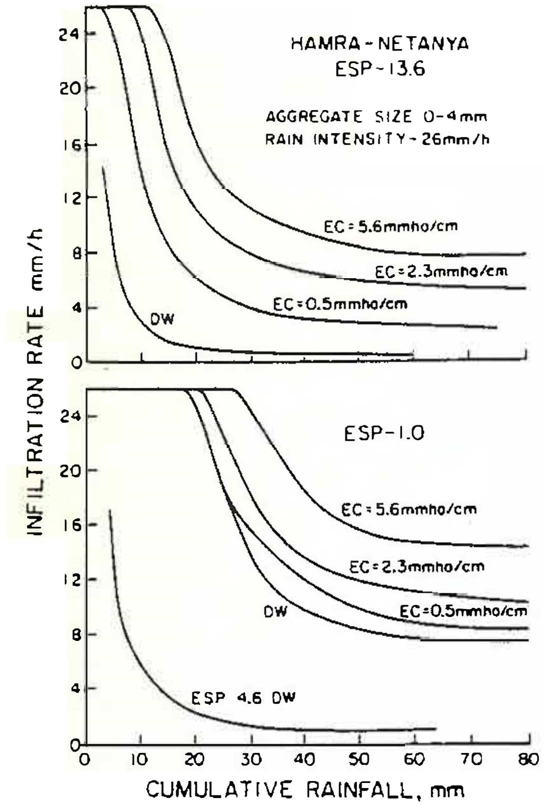


Figure 3. Effect of electrolyte concentration in rain-simulation experiments on the infiltration rate of loess soil (from Shainberg and Letey 1984).

A general decrease in precipitation or an increase in evapotranspiration will cause an increase in the area of soils affected by saline or sodic conditions. This is because in those regions with high evaporation rates capillary rise is accelerated and salts accumulate residually where drainage is nearly absent. Particularly serious would be a decrease in winter precipitation to the extent that seasonally accumulated salts are not flushed from the solum. A change in the duration and intensity of precipitation events would exacerbate salt accumulation where they both decrease and possibly ameliorate the conditions where they increase. A decrease in precipitation or a more adverse rainfall distribution would effect large areas where the annual rainfall is less than about 600 mm. Particularly in Spain an Italy changes in salt accumulation could lead to an increase in the area of soils affected by vertic conditions, in particular by poor physical conditions (low permeability, shrinking and swelling and waterlogging). Irrigation and crop yield management would become more difficult or expensive and the need for crops with higher salt tolerance would increase.

To have an adverse effect, salt concentration need only change slightly in composition or amount. A slight increase in aridity resulting in a shift in the ESP value at the end of dry season could make soils sensitive to dispersion and slaking when the electrolyte concentration is lowered at the onset of winter or autumn rainfall. Dispersion and slaking then lead to surface sealing, lower infiltration rates, more runoff, a high erodibility of the soil and a potentially catastrophic series of erosion and sedimentation problems during extreme rainfall events.

An increase in precipitation or decrease in evapotranspiration could have a positive effect in areas suffering from sodic or saline conditions in cases where higher rainfall leads to better and deeper drainage. However, it is known from Australia and Kenya, that increased rainfall in semi-arid areas can lead to the development of perched water tables, which when they rise into upper soil horizons mobilize salts which are subsequently transported downslope in throughflow. This has led in the countries mentioned above to problems of salinisation and erosion at colluvial slope foot positions and has made runoff unsuitable for irrigation or domestic use.

Temperature increases will increase problems with sodic and saline soils, in as much as they influence the water balance and the mineralisation of organic matter. It seems probable that higher levels of organic matter to some extent increases the degree of sodicity required to produce negative soil structural properties (Shainberg and Letey 1985 and below).

Although it may be concluded that increased aridity and resulting high soil ESP will cause soil physical properties to deteriorate and soil erodibility to increase, the extent to which this will happen at a local scale will depend on various factors controlled by the water balance, soil type, exposition and slope and by the total salt and sodium inputs. Salinity problems would be most severe in areas receiving between 300 and 600 mm of rainfall and would become less important in areas where precipitation dropped below this level. Such areas with generally irrigated agriculture and the occurrence of natric and sodic horizons in the soil profile are not extensive in European and most other mediterranean regions today but there is a large area potentially vulnerable to salt problems.

2 Chemical precipitation of Ca/Mg carbonates

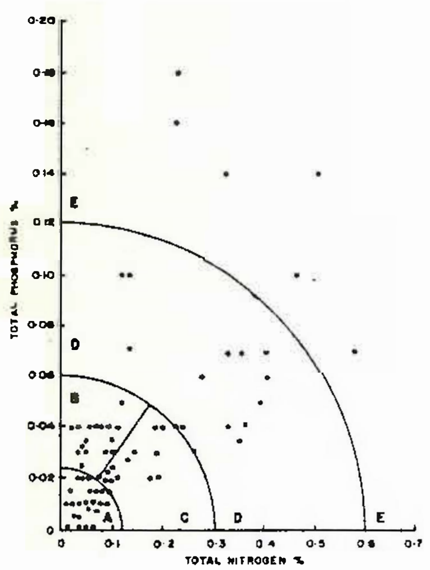
Pedogenic caliche development is restricted to areas with low precipitation (100 to 500 mm) and is often connected with desertification. Caliche accumulation can result from the redistribution of calcium carbonate and some accessory components in the parent material but also from atmospherically supplied material. Under special conditions a distinct caliche layer can develop within several months (Hattman 1983).

Petrocalcic horizons can have serious implications for hydrology where they are situated at or near to the soil surface. With the increased aridity envisaged, however, it is not considered likely that present problems will become much more serious in the coming decades.

Attention should be paid, however, to the effect that the accumulation of calcium carbonate in the solum has on plant growth and net primary productivity. Primary production might decrease in cases where microcristalline chalk (referred to as soft powdery lime) accumulates and inhibits the uptake of trace element, such as iron and manganese (Finck 1982), by plant roots. This may especially affect non-irrigated agriculture.

3 The supply and breakdown of organic matter

The effects of small changes in the supply and mineralization of organic matter could have a large impact on soil structure in certain cases and greatly influence soil and hillslope hydrology. As mentioned above, the Mediterranean area is especially vulnerable to climatic change. In this chapter this will be considered in relation to the low organic matter content in most cultivated Mediterranean soils and to the susceptibility of litter on forest floors to degradation. This is especially significant because of the silty character of many upper soil horizons due to pedological soil development and the deposition of atmospheric dust. Further, many marls weather into silty residual carbonaceous materials.



Relative nutrient levels of surface soils in mediterranean-type ecosystems in southern Australia, based on total soil nitrogen (H_2SO_4 extraction) and total soil phosphorus (HCl extraction) - after Specht (1981d). A: strongly leached soils. B: moderately leached soils (semi-arid zone). C: moderately leached soils (humid, sub-humid zone). D: weakly leached soils. E: nutrient-rich soils.

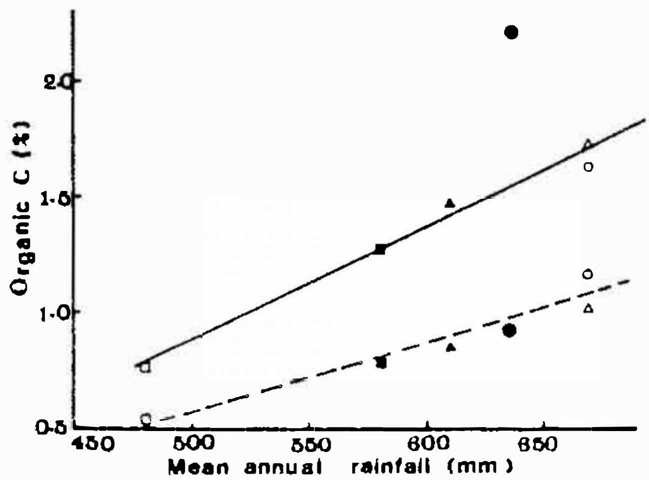
Figure 4. (from Specht and Moll 1983).

According to the nutrient status of different soil types, a distinction can be made according to type of substratum and climatic conditions, of soils with varying degrees of leaching and calcium carbonate content, and of nutrient rich/high pH soils (Specht and Moll 1983; Quezel 1981; see Figure 4, from Specht and Moll 1983). Unless amended, phosphorus and nitrogen are suboptimally supplied and further, if pH values are high, trace elements are poorly available for root uptake.

