8. IMPACTS ON SOIL RESOURCES

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ABSTRACT

Large areas of Spain are currently threatened by desertification processes, in particular by the impact of forest fires and by the loss of fertility of irrigated land due to salinisation and erosion. The climate changes projected would exacerbate these problems in a generalised manner, especially in the dry and semiarid regions of Mediterranean Spain.

One of the essential components of the natural fertility of soils is their organic carbon content. It is estimated that the variations in these contents range from less than 4 kg C. m^{-2} in areas such as the Ebro valley or the southern Mediterranean coast, to over 20 Kg C. m^{-2} in the mountain areas in the North or Northwest, and can even reach 30 Kg C. m^{-2} in some forest soils in Galicia, and it can therefore be said that in Spain, practically the same variation ranges are found with regard to the accumulation of organic carbon as in the rest of the world. A mean value of organic carbon loss of 6-7% is estimated for each degree of temperature increase, and this value can increase or decrease according to the change in rainfall and also according to the characteristics of the soil itself and the uses thereof. The carbon cycle models and studies of climate transects suggest a generalised decrease in soil organic carbon as a consequence of the temperature increase and of the drought projected by the climate change models, which would negatively affect the physical, chemical and biological properties of the soils and would increase the risk of erosion and desertification. The areas in which greater losses of organic carbon could be expected would be the more humid ones (N of Spain), as well as the land uses with higher organic carbon contents (meadows and forests).

Changes in land uses and management provide good possibilities for counteracting the predicted negative effects. Among these are the reforestation of marginal and barren land, and an agriculture system which, through the appropriate management of farming techniques, tilling, irrigation and management of organic amendments, increases the organic carbon content of the soils and their fertility, triggering a multiplying effect of the ecosystems' capacity to fixate atmospheric carbon.

The European Strategy for Soil Conservation, the Common Agricultural Policy, with its agro-environmental measures, the Spanish Forestry Plan and land use planning at different scales of management constitute tools for the conservation of edaphic resources and the mitigation of the impacts of climate change on the soil and the associated ecosystems.

A basic research need in relation to edaphic resources involves an inventory thereof at a scale useful for management (at least 1:50.000), with which to evaluate the state of the resources, to plan management and to project change tendencies. In Spain, abundant local data are available that deal with the characterisation of soils, and these offer interesting possibilities for scientific use. These data, which are varied and heterogeneous with regard to structure, should be compiled and homogenised, universal databases being used as a reference, such as that of FAO-CSIC (Spanish higher scientific research centre). Finally, long-term soil studies in experimental stations, representative of the main land/soil types and uses, within the existing RESEL network of permanent experimental stations (Biodiversity Conservation Dept.), constitutes a reference of great value for the detection of changes in soil properties.

8.1. INTRODUCTION

Soils are the support of primary production in terrestrial ecosystems. Therefore, agricultural production of food and fiber for the human population is strongly dependent on soil resources. At the ecological and human time scales, soil resources are non-renewable. Therefore, soil conservation is a critical factor to ensure increasing food demands.

Soils can be a carbon (C) source and sink. Therefore soils contribute to the regulation of the carbon cycle and its comsequent effects on climate change. Changes in land use constitute the driving force that determines the soil's role as a source or as a sink of C. Tilling of land has led to a loss of organic carbon (which we will refer to hereinafter as OC) and an immediate increase in carbon emissions, whereas the reforestation of croplands causes an increase in carbon sequestration. However, sequestration of C under forestry or other non-agricultural land uses often only slowly replaces OC lost through cropping, and such differences in time scale between loss or change of soil properties due to man and their reversal are commonly several orders of magnitude different. Furthermore, the properties of soils are sensitive to climate change. The predictions by global circulation models for the Mediterranean basin, which would aggravate drought, would increase the risk of intensification of desertification processes.

Many of the impacts of climate change on soils are influenced by soil OC. In mineral soils, the approximate relationship between organic matter and soil organic C is 1.724 x % OC = % organic matter. Temperature increase would cause a higher decomposition rate of the OC. Increased drought would have the opposite effect. The possible increase in plant productivity due to the fertilising effect of an increase in atmospheric CO_2 would lead to an increase of OC inputs to the soil, especially with intensive cropping (assumig no hydrological or nutritional limitations). In natural ecosystems where productivy is limited by N shortage, increased atmospheric N deposition would increase OC inputs to the soil. On the contrary, decreased productivity due to intensification of water stress leads to losses of soil OC. The foreseeable increase in the occurrence of forest fires (see chapter 12) would cause losses of OC (especially of litter) and would increase the risk of erosion. Increased soil erosion causes the loss of upper soil horizons richer in OC. In areas in which forest fires are a recurring phenomenon, like in the Mediterranean basin, the production of highly stable forms of OC during combustion of biomass (charcoal) can contribute to the stabilisation of C in the medium term. All these processes do not exclude each other and some of the feedbacks may be positive, causing a multiplying effect.

OC is intimately linked with the natural fertility and productivity of soils: 1) as a source of macronutrients, especially N and P; 2) in relation to the substrate of the soil's microbial activity; 3) humified carbon contributes greatly to the capacity to retain nutrients and pollutants (capacity for cationic and anionic exchange capacity); 4) humic substances of lower molecular weight (fulvic acids) improve the solubility of some essential micronutrients, and of toxic metals; 5) it is a critical factor in the development and maintenance of soil structure and in the stability of soil aggregates and, consequently, of the physical properties that depend on these factors: water infiltration capacity, water holding capacity for plants, aeration, compaction, erodibility.

Another process that would probably be affected by climate change is soil salinisation. Projected Increasing in evapotranspiration and drought would raise water table, saline intrusion and accumulation of salts in the rooting soil depth in arid and semiarid lands.

In summary, the processes that would most influence the loss of fertility in Spanish soils, leading to their degradation, are: loss of OC content, decreased structural stability, reduced soil biological activity, increased risk of erosion and the spread of salinisation. These processes can be reduced with the application of appropriate farming techniques, tilling, irrigation control and management of organic amendments, along with the reforestation of barren lands. In short, those measures promoting soil fertility would set off a multiplying effect in the ecosystems' capacity to fix atmospheric carbon in the long-term. Of course, land use will almost certainly change as a consequence of climate change, opening opportunities to novel crops and varieties adpated to the new conditions, including the corresponding changes in cropping systems.

8.2. SENSITIVITY TO THE PRESENT CLIMATE

8.2.1. General characteristics of Spanish soils

According to the cartography of Spain's soils by IGN (National Geographic Institute of Spain) (1992, table 8.1, Fig. 8.1):

- Around 17 % of the area corresponds to little developed, shallow soils (many of the Entisols), generally on slopes, plateaus, and mountain areas,
- 1.6 % of valley soils, fertile in the broad sense, on river terraces (Fluvents, included in the order Entisols)
- a total of 60% are little differentiated soils, but modeately deep (Inceptisols) and of medium fertility,
- 9% of soils under arid climates (Aridisols), including soils with accumulation of calcium carbonate, gypsum, and/or soluble salts.
- 9 % of soils with subsurface accumulation of clay (Alfisols), fertile, of which one third are typically Mediterranean red soils.
- soils rich in OC, very fertile, of the Mollisol type, only constitute 0.2 % of Spain's territory.
- 1,6 % of very clayey soils, which crack when they are dry (Vertisols) mostly used for agriculture. The Vertisols are particularly distributed throughout Andalucia and Extremadura regions.
- Well-developed acidic soils (Ultisols and Spodosols) only occupy 0.4 % of the territory, mostly in northern Spain.
- Finally, organic soils (Histosol), with a large content of organic carbon, which are trivial in extent in Spain (0.04 %) although they are of great ecological and scientific value.

Table 8.1. *List of soil types (USDA 1987) in Spain. Source: IGN (National Geographic Institute of Spain) 1992 (de la Rosa 2001)*

Order	Units	Percentage, %	Area, ha
Alfisols	368	8,86	4507160,2
Aridisols	411	9,19	4672759,6
Entisols	830	18,90	9613443,7
Histosols	4	0,04	20813,2
Inceptisols	1612	60,73	30891369,6
Mollisols	2	0,21	104746,5
Spodosols	62	0,22	112146,8
Ultisols	5	0,24	121689,9
Vertisols	51	1,62	826275,5
TOTAL	**3347**	**100**	**50870405,1**

SEIS.net (Spanish System of Soil Information though the Internet (de la Rosa 2001, http//:www.microleis.com) shows in an easy-to-use format the information available on the current state of quality and degradation of soils in Spain, including a Digital atlas of Soil Regions and an on-line Soil Database.

Fig. 8.1. *Map of soil sub-orders in Spain, according to Soil Taxonomy, USDA 1987); IGN* 1*992/SEISnet. (de la Rosa 2001)*

8.2.2. Soil processes particularly sensitive to climate change

By sensitivity of soils to climate change (CC), we understand the intensity and extent of the response generated in the soil properties and processes as a consequence of a modification in the parameters of the climate.

Soil properties that could be modified by CC would be OC content, characteristics of soil biota, moisture and temperature regimes and processes such as erosion, salinisation or physical, chemical or biological fertility. The climatic parameters driving these changes would be temperature, rainfall (quantity, intensity and temporal distribution), together with atmospheric chemistry, especially carbon dioxide and nitrogen and sulphur compounds.

Many of the soil properties are quite resistant in relation to short-term variations in climate, with effects that are difficult to detect due to the great impact of land use and land use changes, especially if we consider the great spatial variability of soils. It is therefore impossible, with the knowledge currently available, to determine the sensitivity of Spanish soils to presently perceived climate changes in an accurate and quantitative manner, but some examples can be given in which these relationships between climate and soil are evident.

a) <u>OC Mineralisation.</u> Taking into account that this process depends, in the first place, on the soil climate, we could presume that, within certain thresholds, the highest the temperature and the highest the number of days with soil moisture greater than wilting point, OC mineralisation will be more intense. Therefore, the coincidence of a thermic soil temperature regime with an udic or even an ustic soil moisture regime (Fig. 8.2) would define those regions in which the sensitivity of Spanish soils to the degradation of and potential for absolute loss of organic matter is greater. It should be emphasised that change in the nature of organic matter, i.e. its composition, can be as important as the change in the amount of OC in the soil.

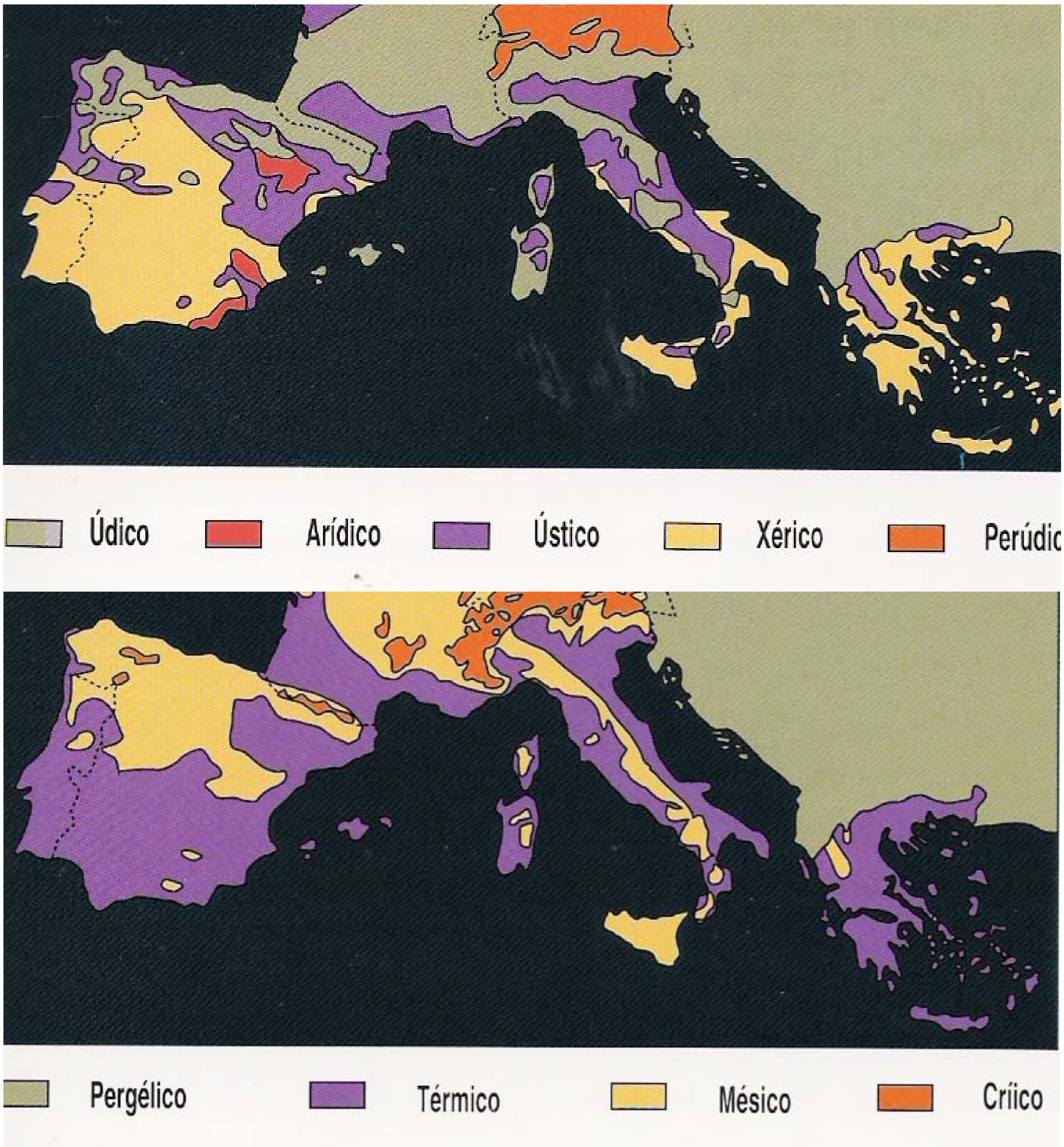


Fig. 8.2. *Soil moisture (above) and temperature regimes (below) according to the Soil Taxonomy criteria for southern Europe. Adapted from the Soil Map of European Communities 1:1.000.000 (CEC 1985).*

b) <u>Physical status of the soil</u>. If we accept, as most authors usually do, that 2.3% soil OC defines a threshold, below which there is a significant acceleration of the processes of physical degradation, then we can consider that those soils with values lower than the aforementioned threshold (in the map of Fig. 8.7, those presenting less than 12 Kg C m^{-2}) will be the ones most sensitive to the physical degradation of the soil, and even to loss of soil fertility through the effects of physical soil properties on biological and chemical processes. However, that threshold is only a very rough indicator that should be considered with care in assessing specific soil conditions.