The ratio Ea/Eo (the actual and the potential evapotranspiration respectively) is a useful index of water availability for plant ecosystems (Specht and Moll 1983). An increase in aridity will possibly lead to an extended period with low ratios and less favourable conditions for nutrition, with consequential shifts in plant and tree species composition and decrease of organic matter input into the soil. A decreasing area of deciduous thermophyllous forests (e.g. montane beech forests) and steppes can be expected in favour of forests with more sclerophyllous components and maquis, with less vegetation cover. This is confirmed by Huis and Ketner (1987). They anticipate lateral shifts of hundreds of kilometers and several hundreds of meters in altitude in some cases. These lateral and altitudinal vegetational shifts could alter the humus form profile of the soil and the soil micro and meso fauna quite dramatically.

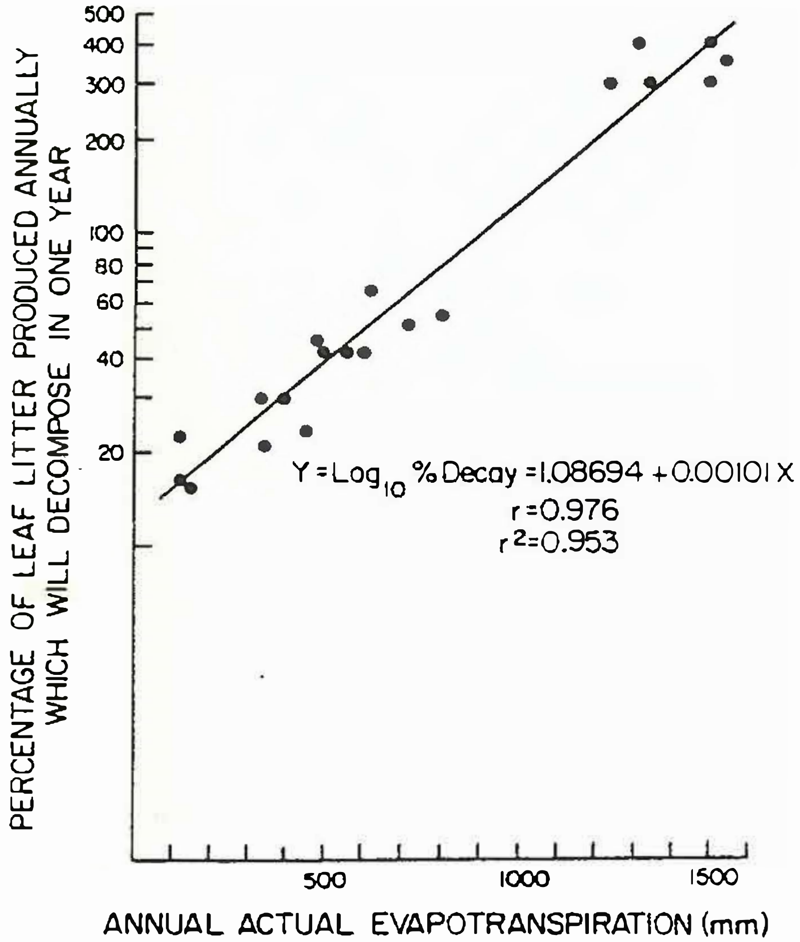
The importance of a lag time in the response of ecosystems and soil characteristics to changing climate must be stressed. In general the organic matter content of the topsoil will adapt to altered vegetation structure and composition quite rapidly. In consequence, in forest ecosystems the vegetation will be the major factor in determining response times to climatic change. Response times for vegetation adjustments are estimated as being at least several decades (Buis and Ketner 1987). This temporal aspect should be taken into account, together with other external factors such as an increased frequency of forest fires and/or forest clearcutting which might result from climatic change.

The organic matter and organic carbon content in soils is highly related to mean annual precipitation. This is due to the positive influence of soil moisture on pedoturbating soil biota. This relationship for an area in southern Queensland, Australia is shown in Figure 5 for virgin forest and land under wheat cultivation for twenty years (Dalal and Mayer 1986). The rate of decrease was also studied during the twenty years of cultivation and was found to be much higher for the wetter locations. Although the amount of organic matter is very highly correlated with precipitation, other climatic and environmental parameters play a role but are difficult to isolate. Berg et al. (1983) and Meentemeyer (1978) have estimated the effect of annual evapotranspiration on organic matter decomposition in non arid regions. (Figure 6; from Meentemeyer 1978). Annual evapotranspiration encompasses both moisture and energy, which are major factors influencing microbiological activity, and is therefore a more valuable variable connected with organic matter decay than is precipitation. A factor which very much complicates the picture is the lignin content of the organic tissue. A high lignin content is considered to hinder decomposition and for this reason should be superposed on decomposition rate-AE relationships. The introduction of more sclarophyllous plant species, with higher lignin content, will probably temper the effect of increasing evapotranspiration on organic matter decomposition, but whether this positively influences the maintenance of soil structure depends on the composition of organic substances. Especially humic and fulvic acids have proved to have positive effects on aggregate stability (Soong 1980).



Relationship between mean annual rainfall and organic C content of virgin soils ($r = 0 \cdot 99$, $P < 0 \cdot 001$) and adjacent soils cultivated for 20 years (predicted from equation 3) ($r = 0 \cdot 97$, $P < 0 \cdot 01$). The regression coefficients (% organic C/mm mean annual rainfall) are 0·0048 (——) and 0·0029 (– – –) for virgin (except Langlands-Logie) and cultivated soils, respectively. ○ Waco; ● Langlands-Logie; △ Cecilvale; ▲ Billa Billa; □ Thallon; ■ Riverview.

Figure 5. (from Dalal and Mayer 1986).



Correlation and regression of estimated annual actual evapotranspiration with measured annual weight loss of leaf litters. At a decomposition rate of 100% all of the available leaf litter is predicted to be decomposed in an average year. At 200% there would be complete decay in six months, and 300% four months, etc.

Figure 6. (from Meentemeyer 1978).

Morgan and co-workers (1986) found that plant cover effects on hill-slope runoff and erosion were not only regulated by a simple linear relation between cover percentage and soil detachment by rainfall. An experiment made clear that with increasing plant cover soil detachment increased by increasing leaf drip action.

Unpublished data from an inventory investigation of relations between vegetational cover, soil erosion and colluviation in NE-Catalonia in Spain show that south exposed slopes are more affected by soil erosion than north exposed slopes. On the latter generally a continuous colluvium layer, covered by an Ah horizon, is present, but this is absent on south exposed slopes (see Figure 7), pointing to higher erosion rates. The percent surface cover of the vegetation on north facing slopes generally exceeds that on south facing slopes, due to differences in soil moisture availability. Two major factors are considered to be related to this slope dimorphism. Firstly, due to greater dryness, fire events will be more frequent on south exposed slopes, leading to less protection of the soil by the vegetation and, therefore, to an increased susceptibility to erosion. Erosion research after forest fires in the United States confirms this (DeByle 1981). Secondly, as mentioned before, from the greater decomposition of organic matter in the topsoil, it may be expected that increased aridity will affect hillslope processes on north exposed slopes in such way that they become increasingly similar to processes currently influencing south facing slopes, increasing losses of topsoil material in the area as a whole.

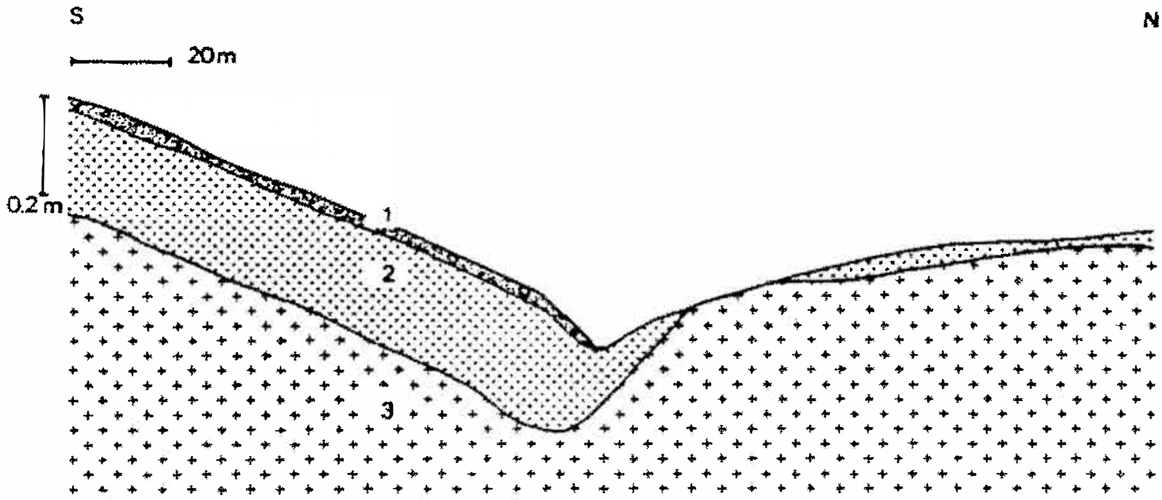


Figure 7. Schematic figure illustrating the different soil horizons present on slopes subject to forest fire. The parent material granite (3) is overlain by BC material (2) and on north facing slopes, where erosion is less severe, by colluvium (1).