c) <u>Soil erosion</u>. According to the Universal Soil Loss Equation, widely used for predicting hydric soil erosion, factor k is the parameter that defines the sensitivity of the soil to soil erosion.

Factor k depends on soil OC, texture and structure, the former and the latter being sensitive to climate change (see previous paragraph). In addition, wind erosion is likely to increase as strominess do so and plant cover is reduced.

d) Salinisation. The increasing aridity of the climate, combined with irrigation of poorly drained soils with waters that could be of deteriorating quality, constitutes a risk of salinisation of the soil and, eventually, of runoff waters.

8.2.3. Land use

In the short term, changes in land use result mainly from cultural, political and socioeconomic factors, more than from the direct impact of climate. The effects of land use changes on the soil can be as great, if not more, than those of climate change itself (Vitousek 1992). In the last half century, the territory of Spain, like that of much of Europe, has been subjected to big changes, which continue to be seen and to interact in a complex fashion with the effects of climate change on soils.

C stocks in soils and vegetation have increased during the XXth century in Spain due to the abandonment of marginal croplands, particularly since the 60s and promoted in the last decade by the EC's Common Agricultural Policy, together with the extensive reforestation carried out (over 3 Mha, ICONA 1989). The large forest fires that started to occur since the 70s must have partially counteracted this carbon accumulation. Wildfires tend to consume part of the understorey, some of the thin branches and the litter (around 65% of the C contained in all these fractions in an experimental high-intensity fire; Serrasolses and Vallejo 1999).

According to data from the European Environment Agency, Spain, after France, is one of the European countries that lost most agricultural land during the 90s (1.8% of the territory). A large part of this territory has been used for housing (0.3%) whereas the rest (1.5%) has become forest (basically through natural regeneration and plantations). The reduction of croplands for housing is especially concentrated along the coast and close to the big cities. In this case, the problem of soil sealing arises, which causes the physical destruction of the soils or profoundly modifies their physical, chemical and biological properties. Furthermore, sealing can cause hydrological problems, local temperature increases, changes in groundwater levels, greater mobility of pollutants and overloading of water courses, particularly during torrential rains. Where polluted waters enter river estuary systems and the coastal zone, degradation of this environment can occur and is related directly to soil problems.

The four economic scenarios by the IPCC involve predictions of changes in land use from 1990 to 2050. Briefly, they can be summarised for those impacts in land use as follows:

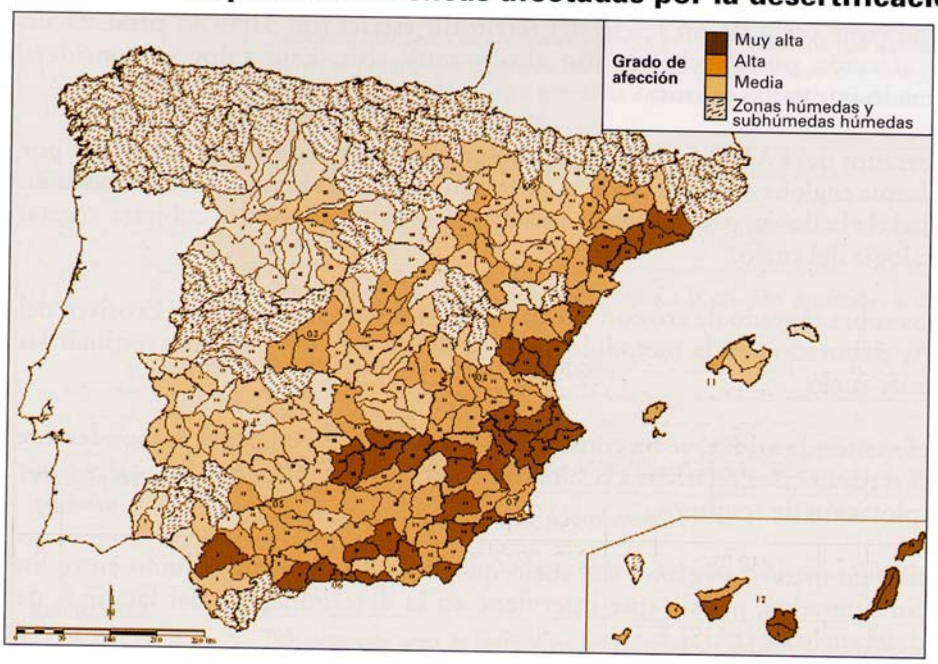
- A1 (rapid economic growth): slight decrease in croplands, increased pastures. Decrease in forests and other uses. This scenario involves the maintenance of previous tendencies in changes in land uses, governed by economic forces.
- A2 (local identities): no changes in land uses have explicitly been developed in this scenario.
- B1 (services and information economy): slighter decrease than in scenario A1 of the area with crops, decrease in pastures and increase in forests and other uses.
- B2 (local economies, sustainability): large increase in crops and pastures, decrease in forests and a sharp decrease in other uses.

These scenarios do not discriminate the location of the change, which will evidently vary geographically. In Europe (and Spain), economic scenarios A1 and B1 would lead, in the medium term, to the continuity of the gradual abandonment of marginal agricultural lands. Probably, in spite of assumptions A1 and B2, there would be an increase in the area occupied by forests expanding in old fields. Options are therefore provided for the appropriate management of marginal abandoned lands and forest restoration.

8.2.4. Desertification

Spain is one of the countries affected by desertification (United Nations Convention on Desertification, Annex IV), exacerbated by human activity under arid conditions (Fig. 8.3). The basins affected are defined using estimates of soil erosion, occurrence of forest fires, the degree of exploitation of hydrological resources and drought intensity (see draft of the National Action Programme against Desertification, PAND, by the MMA – Ministry of Environment). Two fundamental components of desertification in Spain are soil erosion (Fig 8.4) and the salinisation of the soil. At present, it has been recognised that 32.5% of Spain's surface area is seriously affected by desertification (PAND, MMA). According to the same sources, 42% of the country's area is above tolerable erosion limits and mainly involves the Guadalquivir, Ebro, Tajo and Southern basins (Fig. 8.4). In Spain, in 1991, it was estimated that the direct costs of erosion reached 280 million € and the cost of recovery measures would require 3,000 million € over a period of 15-20 years. Water erosion in Mediterranean conditions is highly episodic at present. For example, in a complex of catchments in dry Mediterranean climate conditions in Valencia, only 3 to 4 sedimentary events are recorded per decade, with erosion producing rainfall thresholds between 30 and 60 mm day^{-1} (S. Bautista, personal communication, European project SPREAD). The predicted changes in relation to an increase in extreme climatic events that may affect Spain (Millan *et al*. 2004, in press) would lead to an exacerbation of the risk of soil erosion.

Mapa de subcuencas afectadas por la desertificación



Fuente: Borrador de trabajo del PAND, marzo de 2001. Fuente original: ICONA-MAPA, modificada

Fig. 8.3. *Map of sub-watersheds affected by desertification in Spain.*

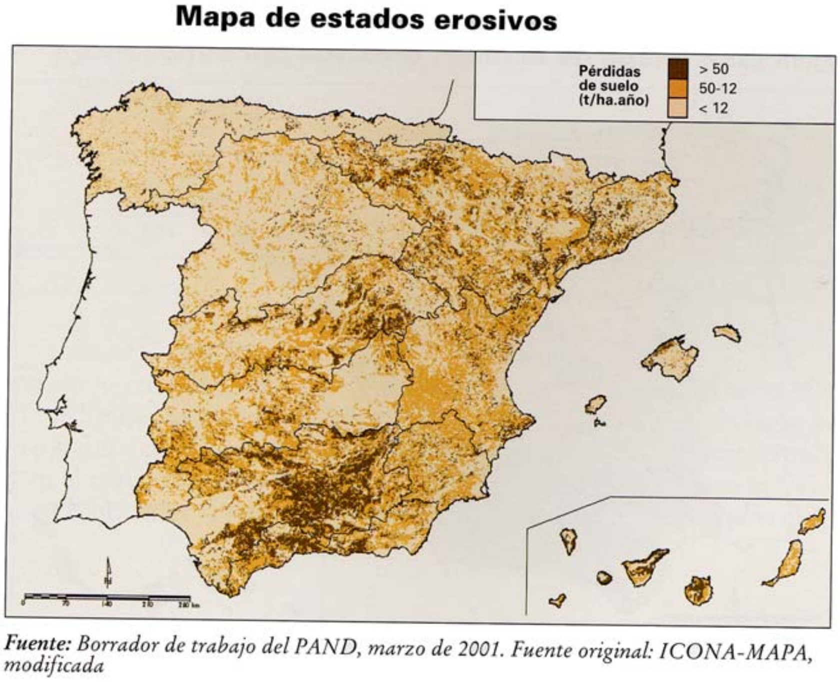


Fig. 8.4 *Map of erosion condition in Spain with estimates of soil loss.*

According to the soil map of Spain, by the IGN 1992 (Fig. 8.1), saline soils (*Salorthids*) occupy around 180,000 ha, 0.35% of the country's surface area. In the EU, salinistion of the soil affects 1 million hectares, mainly in the Mediterranean countries (C.E. 2002). The problem of soil salinisation seriously affects 3% of the 35,000 km^2 of irrigated land in Spain, and 15 % is at great risk, especially in the Guadalquivir, Ebro, Guadiana, Tajo and Southern basins and along the East coast (PAND, MMA).

8.3. FORESEEABLE IMPACTS OF CLIMATE CHANGE

8.3.1. Impacts on the evolution of the soil

The relationship between soil types and temperature, rainfall and evapotranspiration is well known. Only certain properties can be altered, however, over short periods of time, by changes in climatic factors, like, for example, content of soluble salts. In this way, soils affected by salinisation may change their distribution (Salorthids, Soil Taxonomy, de la Fig. 8.1).

Due to possible changes in temperature, more notable in areas of greater latitude, there could be a great and very rapid loss of organic matter in peaty soils (*Histosols* in Table 8.1 and Fig. 8.1). However, the global impact of these losses would be low owing to the small surface area occupied by peat soils in Spain.

8.3.2. Salinisation: in relation to climate change and intensification of agriculture

Salinisation of soils is probably the most important degradation process affecting the production of fibre and foodstuffs in countries with arid and semiarid climates. The most common cause of salinisation is associated with irrigation in areas with poor drainage, with fine-textured soils, with the use of water containing an excessive amount of salts for irrigation, and with marine intrusion. New irrigation programmes in sensitive areas, the intensification of agriculture and the overexploitation of aquifers are the main culprits of salinisation in Spain. The National Irrigation

Programme (Dirección General de Desarrollo Rural 2001) plans for the extension of the irrigation system in Spain up to 2008.

The problem of salinity is associated with the presence of salts more soluble than gypsum in the soil, generally NaCl and Na_2SO_4 (sulphates are more abundant in inland areas). When the water balance of the soil does not produce water surplusses which remove salts from the soil by natural drainage or the soil is not appropriately drained, causing water logging, the salts tend to accumulate on the top soil, osmotically affecting water absorption by the plant (physiological drought) and producing toxicity. Irrigation of soils with a high salt content can aggravate the problem if there is not appropriate drainage because salts are brought to the surface by capillary action and by the increased growth of the irrigated crop. This accumulation of salts is therefore characteristic of climates with a low Rainfall/Potential Evapotranspiration ratio. As the projections of climate change for Spain forecast a decrease in this ratio, the salinisaiton problems can be expected to worsen. Likewise, a possible rise in sea level would exacerbate the problems of marine intrusion in the phreatic layers, along with those related to the spread of salinisation to coastal areas and the possibility that tidal influence of saline waters will extend further inland along rivers and estuaries.