In the same study area, the effect of different types of forest stands, exposition and humus form profile development has been investigated by Sevink (1988; in press). He found that organic profile morphology is closely correlated with vegetational cover and evidently influences hillslope hydrology. This means that extended accumulation of organic matter on the soil surface in some situations delays time to ponding and surface runoff during prolonged rainfall events, protecting the soil from erosion. In his inventory research of several forest sites a clear difference in organic profile morphology between north and south facing slopes at about 1200 meter height was observed. Chemical analyses show that after an initially high release of nutrients, mineralisation is retarded and decomposition mainly involves humification. On the south facing slopes this process seems to be more pronounced and leads to the development of relatively thick F3/H horizons. compared to north-facing slopes. Due to their high water storage capacity and high root content, these organic horizons may protect the soil from erosion. This will be of major importance in open sclerophyllous forests, where significant transport of litter during rainstorms is observed. The significance of the dependence of soil profile development on exposition needs more detailed study, in view of the postulated increase in aridity in the Mediterranean area.

The effect of an increase in aridity will depend on the water retaining characteristics of the soil, the discontinuity of hydraulic processes and on the way in which the frequency of rainfall events of different magnitude is altered.

More research needs to be done in this area before the effects of decline in precipitation can be generalized. In highly calcareous, sandy and silty soils, organic matter plays a vital role in soil fertility because it has a very high exchange capacity and retains nutrients in the soil, and also because it results in a favourable micro-aggregation which promotes relatively high levels of water retention. Lower inputs of organic matter leads to an increased aridity of the soil and to a lower fertility.

It is stressed that at the scale of the Mediterranean basin it is only possible to generalize in a crude way. Local conditions will influence the impact that climatic change is likely to have. The climatic impact will depend also not on average climatic parameters but rather on those parameters which influence the water balance of the soil and the availability of moisture for plants.

In detail, a number of critical soil properties are dynamic and highly sensitive to the soil climate. The way in which a cultivated soil will behave when wet reflects the number of wetting cycles it has already experienced since being ploughed and the moisture content at the moment of wetting. This problem is reviewed by Utomo and Dexter (1982) and discussed by Imeson and Verstraten (1986).

On agricultural land organic matter is critical in terms of its effect on soil structure, particularly in the case of highly calcareous or silty soils where bonding forces between mineral particles are low. Several case studies have documented the scale of these effects in Mediterranean areas. The data from southern Spain (figure 8; from Imeson and Verstraten 1986) clearly indicate how the micro-aggregation of the soil both under forest and cultivation is related to the organic matter content. The data shown are for highly calcareous soils in southern Spain but similar results would probably be obtained for other soils. A compilation of the data shown in Figure 5, 6, and 8 may indicate a very dramatic reaction of the soil system to increasing aridity. Figure 9 (from Swift et al. 1979) shows that decomposition rates are strongly influenced by soil moisture adjustments particularly in warm climates. Undoubtedly, modelling of climatic variables related to soil erosion rates must emphasize these relationships.

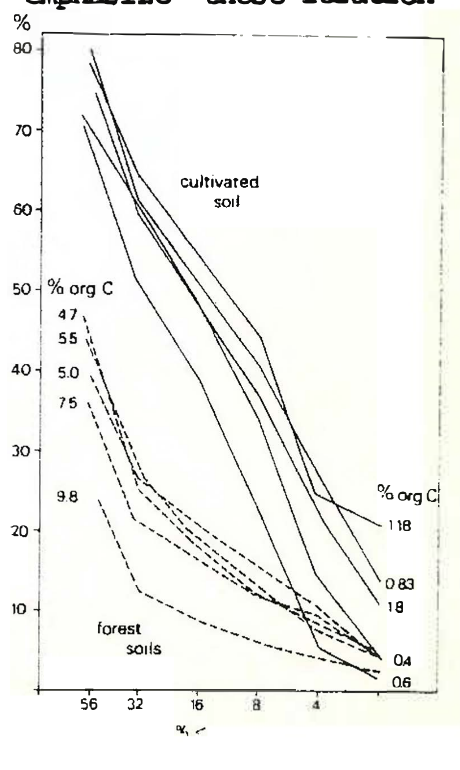
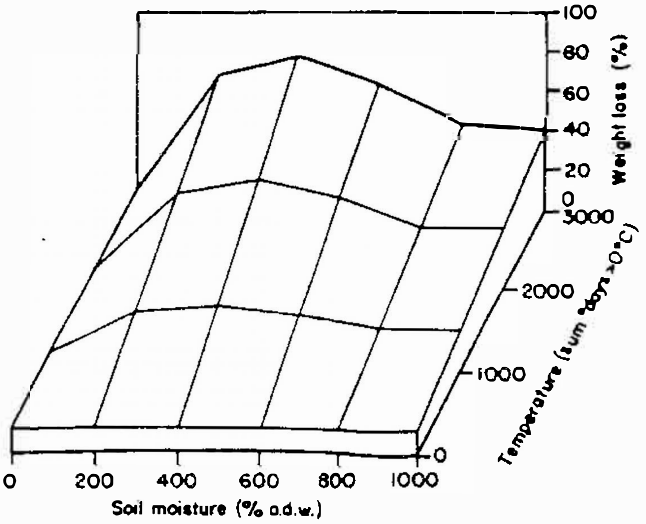


Figure 8. Water-dispersible silt and clay fractions from surface soil horizons from forested and cultivated sites near Teulada, Spain (from Imeson and Verstraten 1986).

Pittock & Nix (1986) have studied the impact of a rise in temperature on net primary productivity (NPP) in Australia. In their preliminary research they use a model which calculates the NPP on the basis of anticipated rainfall amounts and temperatures together with general relations between temperature, precipitation and NPP. Evapotranspiration and soil erosion predictions are not included. Therefore, the results are of restricted value and the model needs to be improved. For the Mediterranean regions in Australia, a decrease in mean annual precipitation is expected and the model used estimates a zero increase in NPP. Upon improvement of the model, which besides soil erosion should include soil moisture and nutrient status, a decrease of the NPP may be expected.



A regression surface showing the interactive effects of soil moisture (% o.d.w.) and thermal environment (temperature sum = $\sum$ degree days at temperatures > 0°C). The regression equation for the relationship of the three factors was $Y = 11{\cdot}62 + 0{\cdot}0147.T.W - 0{\cdot}00289.T.W^2 + 0{\cdot}000152.T.W^3$ ($r = 0{\cdot}769$), where Y = per cent weight loss, T = temperature sum and W = soil moisture

Figure 9. (from Swift et al. 1979).

Forest Fires

Evidence suggests that an increase in temperature and dryer conditions will be accompanied by an increase in the frequency of forest fires. In Spain it seems that in distinctly dry years forest fires tend to be more frequent.

There are several causes for forest fires. Today fires can be usually traced to anthropogenic origins. In Spain fires caused by lightning are of only subordinate importance, but some authors suggest the converse for North America (Kimmins 1987).

Fire can cause a loss of the ecto-organic horizons and a decrease in organic matter content in the upper soil horizon, so that soil nitrogen availability may be reduced significantly. Where erosion does not ensue a forest fire, there is usually a recovery of the forest and a quick regeneration of biomass in the soil. Fires may cause a water repellent layer to develop, which can lead to increased runoff during rainfall in dry seasons. This layer may also protect the subsoil from extreme evaporation. In a review of clearcutting and fire in the United States, DeByle (1980) showed that following fire, runoff, erosion and also nutrient concentrations in runoff increases initially, but that they all decreased later.

From north-eastern Spain it is known that soil losses after forest fires are limited to the upper centimeters and that vegetation recovers rather quickly. Severe erosion, however, is invariably experienced when a dense network of roads is build to make the burned area accessible for forest work. Soil erosion is more pronounced when the organic matter profile has a mor type profile rather than a moder type (Sevink et al. 1988).

In Sardinia forest fires are the most important cause of severe soil erosion (Aru 1984).

Another point of interest is the influence that forest fires have on the water balance by decreasing evapotranspiration. This in particular can have a large effect on the salt balance of the soil. Such effects in southwestern Australia are described by Sharma. Removal of native perennial vegetation decreases evapotranspiration significantly and promotes groundwater transport on slopes, leading to salt seepage at slopefoot positions and increased salinity in streams. Sommerfeldt and MacKay (1982) show that such salt seepage can enhance soil degradation.

Desertification

In this paper, by desertifications is meant the diminution of biological potential and primary productivity due to climatic change and excessive exploitation by man. Land degradation in arid and semi-arid Mediterranean regions (rainfall < 600 mm) has great analogies with desertification and to some extent may be considered synonymous. In Europe almost all of Spain and Greece, the southern part of Italy, Sardinia and Sicily are involved.

Mabutt (1986) summarizes the variables which are understood to be indicators for desertification. Three types (physical, biological and social) of indicator are distinguished. In this paper organic matter (soil and standing biomass), salinization, alkalization, groundwater and vegetation cover have already been discussed. Surface albedo is also one of the major parameters used to quantify desertification. Frequently, positive feedback mechanisms are involved in desertification and man's ability to inhibit or stop the process is very limited. One such mechanism is the sequence of deforestation, increased soil albedo, lower soil temperature, lower convective activity and decreasing precipitation.

The sensitivity to desertification will be significantly increased by any increase in aridity and this might accelerate or reinforce present or past degradation processes.

PART III, LAND DEGRADATION, SOIL EROSION AND RIVER CHANNEL CHANGES

I Introduction

Land degradation in the Mediterranean region dates back to antiquity. Many historians and scientists have attempted to document its occurrence and to relate it to changing environmental conditions or to human occupance. It is not appropriate here to review the findings of the vast body of work on this subject, only to draw attention to a number of conclusions relevant to the potential for further degradation due to the effects of climatic change on climate-sensitive processes.

It should be pointed out that a distinction needs to be made between existing land degradation resulting from past causes and the potential for further degradation under altered conditions. In the past the Mediterranean environment has proved to be sensitive and vulnerable to environmental change so that the landscape has to all intents and purposes been in many places irreversibly degraded. Large areas of the Mediterranean today have only truncated remnants of the original soil cover and there is relatively little potential for further degradation. Two examples of such areas are the Maquis regions in Greece and France. Whereas former degradation is probably greatest on slopes, the potential for present degradation is probably greatest on colluvial and valley fill deposits.

II Land degradation and soil erosion

In considering the relationship between climate change and soil erosion in the Mediterranean region, it is convenient to distinguish between the erodibility of materials subject to erosion and the erosivity of the rainfall, runoff or wind supplying the energy for detachment and transport of soil particles. Most of the discussion below refers to the processes of sheet erosion, which includes erosion in shallow channels or rills.

Rainfall and runoff erosivity

The erosivity of rainfall was first investigated in the eastern United States. Rainfall erosivity, which may be simply defined as the ability of rainfall to cause erosion, is related to properties of falling raindrops, such as size and velocity, which determine the impact force that the drops have upon striking the ground. Raindrop impact forces increase with dropsize and the number of large drops increases with rainfall intensity. Because of this it has been possible to calculate indices of rainfall erosivity based on rainfall intensity and duration parameters. The most well known index is the R (rainfall) factor of the Universal Soil Loss Equation. In Figure 10 (Arnoldus 1977) values are shown from Morocco. This map reflects simply the distribution of high intensity storms. Whilst such maps give a general impression, it must be stressed that the index was not developed from reliable observations. Suitable rainfall data need to be available to calculate such indices on a storm by storm basis. Because such data are often absent more simple indices have been applied like that shown in Figure 11 (Arnoldus 1978).

If it could be established how the relevant properties of rainfall would be influenced by climatic change, it would of course be simple to examine rainfall erosivity under different climatic scenarios. This might become possible should the precipitation forecasts of the climatic models become more reliable. Under the heading soil erosion below the combined effects of erosivity and erodibility are considered together.

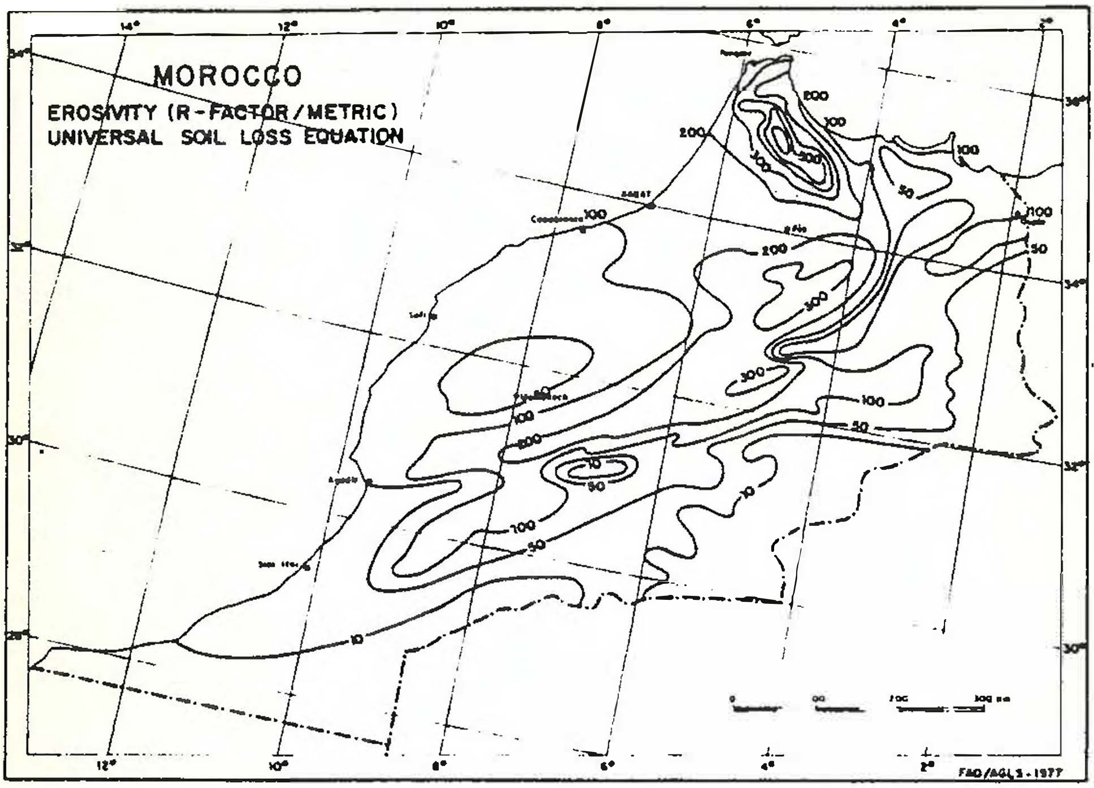


Figure 10. Rainfall erosivity calculated for Morocco (After Arnoldus 1977).

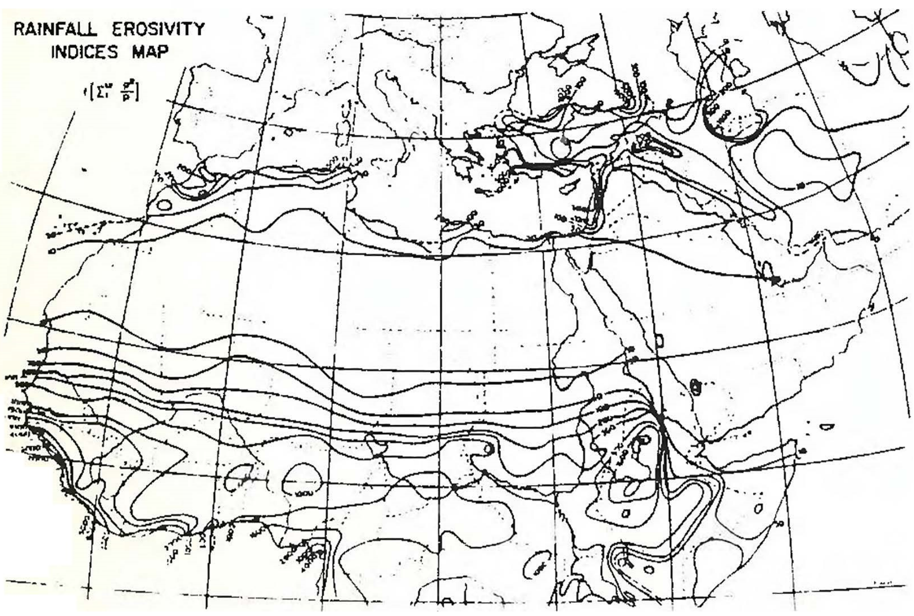


Figure 11. Rainfall erosivity for northern Africa calculated from the index p^2/P (p = max. rainfall in any month; P = total yearly rainfall) (from Arnoldus 1978).

Soil erodibility

The effect of lowering the organic matter content of cultivated soils will be to produce smaller, less stable soil aggregates, so that both the rates of water acceptance and the resistance of soil particles to detachment will be lowered. This will be most marked in soils containing low amounts of clay and could lead to higher concentrations of sediment in runoff, to lower thresholds of particle entrainment and to lower rates of infiltration. What will be affected most of all is the way in which soils respond to rainfall. Whilst soils with a good structure stabilized by organic matter retain their coherence and strength when moistened, soils which contain low amounts of certain necessary types of organic matter, and or are dispersible, can respond by slaking, swelling, dispersion, cracking and mellowing, when they are wetted and can because of this develop surface seals or crusts.