The intensification of agriculture in the large watersheds and in the coastal areas of East and Southeast Spain, accompanied by increasing aridity of the climate, will cause the problem of salinisation to spread (Fig.8.5), with serious consequences related to the reduction of harvests and/or the need for extra investments for mitigating this problem.

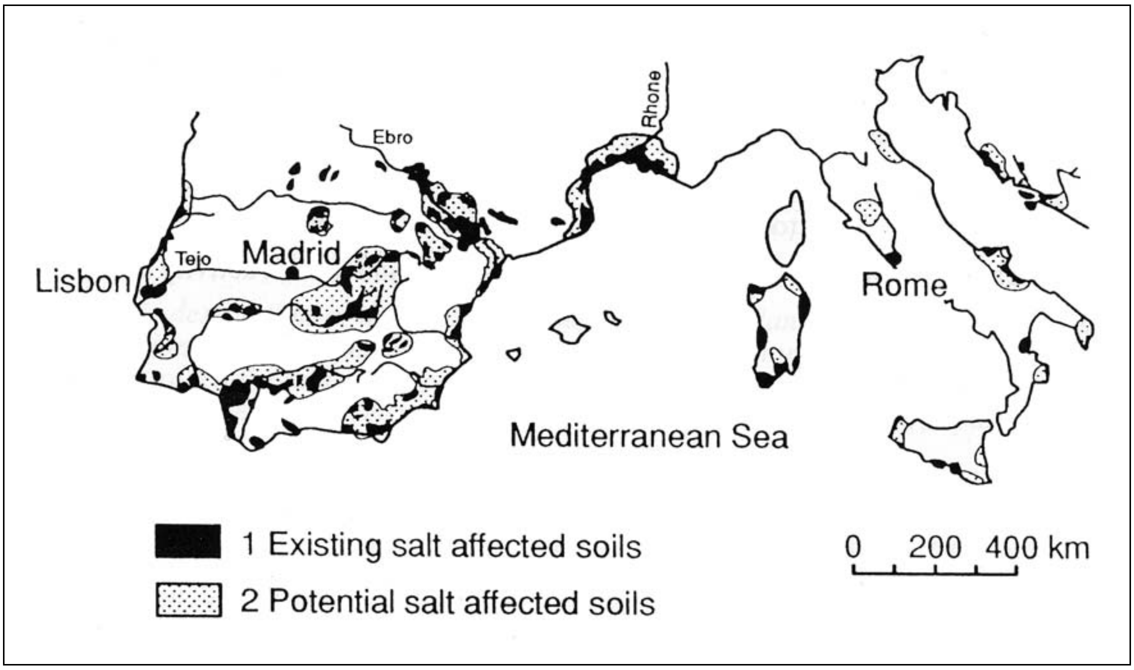


Fig. 8.5. *Distribution of salt affected soils and the potential spread of these as a consequence of climate change (Pérez-Trejo 1992).*

Reclamation of cultivated saline soils is difficult and costly. The techniques are based on leaching out the salts, using drainage and large amounts of non-saline water, together with crops that are tolerant to salinity and farming techniques that minimise the accumulation of salts in the rooting soil depth (for instance mulching). In any case, the reclamation of soil salinity always transfers the problem (the salts) downstream, to the river or to the neighbouring lands at lower elevations (Vallejo 1999) with the possibility of greater salinisation of lands bordering estuaries and further problems in the coastal zone.

In some cases, natural saline soils have been subjected to recovery projects for agricultural use. One example of this is the Guadalquivir marshes, where an area of 50,000 ha was recovered with the installation of a drainage and irrigation system (Grande Covián 1967) and which is currently used for cotton and sugar beet crops with good results. In this area, Moreno *et al*. (1995) studied the dynamics of salts and water, the results showing the good functioning of the drainage system and the salt leaching during cultivation with irrigation.

8.3.3. OC Balance

In a Mediterranean context, in which the soils tend to have a low organic matter content, OC increase could favour the physical, chemical and biological properties of the degraded soils.

8.3.3.1. Impact of the soil on climate change

Apart from the impacts of climate change on the properties and functioning of the soil, it is also of great interest to learn of the influence of the soil on this change. The global amount of organic carbon in the soil has a direct influence on atmospheric CO_2 levels. Slight changes in OC, whether these be positive or negative, can have an appreciable effect on the content of atmospheric CO_2 levels. Furthermore, in permanent or temporal waterlogged soils, emissions of CH_4 (methane) and N_2O (nitrous oxide) also contribute to the greenhouse effect.

Sequestration of organic carbon by terrestrial ecosystems forms part of a very active biological cycle, and a large amount of the carbon currently retained by soils can return to the atmosphere in relatively short time. In this way, carbon sequestration by terrestrial ecosystems should be considered as temporary storage, rather than permanent. In this sense, it is estimated that the soils used for cropping have lost between 20 and 40% of their previous OC under natural vegetation, and it is believed that through the use of conservation tilling practices, the levels of soil OC can be partly recovered.

In terrestrial ecosystems, current carbon stocks are much greater in the soils than in the vegetation, particularly in non-forested ecosystems at medium and high latitudes. Besides, the return of stored carbon to the atmosphere is slower in the soil than in the vegetation. Carbon stored in the soil is also much better protected against fires and other disturbances.

8.3.3.2. Carbon content in Spanish soils

The organic carbon content of the soil is the result of the balance between the OC inputs and mineralisation, both of these depending on climatic conditions. According to the estimates by Tinker and Ineson (1990, reused by Bottner *et al*. 1995 to discuss Mediterranean soils, Figure 8.6), the distribution of the carbon content of soils throughout the world varies from less than 2 kg C m^{-2} for the soils of sub-desert areas, up to over 30 Kg C m^{-2} in the tundra and rain forest areas.

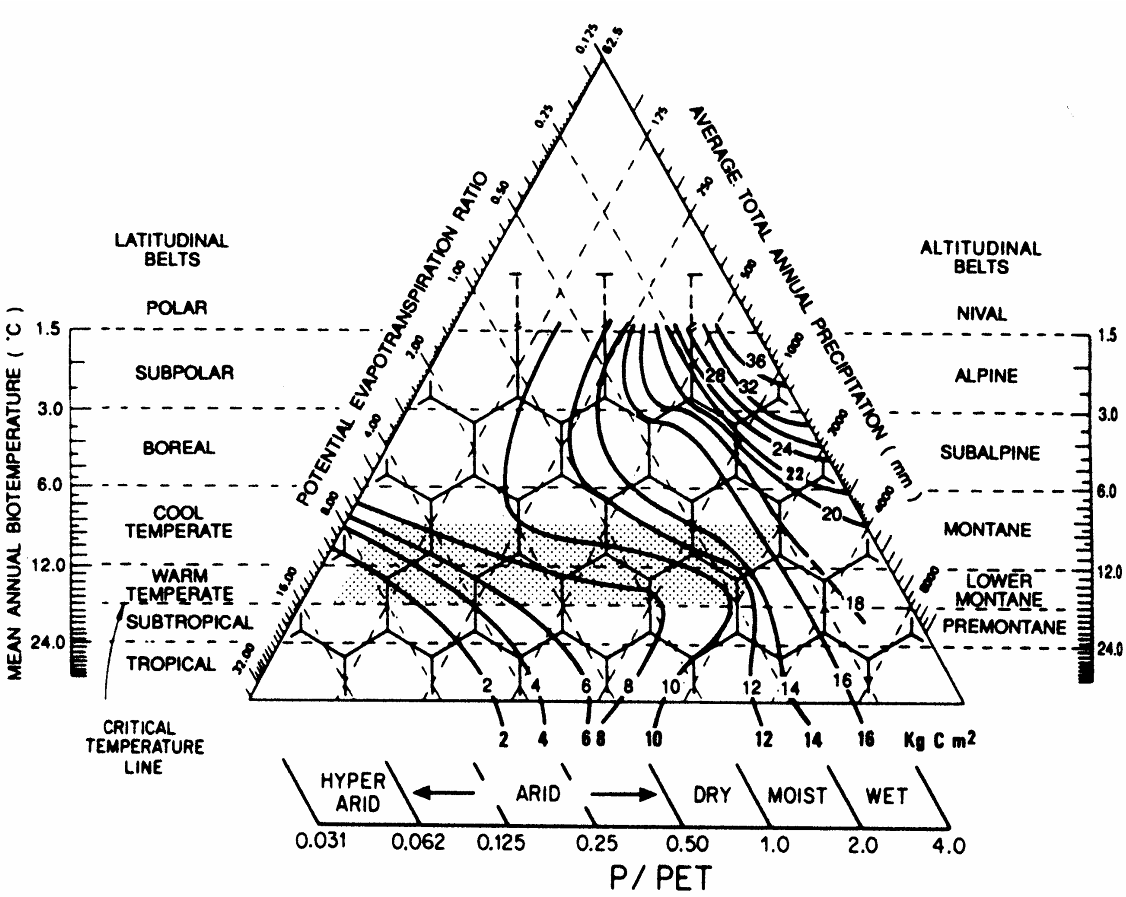


***Fig. 8.6.** Organic Carbon content (in Kg. m^{-2}) of the worlds' s soils. Bottner et al. 1995. The shaded area shows the range corresponding to Mediterranean soils.*

For Spain, Rodriguez-Murillo (2001) used a set of 1,030 soil profiles to study the geographic distribution of their carbon content, and made a map (Figure 8.7) on which the estimated variations range from less than 4 kg C m^{-2} in areas like the Ebro valley or the southern Mediterranean coast, to over 20 Kg C m^{-2} in the mountainous areas of the North or Northwest. In the same sense, for agricultural soils, accumulations of organic carbon are higher in Spanish, Atlantic climate soils than in those existing in the Mediterranean climate (Fig. 8.8). Barral and Díaz-Fierros (1999) showed that the forest soils of Galicia could reach 30 Kg C m^{-2}, which demonstrated that Spain presents practically the same variation ranges of OC accumulation as the soils at world scale.

The second most important factor regulating OC content is the type of land use, along with the type of management the land is subjected to (Table 8.2, Fig. 8.9). The same study by Rodriguez-Murillo (2001) presents a table showing the main land uses with their carbon content, where it can be seen that it is shrubland uses that have the highest proportion, with an average content of 11.3 Kg C m^{-2}, followed by deciduous forest, with values of 9.36, whereas dry farming crops, with 5.08 Kg.C m^{-2} are the ones that present the lowest amount. The cropping systems that include organic amendments such as compost, fallow, burying crop residues, etc., always maintain a higher OC content in the soil than those that do not or that are subjected to burning of stubble, which accelerate mineralisation.

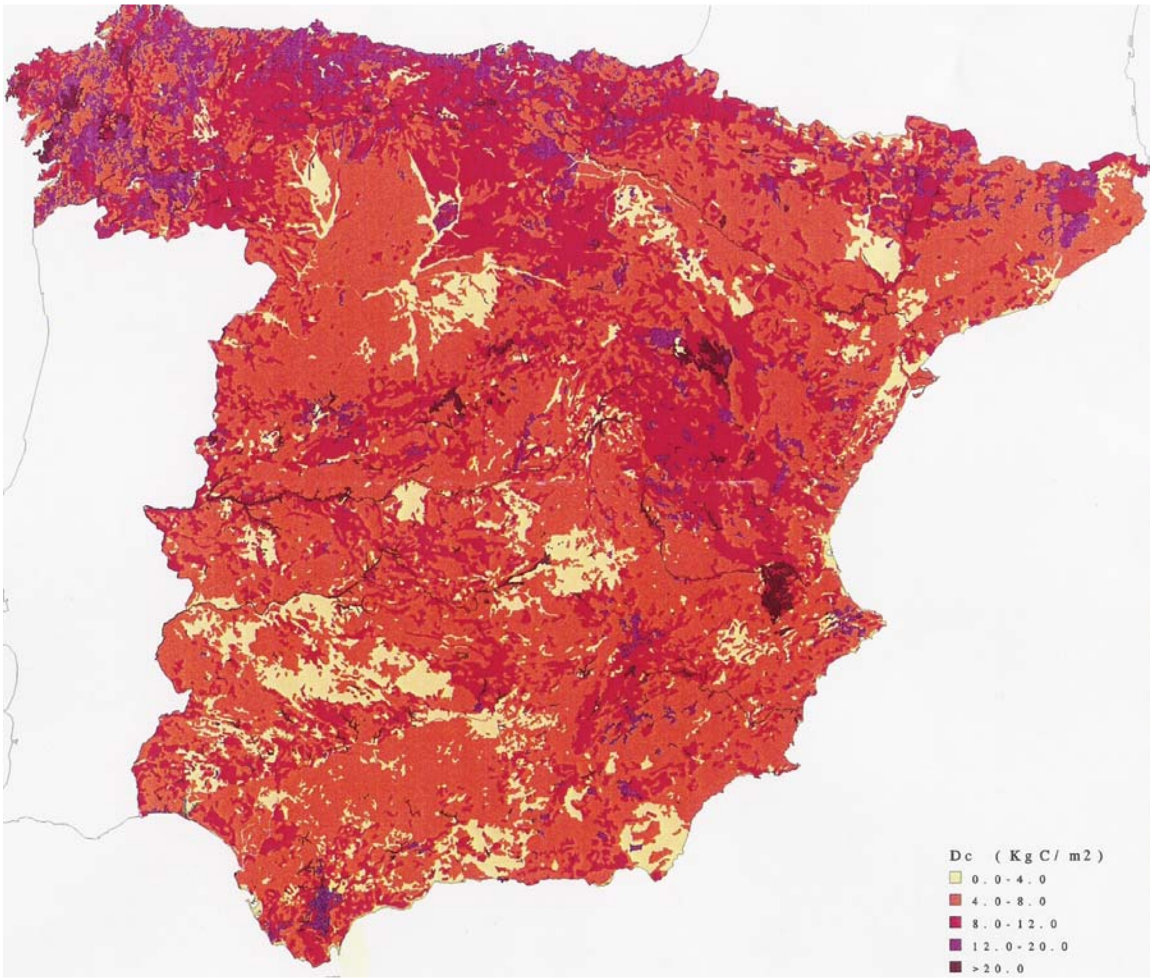


Fig.8.7. *Content of organic carbon (up to 1 m deep) in Spanish soils (Rodriguez-Murillo 2001).*

Table 8.2. *Total carbon under the main land uses on the Spanish Peninsula. According to Rodríguez-Murillo (2001).*

Land use		Area Km^2	Carbon kg m^{-2}	Total carbon Tg
Forests	Conifers	63 010	7.50	473
	Broadleaved species	23 991	9.36	225
	Mixed	18 934	12.1	229
	Total	105 935	8.74	926
Shrubland		78 492	11.3	890
Shrubland + trees		40 938	8.20	336
Dry farming crops		121 740	5.08	618
Others		147 458	6.28	926

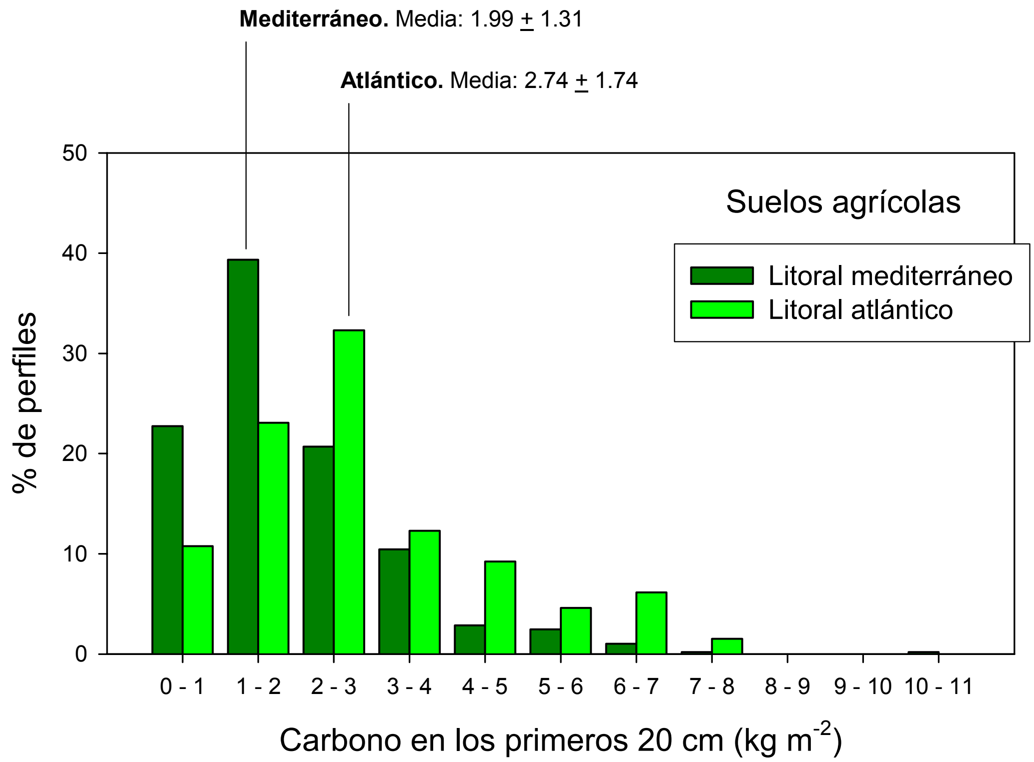


Fig 8.8. *Accumulation of carbon in the arable layer of Spanish soils of Mediterranean and Atlantic climate. Source: Rovira* and *Vallejo (personal communication), Evaluation of C in the soils of the Mediterranean area, OECC.*

8.3.3.3. Effect of climate change on soil OC in Spain

Climate change will have an influence on the OC content in the soil by means of a direct effect on the accumulation and mineralisation processes, and indirectly through the influence on changes in land use. According to different studies based on models, the indirect influence of changes in land use will probably be more important than the direct impacts on the processes regulating the OC balance of the soil (Parshotam *et al.* 2001). It is impossible to make accurate predictions of the response of ecosystems to these changes. There are big knowledge gaps, because most papers published simulated experimentally an increase in atmospheric CO_2, or a temperature increase (with or without decreased rainfall), but not both effects at the same time. Two groups of effects, however, can be mentioned:

A) Effects of an increase in atmospheric CO_2

Possible increase in primary production. If we accept the idea of increased primary production derived from the fertilizer effect of elevated atmospheric CO_2, the maintenance of sequestrered carbon in the soil would be relevant if the excess of fixed carbon is allocated to slow-decomposing forms (structural carbon: lignocellulose, suberin, various resistant forms). The information available seems to suggest the opposite. In meadow ecosystems in the USA, in a Mediterranean climate, Hungate *et al*. (1997) observed over three years an increase in biomass, roots, buried detritus and soil OC. The increase in soil OC, however, appears to be concentrated in labile fractions, the medium-term stabilisation of which is unclear: it could be lost as easily as it is accumulated. More important than the increase itself is the acceleration of the carbon cycle in the soil. The authors are skeptical with regard to the capacity of these meadows to accumulate more carbon. The combination of the increase in CO_2 and in temperature would result in a decrease in primary production in the medium-terrm (see chapter 9 and section B below).

Decreased quality of the OC. Specifically, there is an increase in the C/N index. It is considered to be a probable result of the increase in atmospheric CO_2, which initially should lead to a slower decomposition of plant residues, and therefore to greater accumulation of carbon in the soil. It is unclear whether this really occurs, because the experimental studies have not detected, in a conclusive manner, that the plant residues in CO_2 enriched atmosphere decompose more slowly than the control plants. De Angelis *et al*. (2000) observed a decrease in the decomposition rate of three Mediterranean species, but the decrease observed is minute and would be undetectable in real conditions. Particularly important is the observation by Coûteaux *et al*. (1991), in the sense that the outcome of CO_2-enriched atmosphere depends on the richness of the animal community of the soil and on the complexity of its trophic web: in soils with a poor community and a simple trophic web, the litter obtained under CO2-enriched atmosphere decomposes more slowly than the control litter, but this result is reversed when the soil contains a varied community and a complex trophic web.

Effects on microbial activity. Positive effects have been observed on microbial activities and on various enzimatic activities (Moscatelli *et al*. 2001), which in theory would lead to greater decomposition activity and therefore to a decrease in the organic carbon content of the soil. The effects, however, appear to be short term; in very few years, normal activity values are regained. This result should be considered with care, because it is practically impossible to separate the direct effects on microbial activities from the indirect effects of inputs of root exudates and other labile forms of carbon from the roots, which also undergo an increase due to the CO_2 increase (which does not last more than a few years, either).

B) Effects of temperature increase

Primary production would increase if there was not a substantial decrease in water availability. For Spain, the models project a medium-term decrease in the production of forests, although this would be accompanied by an increase in litter, due to the decrease in their leaf turnover time (chapter 9). A transect of European pine forests, from Scandinavia to Spain, Berg *et al*. (1999), shows that inputs of litter (of the needles fraction) linearly decreased towards the higher latitude in the range between 48 and 67º N, whereas it decreases again in Mediterranean conditions. In this transect, the drought factor probably reduces inputs into Mediterranean plots.

Increase in decomposition rate. Temperature increase affects decomposition rate more than primary production, and the net result should therefore be a decrease in soil C content (Batjes and Sombroek 1997). Initially, the work with real soils appears to confirm this prediction (see below), although the situation would probably be more complex, because if the temperature increase is accompanied by increased aridity, the decomposition rate should decrease. The results obtained in the VAMOS experiment (Bottner *et al*. 2000, Fig. 8.9) illustrate this prediction: in a transect of forest soils, from northern Sweden to the Valencia Region in eastern Spain, the translocation of organic horizons from North to South (from northern Sweden to southern Sweden and from southern Sweden to England) produced an increase in mineralisation rate, which suggests that in these latitudes, temperature is the main limiting factor. The tendency was inverted, however, in the Mediterranean area: on translocating the soil of England to the S of France and from the S of France to more arid Mediterranean zones (Lleida or Castellón) there was a decrease in decomposition rate: mean temperatures ceased to be the limiting factor for microbial activity, and water availability became the main conditioning factor.

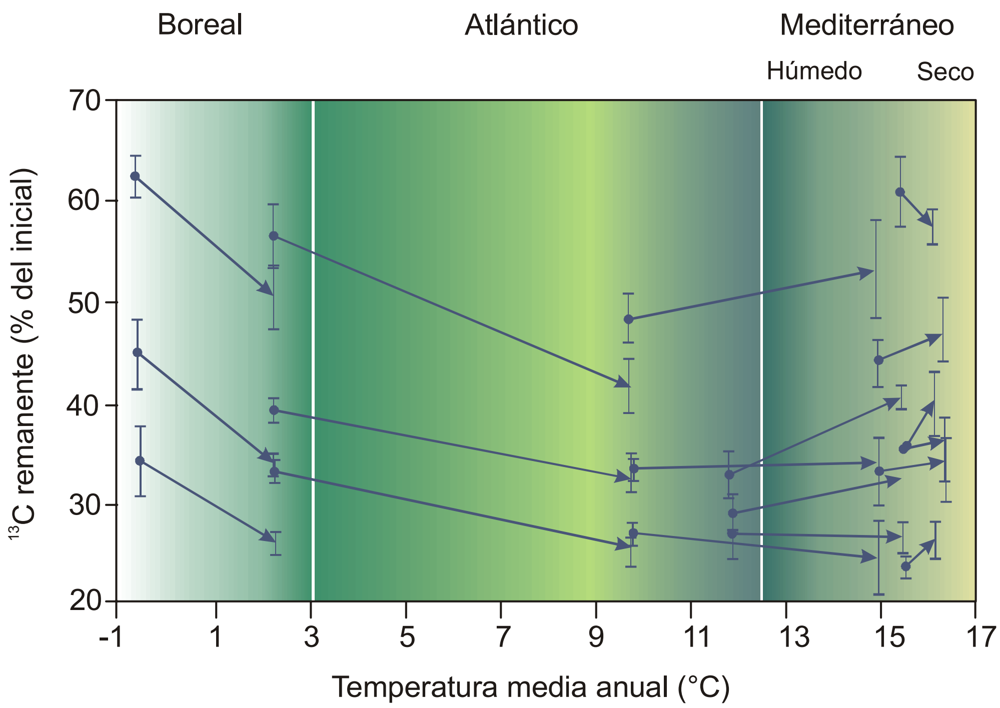


Fig. 8.9. *Labelled residual carbon (^{13}C) in the soil, following incubation, in % compared with the initial for the organic and mineral horizons of pine forests. The arrows connect the two stations subjected to the soil translocation: the origin station (circle) and the destination station (arrowhead), which was always situated further South. It can be seen that, from North to South, within the Boreal and Atlantic latitudes, there is a decrease in the % of remnant ^{13}C, which indicates an increase in decomposition rate. On changing from Atlantic to humid Mediterranean, and from humid Mediterranean to dry, the tendency is inverted, water deficit (and not temperature) becoming the main limiting factor. From Bottner et al. (2000), somewhat simplified.*

In the upper altitudes of mountain areas, icreasing temperatures and no significant reduction in precipitation would enhance microbial activities that would lead to a more rapid breakdown of the soil carbon stores of these soils.