The effect of organic matter on the water stable micro-aggregation of highly calcareous soils from Alicante has already been illustrated in Figure 8. Soils having low organic matter contents are less stable.. The less stable the soils, the lower the infiltration capacity and the more frequently the soils will produce runoff. The frequency with which soils can be expected to produce runoff can be studied by means of experiments that enable the relationship between rainfall intensity and the time to ponding to be established (infiltration envelopes). For example, infiltration envelopes from Alicante in Figure 12 illustrate the effect of crusting on the amount of rain required at different intensities to produce runoff. Relationships between infiltration measurements and soil erodibility parameters can be seen in Table 2 (Imeson and Verstraten 1986). These enable a link to be made with the climate, since the infiltration envelopes can be compared with rainfall-frequency-duration curves.

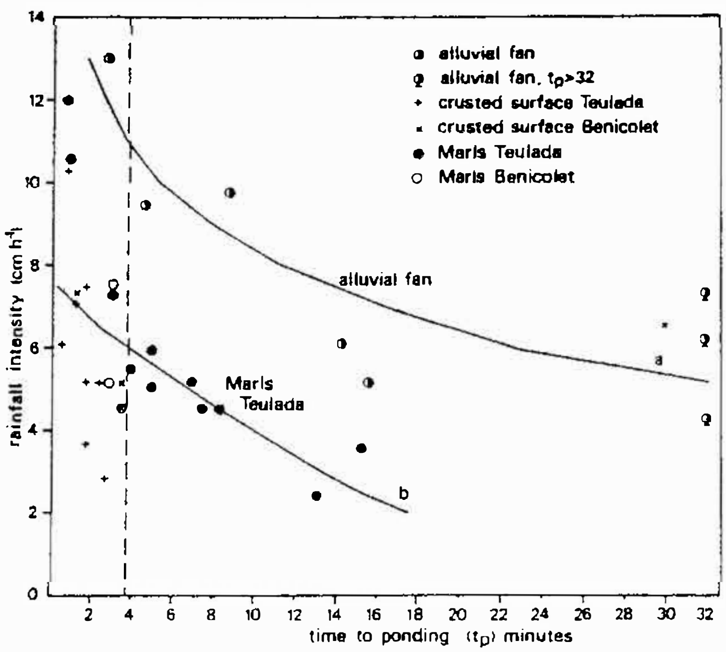


Figure 12. From Imeson & Verstraten (1985). Time required to produce ponding when rain is applied to the indicated intensity. Note how little rain is required to pond crusted soils on both the alluvial fan and marl soils.

Site	infiltration experiment data i = 5.3 cm h^{-1}				soil properties			
	T_{p_5}	$T_{p_{40}}$	T_r	S	SM	DI	AS	BD
A	1.05	3.50	9.35	3.0	20	10	16	1.4
B	0.58	2.36	5.09	2.1	20	3	81	1.1
C	0.24	1.26	1.40	1.4	15	11	8	1.1
D	0.32	0.56	1.15	1.2	17	11	13	1.3
E	3.12	5.46	9.45	2.5	16	11	37	1.4
F	0.39	2.31	7.05	1.8	17	5	37	1.1
G	2.04	3.14	5.30	1.9	14	11	23	1.2
H	1.54	5.22	16.12	2.5	20	11	10	1.1
I	5.51	16.49	n.r.	4.8	18	14	15	1.2
J	2.52	8.3	14.05	2.9	18	9	9	1.0

T_{p_5} = time to 5 % ponding (min, sec); $T_{p_{40}}$ = time to 40 % ponding (min, sec);

T_r = time to runoff (min, sec); S = sorptivity (cm.min$^{\frac{1}{2}}$);

DI = dispersion index Loveday & Pyle (1973)

AS = aggregate stability index (Low, 1954)

SM = volumetric soil moisture at time of test (%);

BD = bulk density

Tabel 2. Some characteristics of the soils and infiltration parameters at the infiltration experiment sites in the Lower Zarqa Catchment, Jordan (data from Marijnissen 1983).

Comparisons between infiltration envelopes and rainfall-frequency-duration data enable a clear distinction to be made between soils which would be sensitive or insensitive to higher rainfall intensities. Especially highly calcareous soils, lacking either pedogenic iron oxides and/or organic matter (i.e. sensitive to slaking and crust development), and soils which swell or disperse would be sensitive to an increase in precipitation. An increase in aridity would increase the area of soils having unfavourable infiltration characteristics.

Recently Lavee et al. (1988) have studied the infiltration characteristics and soil properties in the Judean desert along a transect running from the summit area at about 700 m to 100 m below sea-level neat the Dead Sea. As rainfall decreased from about 600 mm at the highest sites to 100 mm at the lowest locations, on the same calcareous parent material, so the infiltration capacity of the soil decreased from a final infiltration capacity of about 2 cm per hour at the highest site to about 8 mm per hour at the lowest. As conditions become more arid so infiltration rates become lower and the soil erodibility higher.

To summarize, the results of climatic change will be different for different soils but in general it might be expected that the water retention characteristics of many soils would deteriorate, the porosity and bulk-density would increase, the CEC would decrease so that less nutrients can be retained for plants and that the soil would slake and disperse more readily so that crust forming becomes a problem. This last problem is important since it influences the amount of infiltration and indirectly the rate or organic matter production and because a greater proportion of rainfall will become overland flow and have a potentially great effect on erosion.

The changes envisaged in the concentrations and composition of water soluble salts could have a potentially serious effect on crusting.

Irrigation practices may have to be modified to make allowance for increased salinity. There is a large literature describing how this can be done.

The erodibility of a soil describes its inherent susceptibility to erosion. The effect of decreasing organic matter contents and salt concentrations on soil erodibility is well documented. Soil erodibility is easily increased by an order of magnitude, particularly when the changes which occur result in the operation of formerly inoperative processes.

Soil erosion

From a mountainous area in south-east Spain, Sala (1988) quantified the yearly variations in rainfall, runoff and erosion in catchments on two different types of parent material (slates and granite). She measured yearly differences of up to and sometimes more than 100%, with wide seasonal contrasts. Generally, Spring and Autumn rains were most erosive. Rainfall appeared to be closely correlated with erosion within each area, whereas runoff was not significantly correlated with erosion. This means that the response of the soil surface to rainfall is of greater importance for achieving erosion than is runoff alone and points to a marked influence of extreme rainfall events. A great difference existed in the response of the two materials to rainfall. The significance of this kind of research for this paper is that firstly it illustrates the variability in erosion at a local and short time scale and, secondly, that it can be applied to hydrological and soil erosion modelling. Francis et al. (1986) have approached the variability and the interrelations between several variables at an even smaller scale. They conclude that at the scale of the hillslopes in semi-arid regions, significant relationships exist between plant cover, soil organic matter and soil moisture.

Generally, soil erosion is quantified by estimating sediment yields from surface wash and is classified as rill of sheet erosion. That mass movements (e.g. mud flow) can contribute to erosion on a large scale in the Mediterranean is well known and there is currently much concern about the hazards of landslides and mudflows. Any statement concerning the impact of climatic change on mass-movements will require good information about expected changes in precipitation.

An attempt to model the relationship between global climatic change and regional hydrology in a drainage basin in California has been made by Gleick (1987a-b). He states that climatic changes are expected to generate, for instance, shifts in the timing and magnitude of water availability. This would especially have repercussions for vegetation and hydrology response in the Mediterranean growing seasons.

Climatic change will influence the erodibility of the soil through the effects it has on the organic matter content or in the chemistry of the soil solution as described in part II. These effects are usually separated into those which primarily influence the ability of a soil to accept water as infiltration, and which therefore influence the partitioning of rainfall between infiltration and overland flow, and those which influence the resistance of soil particles to detachment. The most important climatic characteristics with respect to erosivity are those which determine the energy of impacting rain-drops (drop-size, wind velocity and plant cover) and the erosivity of overland flow. Field studies which enable the effects of erosivity and erodibility to be isolated and expressed in rates of soil loss or erosion are few because these require replicated measurements over long periods of time. It is however possible to conduct laboratory or field experiments that enable the erodibility of soils to be compared and related to properties that reflect the effects of climate on soil structure. Such studies often consider the aggregate stability or infiltration characteristics as surrogate parameters for soil erosion. For any one soil, erosivity can be studied by comparing soil loss measured on plots, under natural or simulated rainfall, to obtain an evaluation of the erosivity of rainfall and runoff.