In recent years, simulations have been made of the influence of climate change on the processes regulating soil OC content, based particularly on the determination of emissions of carbon dioxide from the soil in variable conditions of moisture and temperature. Studies carried out in the humid zone (Guntiñas *et al*. 2000) or in the Mediterranean area (Peñuelas *et al*. 2003, en prensa) show that reduced moisture decrease respiration and temperature increase also increase respiration of the soil, the effect of temperature being more evident. In any case, it was also obvious, especially in the Mediterranean area, that there is a soil moisture threshold below which the influence of temperature is irrelevant. We could therefore conclude that the effect of temperature increase as an accelerator of soil mineralisation should be seen in the humid area of Spain, whereas the opposite effect could occur in the Mediterranean. However, any increase in summer precipitation in Mediterranean conditions would have a significant increase of soil OC mineralisation (Sanz *et al*. 2004).

In short, the possible direct effects of an increase in atmospheric CO_2 (increased production, decrease in quality of litter, effects on microbial activity) are doubtful in the medium and long term, and for the time being it is reasonable to rule them out in the prediction. The effects of temperature increase are persistent and more consistent. In practical terms, it is therefore reasonable to focus the analysis on the prediction of these effects at global scale: temperature increase together with reduced rainfall.

Predictions based on computerised models

The CENTURY model is the most commonly used for prediction of OC dynamics, as it is the one that best allows climate factors and a possible change in OC quality to be integrated. We give a few examples of simulations of climate conditions similar to those in some parts of Spain.

Paustian *et al*. (1996) use the model to the simulation of agro-ecosystems in the semiarid continental area of the United States for a 50 years period. The results can be taken as a reference for the more continental areas of Spain (the Plateau). The simulation considers effects forecasted by climate change: increased photosynthesis, decreased transpiration per leaf area unit, increase in tissue C/N, increased allocation of C to the roots. The dynamics of soil OC depends more on land management than on climate change itself. Increased production of agricultural residues is predicted, which will lead to an increase in soil OC.

West *et al*. (1994) apply CENTURY to semi-desert ecosystems in the USA. The predictions could also be valid for the more arid areas of Spain (areas of Andalucia, Murcia, Alicante). In all case, a decrease in soil organic C is predicted, along with an increase in carbonates and in soil erosion. OC loss predicted for the next 40 years is between 1 and 1.25%, for a temperature increase of 2ºC, which is much less than that forecasted for other ecosystems, as we will now see.

Bottner *et al*. (1995) apply the CENTURY model to calculate carbon losses in contrasted Mediterranean conditions. The losses calculated, for a temperature increase 3ºC (without modifying rainfall) n the next century, range from 15% for very arid areas, with precipitation (P) < 100 mm (Cairo, Egypt; Bechar, Algeria), to 20% for cooler areas like Montpellier (France) or 28 % for very humid Mediterranean areas (Ain Draham, Tunisia: P = 1534 mm). These estimations would result in a loss of OC between 5 and 9.3% for each degree of temperature increase. According to the same authors, in Mediterranean conditions, there seems to be a more evident effect of water shortage on soil OC dynamics than of temperature increase.

Research based on the study of climatic transects

The method consists of studying the total organic carbon content of soils in a geographic zone and establishing generic relationships between rainfall and/or temperature and OC content. These relationships can be extrapolated to the forecasted climate change, or to a series of scenarios. A temperature increase is generally assumed, but there are doubts with regard to changes in rainfall.

Álvarez and Lavado (1998) apply this criterion to soils of the Argentine pampas. They obtained a good correlation (non-linear) between total carbon in the soil and the rainfall / temperature ratio (r^2 = 0,693). Using the relationship obtained, they extrapolated the result to a forecasted climate change. The problem lies in the uncertain evolution of rainfall. If rainfall increases, total soil OC may increase; if rainfall does not increase, however, they estimate that a temperature increase of 6ºC (considered the most likely estimate for this zone) will lead to a 45% loss of soil OC, which is around 7.5% for every ºC of increase.

With regard to Spanish soils, the work of Hontoria *et al*. (1999) is the main reference available. Using a database of published profiles, they correlate OC content of the soil with (1) land use, (2) total rainfall, (3) annual temperature and, among other parameters, (4) number of consecutive days in which the control section of soil profile is totally dry (parameter used by the USDA taxonomy to classify soils). The correlations obtained are not very high (< 0.5), which can be attributed to the heterogeneity of climate, parent material, vegetation type, etc. Using the relationships obtained, the authors extrapolated the result to four possible scenarios of climate change (Table 8.3). Of 12 possible situations, only in three cases an increase in OC content is predicted, which would be in the case of an increase in rainfall. The greatest losses of OC are obtained for a decrease in rainfall at the same time as a temperature increase, which would coincide with the most recent predictions. Possible carbon loss in agricultural soils was not calculated, but the percentage should be much lower. It should be observed that the loss is much higher in soils under grasslands, which are usually the richest in OC. Furthermore, in agricultural soils, most of the OC is associated with fine fractions (fine silt and clay), physically protected, and initially much more stable and inert than the OC in the soils of forests or grasslands.

Table 8.3. *Calculated loss of organic carbon in soils of the Iberian peninsula in different situations of climate change. According to Hontoria et al. (1999).*

Climatic Parameter		Vegetation type		
Temperature	Rainfall	Forest	Shrubland	grassland
No change	- 10 %	- 7.8 %	- 5.5 %	- 9.0 %
+ 10 %	No change	- 5.6 %	- 4.0 %	- 6.5 %
+ 10 %	+ 10 %	+ 0.8 %	+ 0.6 %	+ 0.9 %
+ 10 %	- 10 %	- 12.9 %	- 9.1 %	- 14.8 %

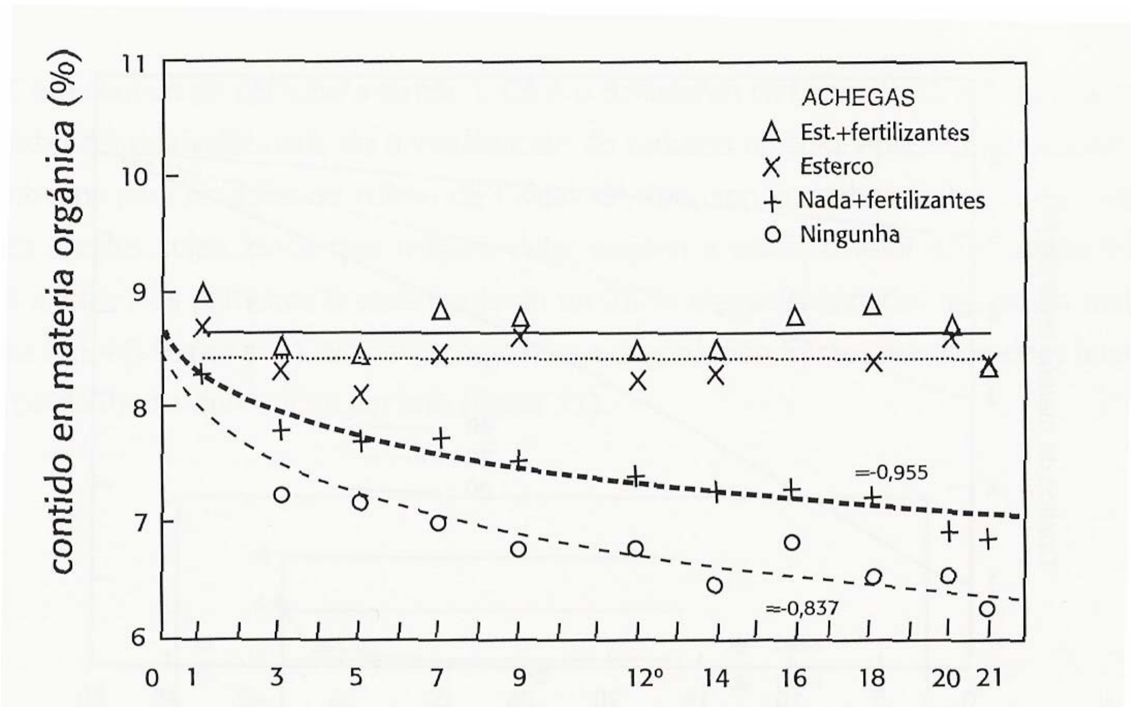
If there is no increase in rainfall, the OC content should decrease at worst by almost 15%. The biggest losses will occur if, besides a temperature rise, rainfall is also reduced. Taking Barcelona (mean temperature: 15.5°C) as an example, we see that a 10% increase in temperature would cause an increase of approximately 1.5ºC. In this case, the carbon loss would be, at worst 14.8 / 1.5 = 9.9 % for each degree of increase. In the case of shrubland, it would be, at worst, 9.1 / 1.5 = 6.1 % for each degree. This result is similar to what was obtained by Álvarez and Lavado (1998) for the Argentine pampas and consistent with the aforementioned calculation by Bottner *et al*. (1995).

The coherence of these three results (Bottner *et al.* 1995; Álvarez and Lavado 1998; Hontoria *et al. 199*9) suggests that a mean value of 6-7 % carbon loss for each degree of temperature increase could be accepted (that is approx. between 3 and 8 Mg C ha^{-1} loss per each degree of temperature increase), and that this value can increase or decrease depending on the change in rainfall and also depending on the characteristics of the soil and land uses.

Climate change can affect the different OC compartments (Coûteaux *et al.* 2000) in different ways, and carbon loss can therefore be distributed unequally in the soil. Contrary to what might be expected, in our soils, the OC of the deep part of the profile is often less stable than that of the top soil. Although the physically protected carbon percentage is higher in deeper soil horizons, it is also relatively richer in carbohydrates and less so in recalcitrant fractions (Rovira 2001). Given that the deep soil is more likely to be able to maintain moisture throughout the summer, it is possibly the carbon from the deep soil horizonsof the fraction that suffers the greatest loss. This is uncertain, however, as Bol *et al.* (2003) recently verified that it is the most recalcitrant and oldest OC fraction that responds most clearly to a temperature increase.

8.3.4. Changes in land use

Changes in land uses and management, along with the occurrence of disturbance, such as wildfires, affect soil OC content. Of great interest, because of its duration, is the study carried out in Pontevedra (Sánchez and Dios 1995) on the evolution of soil OC in a plot of corn subjected to different systems of fertilisation over a period of 21 years. The results (Fig. 8.10) shows how the plot in which organic fertiliser was suppressed underwent a progressive decrease in OC content, which, at the end of the study period, reached 30% reduction. Another study, also carried out in the humid part of Spain, based on the analysis of three soil maps made in different years (1958 1964 and 1997) shows how the soils used for corn, with little or no organic fertilisation, lost 43% of their initial OC content in 39 years. Furthermore, comparison of the mean soil OC content in humid areas of forests or shrubland with croplands of potato or cereal always present a decrease in OC content which is between 30-40% (Calvo de Anta *et al*. 1992). In a Mediterranean area, the OC content of the soil in a pine forest, 9 years after clearcutting, changed from 2.34 % to 1.61%, this loss mainly being due to mineralisation and by less than 1% to soil erosion (Martinez Mena *et al.* 2002).



Years after treatments application

Fig. 8.10. *Evolution of the organic matter content of a soil used for maize in the Misión Biológica, CSIC (Pontevedra, Sánchez and Dios 1995) with different treatments (0 none, + mineral fertilisation, x organic fertilisation, Δ mineral + organic fertilisation). % Organic matter/1.724 = % OC.*

The ploughing of forest soils always leads to loss of soil OC (for example, Fig. 8.11). The figure shows that recovery of the initial levels, in sandy soils as in this case, can be relatively rapid (around 80 years in the abandoned and afforested cereal fields) and even more so when a fast-growing species is introduced (*Pinus radiata* in this case). When the soils have suffered losses by erosion, however (vineyard soils on slopes), the recovery is slower.