In general, the way in which long term erosion is related to rainfall, and to some extent temperature, can be inferred from sediment yield data. Various authors have attempted to evaluate the information available and some of their results are summarized in Figure 13, taken from Yair and Enzel (1988). The suggestion is that erosion is highest in areas receiving between 400-600 mm of rainfall per year. Yair has questioned the validity of such relationships in Israel because higher rates of erosion occur in areas having less than 100 mm of precipitation, than in more humid areas. The applicability of sediment yield data to this problem in the Mediterranean region is difficult to verify due to limited field data. A more realistic approach is to consider interactions between climate vegetation and erosion in simulation models.

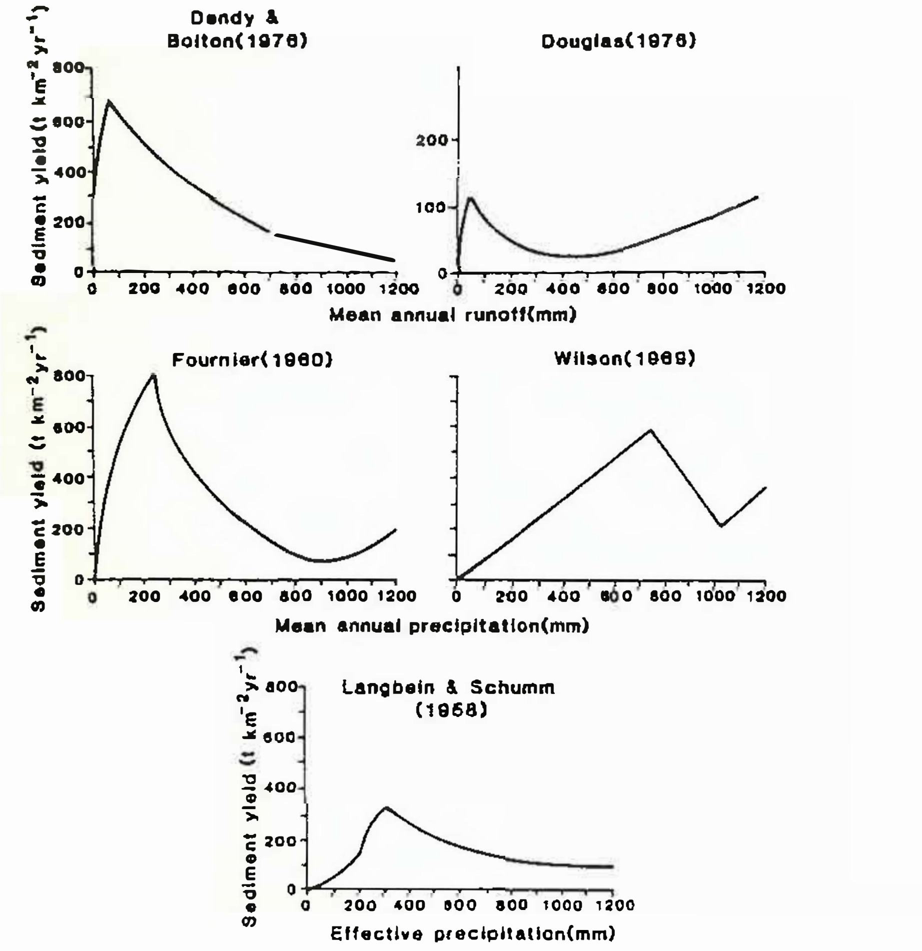


Figure 13. The relationship between sediment yield and annual rainfall (from Yair and Enzel 1985).

A promising attempt to do just this is made by Kirkby and Neale (1986). Their model is based on vegetation models, models for catchment hydrology and the Universal Soil Loss Equation and it embodies seasonality. Figure 14 shows global erosion rates when mean annual temperature and rainfall are input and maximum rainfall is in summer. Although the authors have presented results from their model for realistic seasonality and number of raindays, the effect of seasonality must be approached with caution. Figure 15 shows the substantial effect of seasonality on simulated erosion rates. Mediterranean climates are characterized by precipitation low in Summer and high in Winter or Autumn and Spring. The picture in Figure 15 is then altered according to curve -50% in Figure 16, which indicates that high rainfall peaks in periods with relatively thin vegetation (early Spring) and low soil organic biomass (Autumn). This is illustrated in Figure 17 for an arid Mediterranean area in southern Spain.

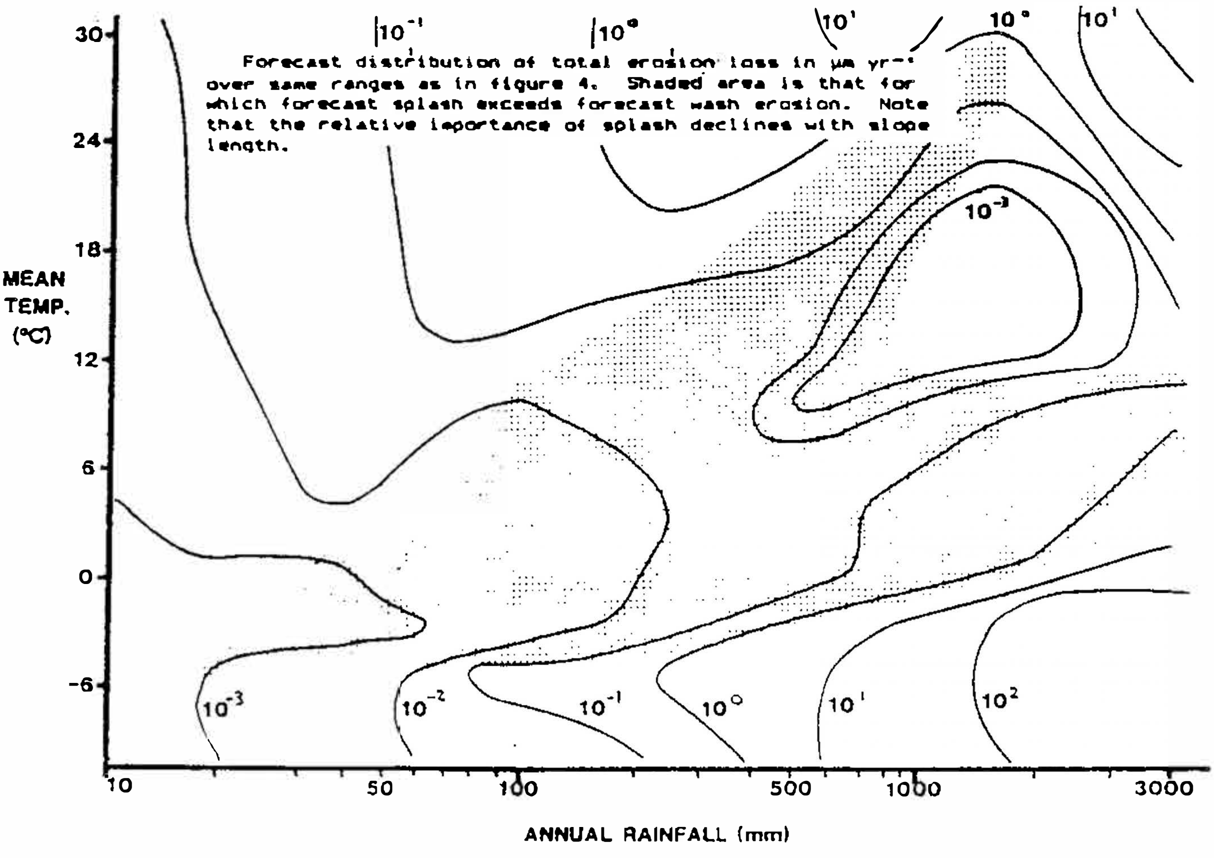


Figure 14. Relationship between forecasted erosion loss and average annual rainfall (from Kirkby and Neale 1986).