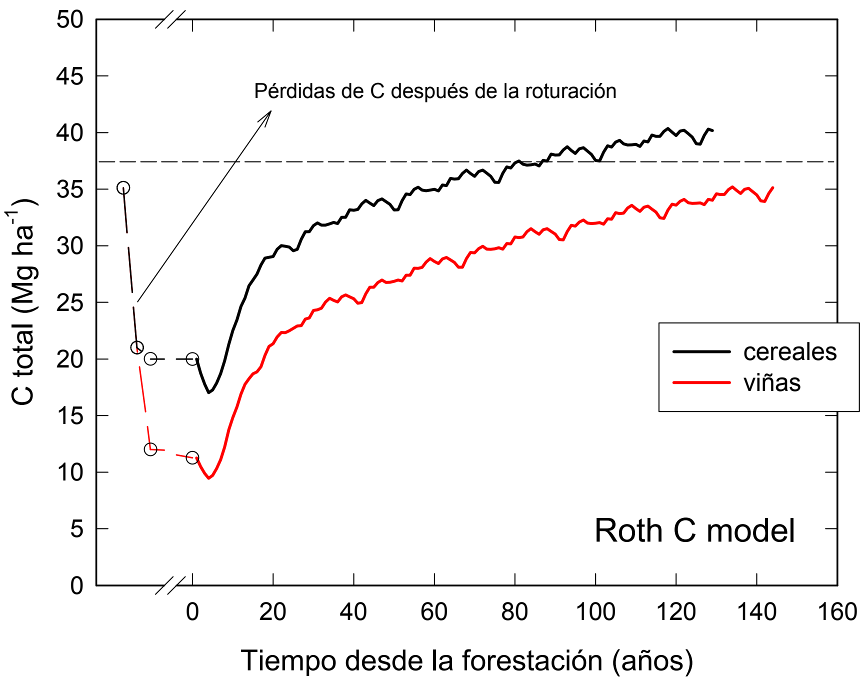


Fig. 8.11. *Changes in soil OC following ploughing and afforestation with Pinus radiata in Mediterranean conditions according to the Roth C model. The broken line refers to the carbon levels of the autochthonous Holm oak forest (Romanyà et al. 2000).*

Lastly, accidental disturbances such as forest fires that may increase as a consequence of climate change (Piñol *et al*. 1998) are likely to cause losses of soil OC content which can range from values of less than 5%, when temperatures are below 170ºC, to higher than 90% when they are over 450ºC (Soto*et al*. 1991) in the top few cm of the soil. During a forest fire, a large amount of CO_2 is released into the atmosphere, but as the affected ecosystem grows again and recovers, the CO_2 is captured and fixed via photosynthesis, and incorporated into the system once again; it can therefore be considered that the medium-term net C balance is zero (Levine 1996), when soil erosion is not significant. During fires, however, changes occur in the dynamics of the organic matter, giving rise to the creation of more degradation-resistant forms and therefore to C sequestration processes in the geosphere (González-Vila and Almendros 2003; González-Pérez *et al*. 2004). This effect can be particularly relevant in regions like the Mediterranean basin, where forest and vegetation fires are a recurring phenomenon. The production of this type of refractory OC in Andalucia has been estimated at up to 31,000 t/year (González *et al*. 2002). As a consequence of the high temperatures generated by the fire, hydrophoby is occasionally created on the surface or subsurface layers of the soil, which reduces water infiltration with the consequent negative effects on surface runoff (which substantially increase up to values of over 20% of rainfall, Soto and Díaz-Fierros 1998) and water content of the soil. In fine-textured soils, especially when the silt fraction predominates, the temporal loss of vegetation cover caused by the fire creates a surface crust which reduces infiltration of water into the soil and increases runoff (and the risk of flooding) (Bautista *et al*. 1996).

In summary, forest fires often produce OC losses in the top soil. These losses may be partly counteracted by the formation of recalcitrant OC compunds during combustion. Plant regeneration may re-establish OC balance in the medium/short-term. Finally, soil physio-chemical changes induced by forest fires may increase soil erosion and runoff, and limit plant recovery.

8.3.5. Synthesis of the effects of climate change in soil OC

Soil OC results from the balance between inputs – input of litter (or organic amendments in crops), including dead roots, and outputs – decomposition (plus lixiviate of soluble OC). In forest ecosystems, litter inputs could increase according to the models estimates (chapter 9), although, on comparing climatic transects of current forests, it appears that drought reduces these litter inputs. Furthermore, in multi-temporal studies of Holm oak forests in Catalonia, litter production is related in a linear and significant way to the net primary production of the aerial part of the forest (Ibáñez *et al*. 1999). In wet conditions (North of Spain), an increase in inputs is to be expected, but in the dry part of Spain, this aspect remains quite uncertain. With regard to decomposition rate, all studies coincide in that it accelerates with temperature increase, unless there are increased drought conditions (Fig. 8.9), in which case the decomposition rate would be reduced. In Mediterranean conditions, soil respiration and OC mineralisation are limited by temperature in winter and by drought in summer (Casals *et al*. 2000, Rey *et al*. 2002). According to the latter authors, a general decrease in soil respiration is to be expected in the climate change scenarios accepted for Mediterranean conditions. The projected changes would therefore cause an increase in decomposition rate in humid Spain and a decrease in Mediterranean Spain.

OC cycling models and studies of climatic transects (Table 8.3) suggest a decrease in soil OC as a consequence of the increase in temperature and drought. The data from the transects are quite consistent, as they are based on direct analyses of soil OC. These data are not compatible, however, with an increase in inputs and a decrease in decomposition rate, assumed in the previous paragraph for the Mediterranean region. We could therefore expect that there would more likely be a general decrease in soil OC content, which in the Mediterranean areas would be determined by reduced litter inputs, with the uncertainty associated with this process.

8.3.6. Effects of climate change on the microbial and faunistic community of the soil

The organisms in the soil are very much influenced by plant cover in general, hence alterations are to be expected in the composition of communities of organisms in the soil in consonance with changes in land uses and those derived from climate change.

Microbial flora

According to Panikov (1999), the microflora is adapted to survive large temperature changes in the soil (day-night changes of tens of degrees in summer; also large seasonal changes) and in water content (great seasonality in the Mediterranean climate); these changes are of a greater magnitude than predicted increases in mean temperature or increases or decreases for rainfall. The direct effects should therefore not be very significant. The results obtained by Moscatelli *et al*. (2001) in Mediterranean soils tally with this prediction: microbial activity exposed to an atmosphere enriched in CO_2 returns to the level of the control soils in barely two years. This could be due to the great redundancy of the microbial community; many different taxa appear to occupy the same ecological niche, competing for the same substrates. Some of these may be favoured by climate change, while others could be negatively affected; in any case, there are always taxa prepared to take over the function of those negatively affected. Even if we assume that microbial diversity would be harmed (which is yet to be proven), it is not clear that this would affect the functioning of the soil in the global ecosystem. This is the result of most of the studies in which the microbial biodiverity of the soil was artificially reduced, through fumigation or irradiation.

With a temperature rise, there is an increase in respiration, but the effect depends on the nutritional state of the soil, and is less evident in oligotrophic soils. The increase in respiration is due to the activity of the microflora, because the temperature increase causes a decrease in microbial biomass (Álvarez *et al*. 1995). In the case of non-agricultural soils, impoverished in nutrients, microbial activity would be less affected by the temperature increase, and it is therefore the soils rich in OC (which also tend to be the ones rich in N and P) which are most threatened.

Soil fauna

As a whole, the effects of climate change on the fauna of the soil are much less predictable than the effects on the stocks of organic carbon. There are quite many studies carried out in microcosms, but the diversity of the results makes it difficult to establish a clear pattern It is usually accepted that an increase in atmospheric CO_2 alone would have little effect on the soil fauna in the soil because this fauna is already adapted to the soil atmosphere which is very rich in CO_2 (Van Veen *et al*. 1991). However, Zaller and Arnone (1997) observed an increase in activity of earthworms in soils subjected to a CO_2 enriched atmosphere. If this were to be confirmed, these results would be of great relevance because of the important role played by earthworms in the maintenance of the natural fertility of soils and in OC dynamics.

Few studies in which soil temperature was artificially raised in field conditions showed an increase in the biomass and diversity of the mesofauna, provided that there was not an excessive decrease in water availability: if this occurs, the effect becomes negative (Harte *et al.* 1996).

Species unable of resisting prolonged summer droughts can be expected to disappear. It is unclear what effects this disappearance can have on the functioning of the soil as a global system. The effect may not be great because the trophic web of the soil is highly redundant, with a number of species much greater than what is needed for the efficient functioning of the biogeochemical cycles (Freckman *et al*. 1997). In any case, the simplification of the animal community of the soil should provoke the acceleration of biogeochemical cycles, because a rich and complex trophic web reduces the intensity of OC decomposition, due to the depredation the decomposing organisms are subjected to (bacteria, fungi, actinomycetes) by micro- (protozoans, nematodes) and mesofauna (microarthropods) (Setälä and Huhta 1990, Scheu and Wolters 1991).

8.3.7. Soil fertility

As a result of the intensification of agriculture and of the changes in land uses that have occurred since the middle of the XX century, the fertility of European soils is currently in a dichotomy. Whereas the intrinsic fertility of agricultural soils at present has decreased (see for example the generalised loss of OC in English soils, Ministry of Agriculture Fisheries and Food, United Kingdom) forest soils, resulting from the abandonment of agriculture, recover fertility and physical properties, with an increase in OC concentration in the surface horizons (Romanyà *et al*. 2000), provided that the climatic conditions of the site have permitted sufficient recovery of the vegetation. In semiarid climates, it is frequent that the quality of abandoned soils has been insufficient to sustain the development of a minimum plant community and to initiate a recovery process. In these cases, a spiral of soil degradation would be initiated which would not allow for the autogenic recovery of soil fertility. Furthermore, in the case of old forest soils, there may be a general increase in nutrient demand as a result of the increase in atmospheric CO_2, which will depend on the species considered (Peñuelas *et al*. 2001). This differential increase, according to species, in the demand for nutrients, may, on one hand, determine the future composition of ecosystems, and on the other, reduce the quality of the litter produced. With regard to nitrogen, changes in atmospheric deposition, in some cases associated with pollution, could counteract the increased demand by the vegetation.

In this section we discuss aspects of atmospheric pollution not directly linked to climate change but that may strongly affect the impacts of climate change in the soil fertiliy. Atmospheric deposition have increased the nitrogen input to ecosystems throughout the world in general. This effect is the result of the increase in nitrogen oxides in the atmosphere caused by industry and transport activities and to intensive agriculture and livestock farming (Vitousek *et al*. 1997). In the Mediterranean, these increases have also been noteworthy, although in the last 15 years, according to data from the Montseny area (Barcelona), they have remained relatively constant, between 15 and 22 kg N ha^{-1} $year^{-1}$, whereas in the same period, sulphur has decreased (Rodà *et al*. 2002). Other measurements taken in Mediterranean areas further away from the large urban concentrations have provided values of atmospheric inputs of between 3 and 10 kg N ha^{-1} $year^{-1}$ (Bellot J. and Escarré 1991, Moreno and Gallardo 2002, Sanz *et al*. 2002). The highest values include wet and dry deposition (Sanz *et al*. 2002). The studies carried out in the Atlantic areas of Spain present higher minimum values than in the Mediterranean and maximum values that coincide with Montseny (from 11 to 22 kg N ha^{-1} $year^{-1}$; Amezaga *et al*. 1997; Fernández-Sanjurjo *et al*. 1997). Camarero and Catalán (1993) found less acidity and less nutrient deposition in rains of the Pyrenees, compared to the Alps, with greater nutrient deposition in the rainier areas. In more recent studies, apart from greater inputs of N and of organic pollutants in the rainier areas of the Pyrenees, coinciding with the higher altitudes (Carrera *et al*. 2002) and along the crests, signs of significant inputs of potentially toxic elements have been found both in soils and in sediments (McGee and Vallejo 1996; Camarero *et al*. 1998).
The low concentration of atmospheric inputs measured in the Sierra de Gata mountains (6 kg N ha^{-1} $year^{-1}$) contribute positively to the nutrition of deciduous oak forests in the area (Moreno and Gallardo 2002), although inputs of other nutrients like S and Zn are greater than the demand of the forest. Due to the high production rates of Atlantic forest and meadow ecosystems, it seems reasonable to think that the moderate inputs of N in some of these areas (20 kg ha^{-1} $year^{-1}$) could be partly absorbed by the vegetation. Even in the case of quite unproductive ecosystems, for instance the heaths of *Calluna vulgaris* in the NW of the Peninsula, it has been seen that the vegetation is capable of recycling amounts of N greater than those deposited by the atmosphere (Marcos *et al*. 2003). Mediterranean Holm oak forests are able of internally recycling the highest amounts of N in atmospheric deposition measured in Spain (20 kg ha^{-1}). Given that the growth rate of the Holm oaks is not sufficient to consume all this N, it seems that much of the deposited N is temporarily retained in the soil (Rodà *et al*. 2002). The more long-term fate of this N in these Holm oak forests remains unclear. In Mediterranean shrublands, N mineralisations have been measured of between 20 and 40 kg ha^{-1} $year^{-1}$, whereas in dry grasslands, mineralisation is clearly higher (40-70 kg ha^{-1} $year^{-1}$; Romanyà *et al*. 2001). These data suggest that in Mediterranean shrublands, atmospheric deposition can double the amount of available N, and can therefore lead to big changes in the nitrogen dynamics. In agricultural ecosystems, the inputs of atmospheric N, although it may be lower than the demand of most crops, could contribute to overfertilisation.

Given that the atmospheric deposition of phosphorous is very low (Vallejo *et al*. 1998), the atmospheric inputs of N may result in a greater relevance of phosphorous limitation in terrestrial ecosystems. There is quite a lot of evidence of a general limitation of phosphorous in Mediterranean forest ecosystems, at least for carbonated soils (Vallejo *et al*. 1998). Analysis of tree nutrition in the forest inventory of Catalonia, using the DRIS system, indicated a generalised phosphorous deficit in the pine forests of regions dominated by carbonated soils (Serrano, unpublished data). Furthermore, fertilisation tests with forest seedlings on carbonated lutites have also shown a positive response of phosphorous nutrition to fertilisation with sewage sludge (Valdecantos 2001). In Atlantic forest soils, the availability of P also appears to be a key factor in the nutrition of plantations of *Pinus radiata*, especially in soils with very acidic pHs (Romanyà and Vallejo 1995; Sánchez-Rodríguez *et al*. 2002; Romanyà and Vallejo 2004). The increased availability of nitrogen associated with atmospheric pollution could result in increased demand for phosphorous, thus exacerbating the deficit of the latter. Furthermore, both the high levels of available nitrogen and the lack of phosphorous could hinder N_2 fixation (Binkley and Giardina 1997) and therefore favour the development of non-N fixing plants.

With regard to the possible impact of pollutants, using the Pantanal model (MicroLEIS DSS; de la Rosa *et al*. 2004) and assuming a foreseeable climatic disturbance for the year 2050, it was seen that the risk of diffuse pollution in soils in Andalucia, resulting from the use of nitrogen and phosphated fertilisers, heavy metals and pesticides, increases in 60% of the soil surface, whereas it decreases in 40% of the area. The former soils are located on the coast of Cadiz and in the highlands of Jaen. The soils in which the risk of pollution decreases are located mainly in the lowlands of Cordoba, the Huelva and Malaga coasts, and in the best agricultural areas of the province of Seville. Considering each type of pollutant separately, the risks constituted by heavy metals and pesticides are proportionally greater than the risks caused by the use of fertilisers (de la Rosa *et al*. 1996).

8.3.8. Impacts on the physical degradation of the soil and soil erosion

The physical properties of the soil can be particularly altered by certain types of land management and by fires, and in general by the loss of OC, which is an essential factor of soil structure. The degradation of the physical properties may lead to soil sealing and surface crusting, compaction, incresed hydrophoby of soil surface, loss of structural stability, decreased infiltration capacity (which exacerbates drought conditions) and increased stress through cracking in vertisols.

In conditions of climate change, mean rainfall can be expected to decrease, and extreme events can be expected to be much more frequent. This could bring about a dangerous increase in soil erosion in vast areas of the country.

Considering the EC climate scenario for the year 2050, the risk of erosion of the EU's agricultural soils is expected to increase by 80% (UNEP-EEA 2000). This increase would mainly be in the areas that already present a severe risk. According to the same sources, a 20% increase is expected in relation to the agricultural area in Spain threatened by a very high risk of erosion, whereas the areas with high and moderate risk levels would decrease by 8 and 19%, respectively.

The influence of rainfall on the erosivlity of soils can be estimated by using factor R of the USLE model, or with the use of more simple relationships that base the estimate on monthly or annual rainfall values (Renard *et al*. 1994). Nearing, *et al*. (2004), applying the WEEP model to soils characteristic of the USA, determined that for each 1% increase in annual rainfall, there is a 2% increase in surface runoff and that erosion increases by 1.7%. The lower sensitivity of erosion than runoff to change is due to the fact that the soil is protected by the increase in aboveground biomass, resulting from increased rainfall. Rainfall intensity is also expected to increase in accordance with the intensification of the hydrological cycle which is expected to cause global warming.

Furthermore, as a consequence of the increase in temperatures and in summer drought predicted for Mediterranean areas, it is believed that there will also be a greater incidence of forest fires, and the changes that these will cause in relation to the soil erodibility and vegetation protection of the soil will therefore be added to those generated by the increased erosivity due to rainfall. At the same time, the decreased soil OC content will also have the same effect, that is, increased soil erodibility (factor K of the USLE).

In the case of Andalucia, making use of the Raizal model (MicroLEIS DSS; de la Rosa *et al*. 2004) and assuming a foreseeable climatic disturbance for the year 2050, it was found that the risk of water erosion increases in 47% of soils, although it decreases in 18% of the soils in other areas. The former soils are located in the Northeast of Almeria, the northern mountains of Cordoba, the Northwest of the Granada province and southern Jaen. The soils in which the risk of erosion decreases are mainly located in the southern mountains of Cordoba, the centre of the province of Granada and northern Jaen, and in the best agricultural areas of the province of Seville (de la Rosa *et al*. 1996). However, land use change as a response to climate change may significantly modify erosion impacts, e.g. through the introduction of new crops and new management practices, or promoting land abandonment.

Table 8.4. *Summary of the results of the evaluation of erosion risk in Andalucia, for the present climate situation (1961-1990) and for the climate disturbance predicted for the year 2050 (temperature increase and reduced rainfall). Source:* de la Rosa *et al. (1996)*

Type of vulnerability	Present scenario		Change scenario	
	km^2	%	km^2	%
V1. None	4253	5	4253	5
V2. Very low	3906	4	6219	7
V3. Low	14643	17	13285	15
V4. Moderately low	13918	16	12963	15
V5. Slightly low	5177	6	5247	6
V6. Slightly high	21219	24	20952	24
V7. Moderately high	10573	12	5826	7
V8. High	7887	9	12569	14
V9. Very high	4925	6	3560	4
V10. Extreme	773	1	2400	3

The application of the suppositions of climate change in chapter 1 of this report to the estimate of erosion risk using the USLE, in the Valencia Regional Autonomy (Fig. 8.12 and 8.13) only produces moderate increases in the risk of extreme erosion, by between 5 and 6%.

Separate consideration should be given to the changes in uses and vegetation types that could be caused by climate change. Changes in uses, particularly when they evolve from forest and shrubland to intensive cropping, have a clear negative effect in relation to risks of soil erosion. In addition, the predicted tendencies of change towards enhanced Mediterranean-type features in forest and shrubland would clearly influence the risk of fire, which would logically increase.

Finally, with regard to the series of processes of physical degradation of the soil (e.g. compaction), it ought to be pointed out that maintaining therein OC levels higher than 2.3% is the best method of protection against this type of degradation. If we consider that this soil OC threshold is practically equivalent to a carbon content 8 $kg.m^{-2}$ and that many Spanish soils are below this value (Figure 8.7) we could conclude that the risk of physical degradation of the soil should increase according to the expected decrease in soil OC due to climate change.

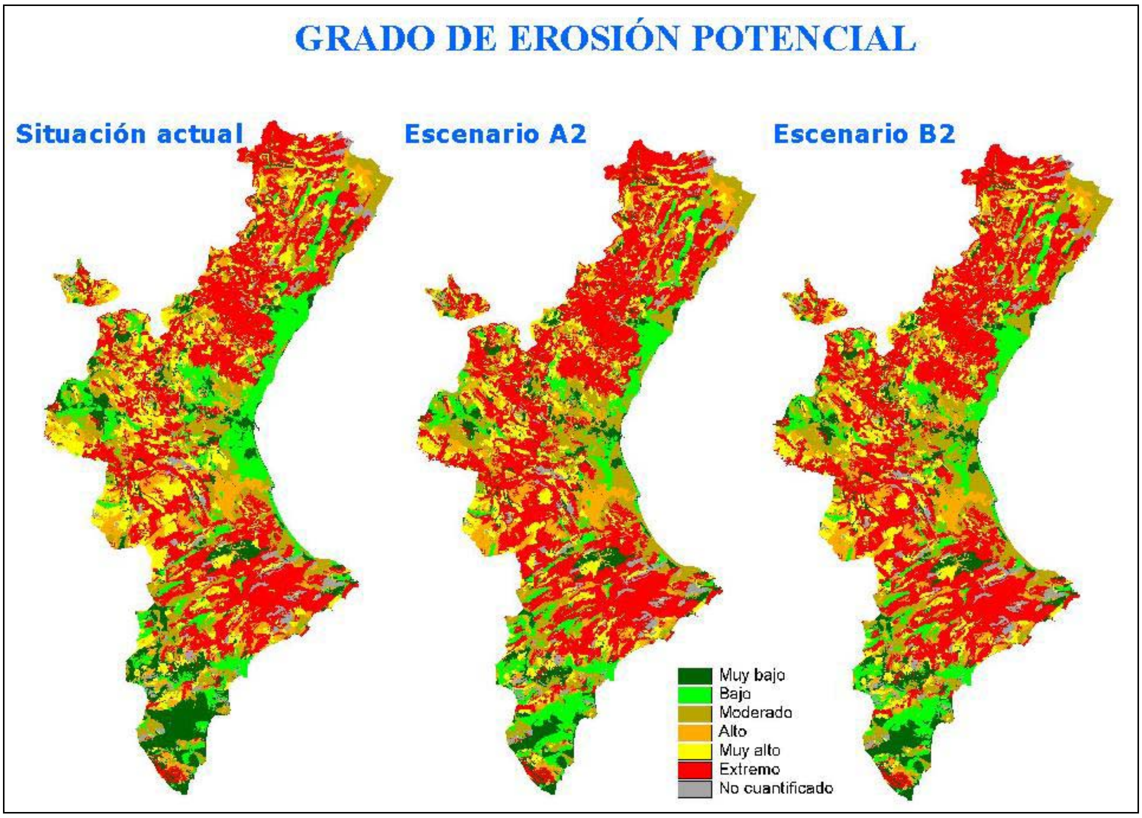


Fig. 8.12. *Estimation of the degree of erosion according to the predictions of climate change for the Valencia Regional Autonomy. Factor R has been modified (erosivity of rainfall in USLE model) in accordance with the predictions of changes in rainfall regime.*

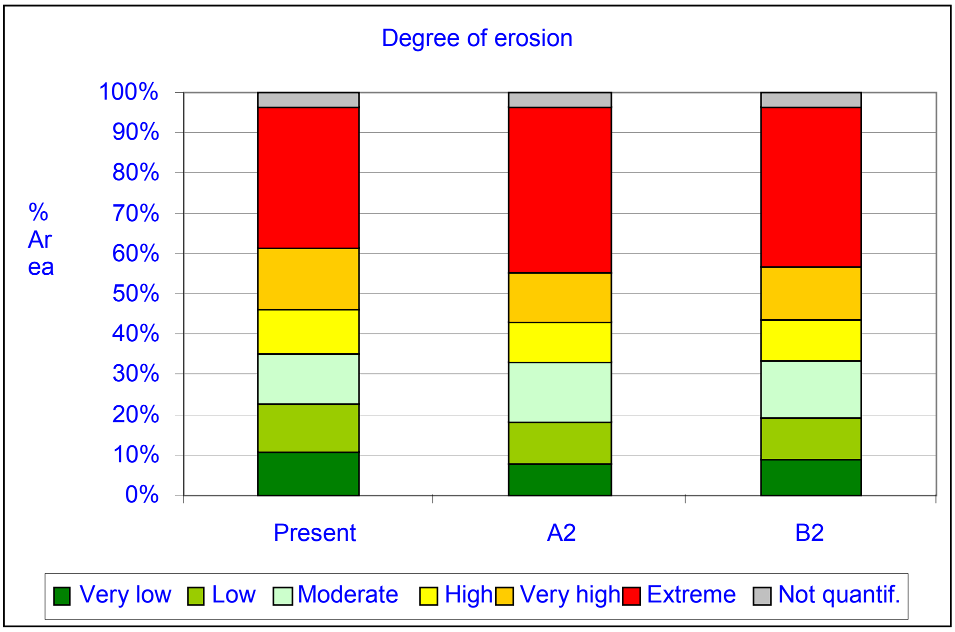


Fig. 8.13. *Percentage of area affected in the Valencia Regional Autonomy by different degree of soil erosion (data from Fig. 8.12) for socioeconomic scenarios A2 and B2. The area affected by the "extreme" degree would increase by between 5 and 6%, whereas the set of degrees "high + very high + extreme" would only increase by 2 %.*

8.4. MOST VULNERABLE AREAS

The most vulnerable areas are those that are most affected by processes of desertification (Fig. 8.3, 8.4 and 8.5, including the predicted increases in forest fires, chapter 12), which are expected to be accentuated in the assumed increases in aridity of the climate.

With regard to the change in OC content, the areas in which the greatest losses are to be expected would be the more humid ones (North of Spain) as well as the land uses that promote higher soil OC contents (meadows and forests). In the driest areas, small OC losses may drive crossing critical thresholds for the maintenance of essential soil functions.

8.5. MAIN ADAPTATIONAL OPTIONS

In relation to the possibilities of improving carbon fixation, the measures considered by the IPCC include: crop management aimed at producing greater C inputs to the soil, irrigation management, conservation agriculture, erosion control, ricefield management, grazing management, increased productivity of pastures, fire management in pastures, forest regeneration, restoration of old wetlands and restoration of very degraded soils.

8.5.1. Influence of agricultural practices

The sustainable land use and management systems have great potential for carbon sequestration in agricultural lands by means of the reduction of soil organic carbon losses and increased biomass production (Lal and Kimble 1998). It is estimated that farmed soils contain, in general terms, between 20 and 40 % less OC than unfarmed ones (Davidson and Ackerman 1993). The loss of OC in agricultural soils can be recovered by means of the application of appropriate management practices (Lal *et al*. 1998). According to estimates by the FAO (2002) for the year 2030, the amount of OC fixed in agricultural soils, as organic matter from crop residues and manure, may increase by 50% if the corresponding management practices are introduced. OC lost from the onset of agriculture is estimated between 40 and 90 Pg C (Raupach *et al*. 2003). Annual rate of OC recovery through changes in agricultural management could be of the order of 0.3 to 0.9 $PgC \cdot y^{-1}$ (Lal 2004, Smith 2004). Therefore, some 50 to 100 years will be required to compensate those OC losses, in the better possible scenario.