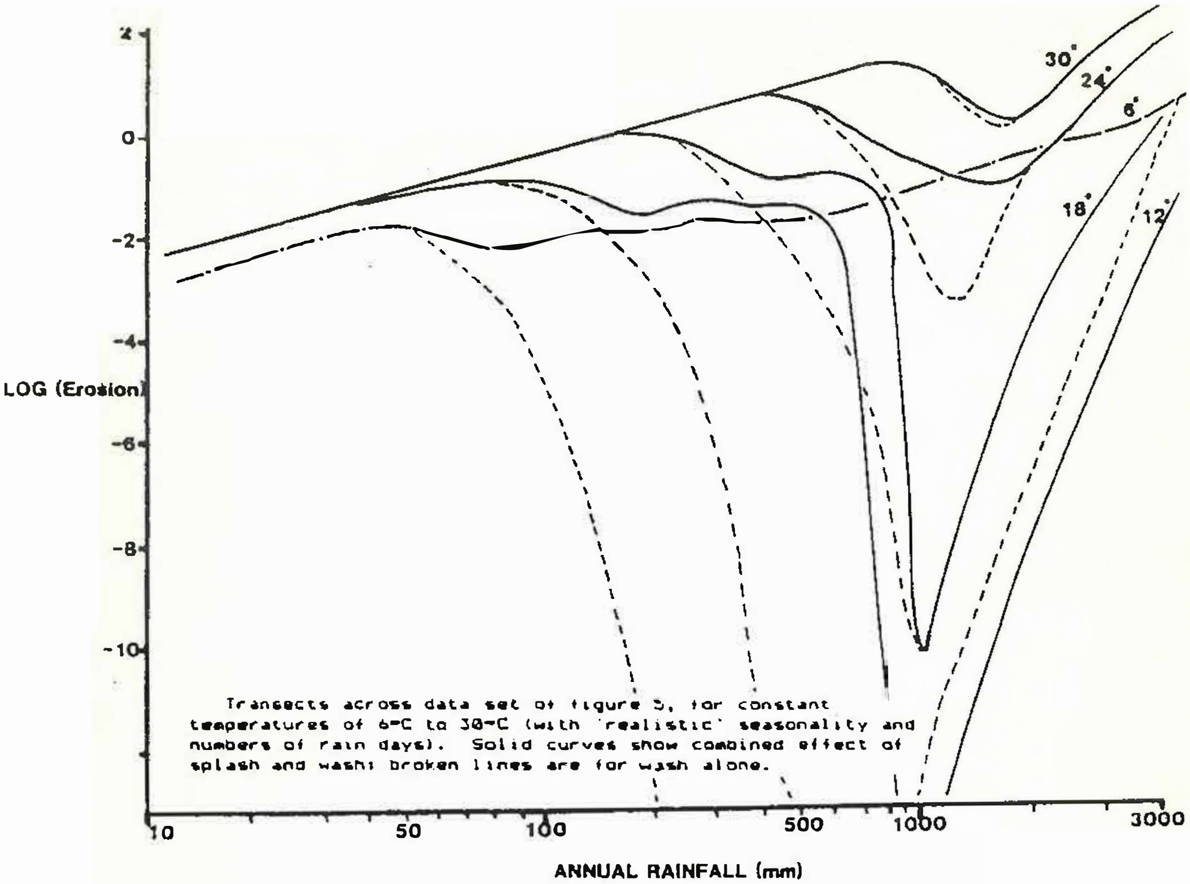


Figure 15. (from Kirkby and Neale 1986).

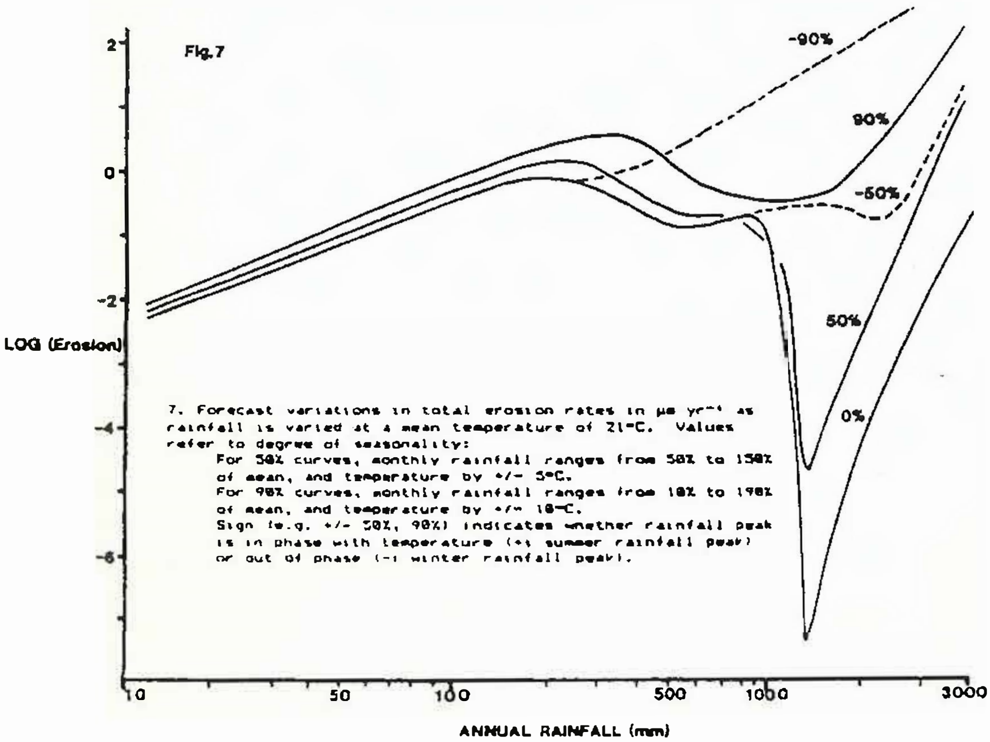


Figure 16. (from Kirkby and Neale 1986).

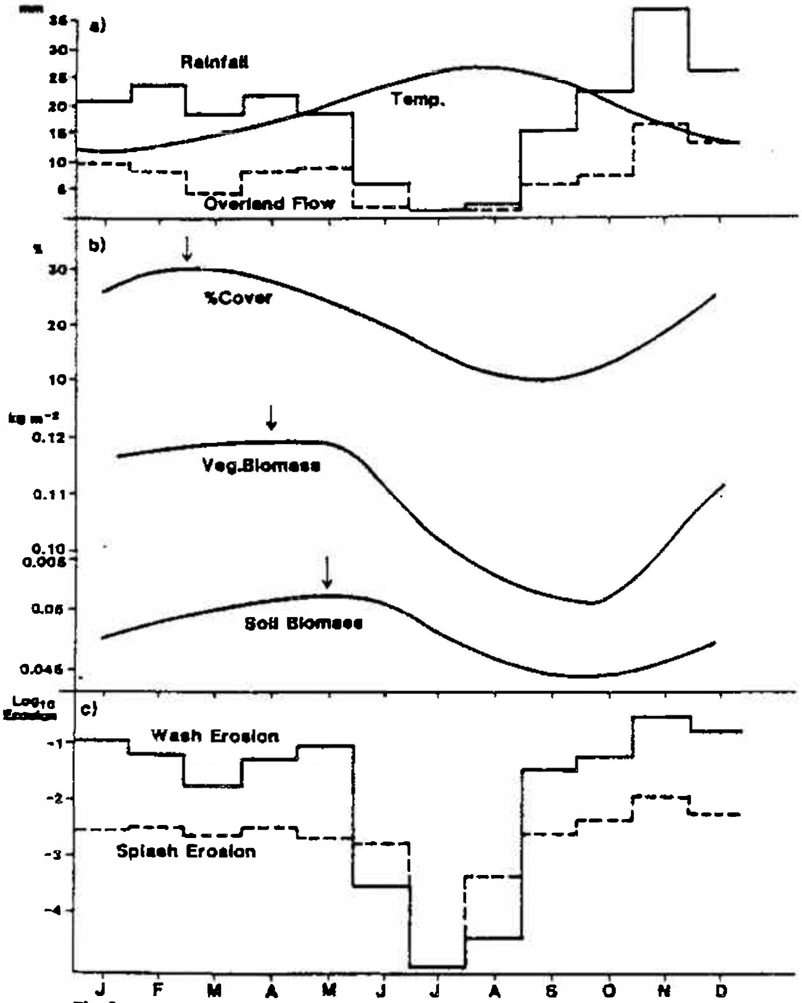


Fig.3 The annual march of climate and forecasts of vegetation and erosion for Almeria, S.E. Spain.
(a) Input monthly rainfall (mm) and temperature (°C), with forecast overland flow (mm).
(b) Forecast vegetation biomass (kg m⁻²), organic soil biomass (kg m⁻²) and vegetation cover (%).
(c) Forecast denudation by wash and splash in μm yr⁻¹, for a 10 m convex slope, falling from a level divide to 10° at base of plot.

Figure 17. (from Kirkby and Neale 1986).

Disregarding the effect of increasing precipitation, the decrease in organic soil biomass and the increase in soil erosion for a 4 °C temperature rise are estimated for two areas.

Organic soil biomass (kg/m²):				
Crete	500 mm,	15 --> 19 °C	2.8 --> 1.5	
SW Spain	600 mm,	17 --> 21 °C	2.6 --> 1.3	
Erosion rate:				
Crete	500 mm,	15 --> 19 °C	0.1 --> 0.4	(4x)
SW Spain	600 mm,	17 --> 21 °C	0.12--> 0.8	(7x)

At present Thornes an co-workers at Murcia (1987) are attempting to collect data to test and validate such models.

General relationships between climate and erosion need to recognize the importance of strong seasonal contrasts. The erodibility of the soil, for reasons partly explained in part II is dynamic, often being at its highest after a prolonged dry spell. Consequently, it is at such times that storms with a relatively low erosivity often cause more erosion than general relationships might predict.

It is, therefore, unrealistic to expect good statistical relationships between soil loss measurements and rainfall parameters. Soil loss measurements on plots from various locations in the Mediterranean have been examined for many locations. Poor relationships between rainfall parameters and soil data from Florence, Morocco, Valencia, Catalonia and Murcia for example all illustrate the lack of any simple correlation between soil loss and rainfall. What is nevertheless in all cases found, is that one or two rainfall events each year produce an extremely high proportion of the total yearly soil loss, in many cases upwards of 80 percent. These rainfall events are not always the most extreme with respect to duration, amount or intensity of rainfall. They are related to the effects of land use and weather on the soil structure and to various erosional thresholds.

Erosion takes on several forms. Sheet or wash erosion caused by overland flow and flow concentrated in shallow channels or rills, occurs where infiltration rates are low or where flow is concentrated in various ways. A large number of models have been developed to predict soil erosion rates by this type of erosion, as a function of climatic, soil, vegetation and land use parameters. These models are difficult to test due to a lack of data and are usually used to predict the impact of changes in land use. They could easily be used to estimate the impact of climatic change.

Gully erosion occurs under specific field conditions in various forms. Arroyo type gullies which occur in valley fills are likely to become active as they are related to peak discharges in ephemeral channels. Gully incisions could also be reactivated in alluvial fans. Gully erosion in alluvial fans has in the past been associated in a complex way with climatic change (Harvey 1987). The types of gully associated with dispersive soils or sediments are also likely to become active or extend their distribution. This is because areas of dispersive soils will increase due to altered salt balances and because the amount of runoff will increase due to higher degree of subsurface and surface runoff concentration. To model the increase in gully erosion that might result from climatic change is feasible but much more difficult than in the case of sheet erosion due to the general lack of research in this area.

The possibility that wind erosion might increase as a result of increasing aridity can not be overlooked. Certainly, the potential for wind erosion (higher soil erodibility) will increase and this can be quantified. However, it is not known how the frequency of erosive wind velocities will change.

Sediment budgets

The sediment derived from the more intensive erosional processes postulated above can be considered as a component of the sediment budget. In this budget, sediment is supplied by land surface and channel processes to river systems, where it is either stored or transported as an output to the ocean. Studies of sediment budgets are few and recent because of difficulties in obtaining data. Nevertheless, a number of general statement relevant to the scenario of increased erosion due to higher aridity can be made for the Mediterranean areas.

With increased aridity and higher erosion, sediment will accumulate at slope foot positions and in small order drainage basins. Where rivers are ephemeral and have an effluent character as in south-east Spain and north-east Morocco, for example, they are characterized by high transmission losses so that discharges produced by flood-events decrease downstream. Particularly in mountainous areas supplying coarse sediment, rivers will develop steep channel gradients as coarse bedload accumulates. Much of the coarse sediment leaving mountainous regions in southern Spain and elsewhere is deposited in alluvial fans at pediment or basin boundaries. Relationships between climate and processes on alluvial fans have been studied by Harvey (1987) and compared for the semi-arid southwest of the USA and for southern Spain. Under present conditions, most alluvial fans in south-east Spain are dissected by channels so that extremely high discharge events can carry material across the fan to adjacent river systems. Under the dryer conditions prevailing in the semi-arid southwest, and in the driest part of south-west Spain (< 250 mm/year) channels capable of carrying coarse debris across fan boundaries do not occur and material transported during floods accumulates on the fan. With increasing aridity, therefore, in spite of higher rates of erosion, there will be a greater tendency for any transported material to accumulate on fans and consequently for a lower supply of coarse material to river channels. Since most mountains bordering the drier Mediterranean regions are bordered by coastal plains or lowlands on which fans are developing, there will be very few areas where coarse sediment input into the Mediterranean Sea will be increased.

In the Mediterranean region there are extensive areas of marine marls or shales which weather into a highly erodible regolith. These deposits supply large amounts of silt and clay to river systems, particularly where badlands have developed. Increased erosion in such areas will of course increase sediment and solute levels in rivers receiving water draining from them. Morphological adjustments in river channels in these area will be different from those where coarse sediments predominate.

A higher sediment input into low order rivers, and the accumulation of this material in the channels of rivers in the dryer parts of the Mediterranean basin, will be a major impact in these regions. The types of adjustment that will occur in the morphology of the river channels is well understood (see Petts 1984 for example), as are the implications for flooding and river engineering. In more humid regions of the Mediterranean basin, without information on the altered precipitation regimes it is difficult to hypothesize about the impact of temperature alone. Nevertheless, in the Mississippi basin Knox (1984) has shown that colder periods are accompanied by lower peak discharges. If these findings can be translated to the Mediterranean, lower sediment inputs into rivers and oceans could be hypothesized.

Because most studies of river sediment yields in the Mediterranean regions have not been considered as elements of budgets, it is difficult to provide data which could be used to substantiate the above without a substantial analysis of the data. An analysis of available sediment yield data for selected drainage basins could provide useful information.

Salinity and water quality

The altered hydrological regimes described above might be expected to produce a general increase in the solute loads of drainage waters. The trend towards an increase in salinity, although general, will depend very much on the seasonal rainfall and runoff distribution and on the relative contributions of water following different pathways to river systems.

The increase in aridity and the resulting soil degradation will result in a general decline in percolation and eventually in a decrease in the contribution of delayed flow supplying water in equilibrium with the minerals present in the drainage basin. This is often water in equilibrium with calcium carbonate or gypsum. A decrease in the discharge of such water might mean that there will be a shift towards streams having perennial or ephemeral regimes.

Evaporation of water present in the sediments of perennial or ephemeral channels will lead to salt accumulation. These salts together with those which seasonally accumulate in the soil will be transported during relatively short periods of flow. The degree of deterioration in water quality will reflect the balance between dilution and accumulation.

A problem can arise when the runoff has a high sodium adsorption value (SAR). In combination with relatively low electrolyte concentrations this can lead to a common situation whereby transported clayey sediments become dispersed. The viscosity of the water is increased by the dispersed clay to such an extent that sand particles remain in suspension and hyper-sediment concentrations occur giving the runoff the character of dilute mudflow. This makes the water completely unsuitable for domestic use and causes problems of sedimentation at water intake points and in irrigation channels.

PART IV, CONCLUSIONS

Limitations

This review of the potential impact of climatic change on soil erosion in the Mediterranean is unfortunately limited by a number of constraints. These include:

1. The lack of information concerning the nature of the climatic changes that will occur at a regional scale.

2. In the Mediterranean and elsewhere there are very few actual measurements of erosion that can be used to test model hypotheses. Such measurements are required to establish relationships between climate or weather phenomena and climatic sensitive processes.

3. The complexity of the system being considered (see Introduction).

4. The only conclusions that can be made are rather obvious generalizations. Although a scientific basis for most of them is argued some links are unsubstantiated.

Major impacts

An increase in the temperature of 3 to 4 °C as predicted by the GISS model is argued to have the following impacts:

1. An increase in aridity due to higher PE.

2. An increase in soil degradation due to the effect of increased temperature and PE on soil organic matter, highly soluble salts and the moisture balance of the soil.

3. An increase in soil erodibility due to lower rates of water acceptance and a decrease in aggregate stability.

4. Higher rates of erosion on slopes and either relatively or absolutely more overland flow during extreme rainfall events.

5. Higher sediment concentrations in slope runoff.

6. Higher sediment and solute supply from badland and/or marl areas.

7. An increase in the risk of rill and gully erosion.

8. Higher sediment and lower runoff inputs into higher order streams.

9. An increase in the discontinuity of runoff and sediment transport in drainage basins.

10. Lower rates of sediment transport in the major rivers.

11. Adjustment of river channels, especially those carrying coarse load. Channel capacity will decrease, braiding will increase, fans will grow

and form barriers and flooding will be more frequent.

12. A higher susceptibility to forest fire and a decrease in biodiversity.

13. More arid soil conditions and a decrease in the area suitable for profitable agriculture.

14. Increasing management costs in agriculture to maintain crop yields.

Research requirements

As has become clear from this review, numerous studies have been made on the effect of (changing) precipitation, temperature and evapotranspiration on the soil system, even if not always carried out in the context of climatic change. Many workers have tried to find general relationships between climatic variables and parameters which are commonly used to assess soil erosion and soil erodibility. Others have made attempts to construct models which generate quantitative approximations of, for example, primary productivity or soil erosion rates. The complexity of the systems considered, however, impedes reliable assessments. Knowledge of the behaviour of, and interrelations between, any kind of subsystem involved still needs to be improved considerably. It seems worthwhile to make more use of instrumental-data-based scenarios considering actual climatological and environmental situations, as well as of historical instrumental data. A large number of case studies which integrate climatic, biotic an abiotic aspects in the Mediterranean area are available.

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