With regard to land use type, the best fit between the potentialities and limitations of the different soils, and the soil requirements of the possible crops, should be attained. To this end, agro-ecological zoning constitutes a previous and indispensable study in any area or region. The diversification of crops will be conditioned by these studies of spatial variability of soils and climate. In turn, the detailed segregation of vulnerable or marginal areas for agriculture will be a consequence of agro-ecological zoning.

Agricultural management has a significant influence on the amount of carbon stored by soils over time. Certain changes in agricultural practices can determine how much and how fast carbon is stored or released by soils (Ringius 1999). The environmental sustainability of agricultural practices, adapted to the agro-ecological conditions of each area, refers especially to the following aspects: restoration of the soil organic matter content, intensity and direction of tilling, consideration of soil moisture for each operation, type and weight of the machinery to be used in order to avoid compaction, and rationalisation of the use of fertilisers and pesticides.

Agriculture adapted to each soil type, placing particular emphasis on maximising the production of crop residues, to be incorporated into the soil, and on reducing and diversifying tilling, will facilitate the sequestration of soil OC, along with all the other associated benefits relating to physical, chemical and biological soil properties. Furthermore, the maximum use of crop residues is a very efficient method of erosion control. Conservation agriculture (reduced tilling with recycling of crop residues in the form of mulching) is very effective for controlling erosion and also involves considerable savings on fuel. These practices are slowly but steadily expanding in Spain.

In the recovery of degraded soils, the level of carbon sequestration can serve as an indicator of this recovery: thus, if degradation decreases, sequestration increases, and vice versa. In semiarid areas of the world, it has been estimated for the next 50 years that if effective conservation and soil rehabilitation measures are implemented, an annual carbon sequestration rate will be reached between 1.0 and 1.3 Gt per year (Squires 1998). Fig. 8.14 shows the distribution of agricultural soils with ochric epipedon, the properties of which would be improved with the addition of organic amendments. The ochric epipedon is defined by properties that are initially associated with OC content (Soil Taxonomy), such as a more or less dark colour and structure. There are, however, agricultural soils with ochric epipedon in northern Spain which have high OC contents, which means that in this case properties are not necessarily improved by adding organic amendments.

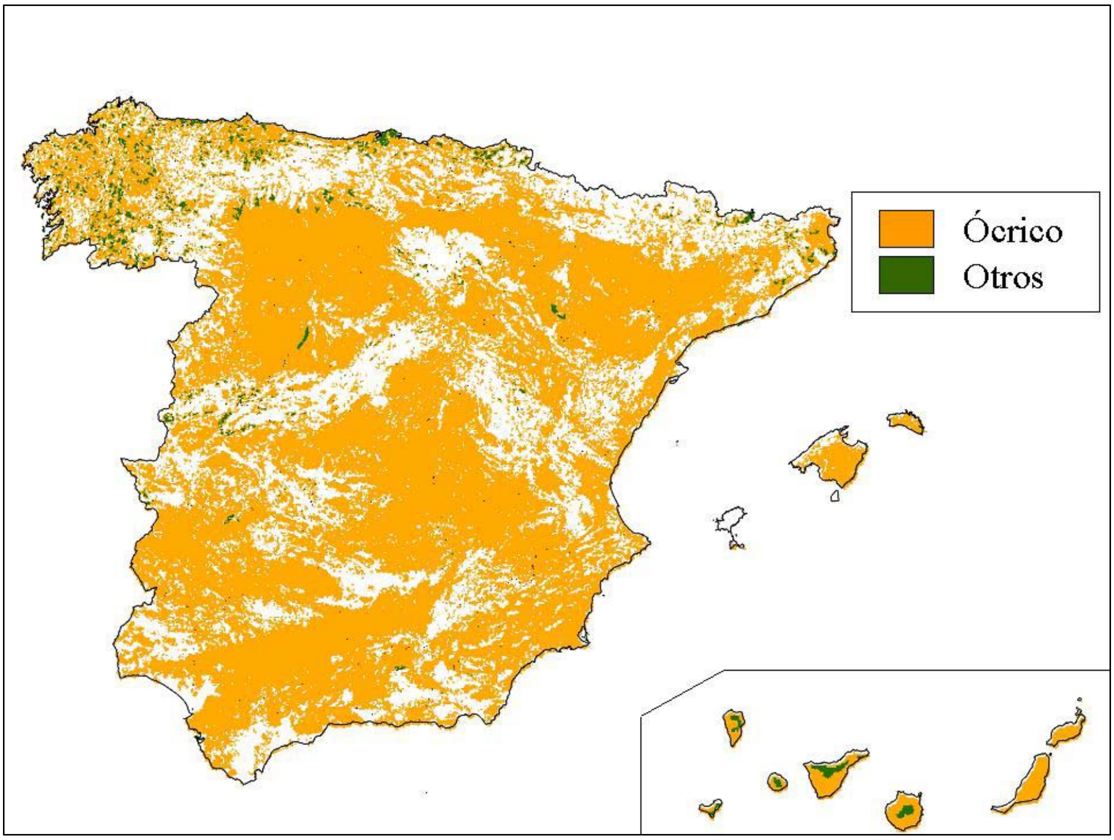


Fig. 8.14. *Agricultural area on soils with ochric epipedon the quality of which could be improved with the addition of organic amendments (96 % of the area used for agriculture in Spain). Map based on cartography of land uses CORINE from 1991 and from the IGN soils map from 1992.*

8.5.2. Abandonment of croplands

At the present time, both the structure and the dynamics of Mediterranean wildlands bear the effects of old land uses. The large areas occupied by colonising vegetation, basically in abandoned agricultural areas, have led a great amount of our forest soils to aggradation phases, whereas in areas in which forest productivity is severely limited (for instance in areas with a high recurrence of forest fires or in semiarid climates) degradative processes can prevail.

Abandoning unproductive croplands provides the opportunity to increase carbon sequestration by turning them into forest or shrubland. In semiarid climates, however, abandonment can lead to greater degradation if the restoration of the ecosystems is not managed. In dry sub-humid Mediterranean climatic conditions, the greater production of vegetation biomass and fuel favours the spread of forest fires. The abandonment of crops therefore provides management possibilities for counteracting the impacts of climate change and also for avoiding the degradation of abandoned lands.

8.5.3. Afforestation/reforestation

One of the main objectives of the afforestation plans of Mediterranean countries is soil protection. Indeed, large forest restoration projects have been documented in Spain since the end of the XIX century, aimed at protecting basins that were frequently flooded (Gómez 1992).

In early stages of succession, soil is a critical factor that controls the development of ecosystems (Bradshaw 1997). In situations in which soil cover is very low (less than 30%), a cycle of degradation can be initiated. In these situations, actions should be implemented aimed either at directly improving the soil (application of organic amendments, mulching) and/or at introducing herbaceous or woody species (sowing, plantations, introduction of mycorrised plants) which, through synergy, can reverse the soil degradation process (Vallejo *et al*. 2003). Revegetation is the most efficient means of controlling soil degradation in barren lands. The insufficient availability of water characteristic of the Mediterranean climate could be exacerbated in a context of degraded soils, which favours the formation of a surface crust (Maestre *et al*. 2002) and loss of structure (Caravaca *et al*. 2002) of the soil, which hinder infiltration and the capacity to retain water. In agricultural soils the formation of the surface crust can reduce the productivity of the crops (Amezketa *et al*. 2003). For these reasons, both the agricultural management of Mediterranean soils and projects aimed at the restoration and recovery of degraded soils focus at improving the physical properties of the soil (Caravaca *et al*. 2002, Bellot *et al*. 2001, Querejeta *et al*. 2000). However, inappropriate restoration practices could result in deletereous effects on soil quality and conservation.

Introducing determined species is known to favour soil conditions. On occasions, these species can even facilitate the establishment of other species within their area of influence (facilitation) (Pugnaire *et al*. 1996, Maestre *et al*. 2001, Castro *et al*. 2002, Caravaca *et al*. 2003a). The joint use of organic amendments with the introduction of plants has facilitated the recovery of the vegetation and, finally, has contributed to improvement of the soils. In some cases, it has been seen that the introduction of target organisms (e.g. inoculation of mycorrhiza) can slightly improve the results of applying only organic amendments, with regard both to the growth of the plants and to soil quality (García *et al*. 2000, Caravaca *et al*. 2002, Caravaca *et al*. 2003b).

Macías *et al*. (2001) have demonstrated the efficiency of revegetation with fast-growing species (eucalyptus) in C sequestration in quarry spoils.

8.6. REPERCUSSIONS FOR OTHER SECTORS

As the soil is the basic support of primary production, the degradation thereof will have a considerable impact on the functioning of terrestrial ecosystems, including agriculture, livestock farming and forestry production sectors. Furthermore, when the degradation is severe, it becomes irreversible, and huge investments of energy are required to recover the productivity of the soils. Apart from the direct impact on terrestrial ecosystems, soil degradation in the form of erosion, sainisation or pollution can have negative impacts on other systems, such as continental waters (siltation in reservoirs, for instance) and public works.

8.7. MAIN UNCERTAINTIES AND KNOWLEDGE GAPS

Most of the analyses made throughout the chapter present a varying degree of uncertainty. Table 8.5 summarises the degree of reliability of the impacts.

Table 8.5. *Synthesis of the foreseeable direct impacts of climate change on soils and associated degree of reliability. (vr): very reliable, (ir): intermediate reliability, (i): uncertain. (u); + : the impact involves an increase; -: the impact involves a decrease; 0: no significant effect is expected.*

Variables associated with climate change	Organic carbon content	Soil erosion	Salinisation	Microflora and fauna biomass and activity	Fertility
Increase in CO_2	+ (u)	-(u)	0 (vr)	0 (ir)	- (u)
Temperature increase	- (vr)	+ (u)	+(vr)	- (u)	+ (u)
Increased drought	- (vr)	+ (vr)	+(vr)	- (ir)	- (u)

Apart from the uncertainties associated with climatic and socioeconomic projections, in direct reference to soils, we can highlight:

- The impacts of climate change on soils interact in a very significant way with land uses and management. These interactions, along with the evolution of the socioeconomic factors that will regulate the types of use and management practices, constitute big uncertainties.
- Many basic studies used to estimate the impact of climate change on the production capacity and the risks of degradation of soils have been carried out in other countries in similar conditions. The degree of applicability of these observations to the conditions of Spanish soils is therefore uncertain.

8.8. DETECTING CHANGE

In Spain, there are not many studies that can provide data on the soil processes associated with climate change, although the possibility exists of analysing and interpreting certain historic soils archives, which could provide valuable information on the change tendencies of soil OC contents. Data are available from the years 1940-50, when cartographic studies of soils were carried out at a scale of 1:50.000, showing sampling sites and tabulations of OC contents. Subsequently, around the 60-70s, other soil cartography studies were made (e.g. the agrological maps by MAPA) which also present sampling and tables of data on Spanish soils. Finally, in the 90s, the LUCDEME Project designed systematic cartography of Spanish soils in the Mediterranean semiarid area. If we add to this the innumerable local or regional studies from the last fifty years, we would have a great deal of data, which, duly analysed and processed, could provide valuable information on the change tendencies of soil OC content under different climate conditions and types of use and management. The network of permanent experimental stations (RESEL, Rojo and Sänchez 1996) run by the Environment Ministry, is a very useful initiative in this sense.

Suggestions for improving follow-up

There are abundant local databases of soil characterisation, referring in particular to the results of agricultural analyses. The difficulty lies in their dissemination, their inaccessibility and that the format of the data will be heterogeneous and hard to compute. The homogenisation of this information would be of great value for increasing our knowledge of Spanish soils. To this end, the use of universal databases is recommended, such as the FAO-CSIC (2003) database, SDBmPlus: Multilingual Soil Profile Database, for the collection of information on soil profiles (data and metadata).

There are no sufficiently old and continuos studies for monitoring aimed at establishing tendencies of soil evolution or soil degradation. There exists, however, a contrasted experience dealing with the application and validity of different models that predict erosion with the use of climatic, soil and land use parameters, such as the models USLE, RUSLE, EUROSEM, LISEM, KYNEROS, WEPP, etc. To this end, knowing the expected evolution of these parameters in conditions of climate change, it would be possible to make predictions of erosion with a reasonable degree of certainty. Greater attention should therefore be paid and support given to the few long-term experiments existing in Spain, and to the maintenance of the collections of soil samples.

In relation to soil OC monitoring, the complex interactions between the effects of climate and land use change, together with the intrinsic spatial heterogeneity of soil OC, make the detection of changes very difficult, especially those related to climate change which are expected to have slowlier impacts. Therefore, the detection of change in soil OC would require long-term approaches, and the stratification of permanent sites both considering climate and land use gradients. Sampling intervals of at least 10 years would be requiered for monitoring climate change effects, although changes in land use require much shorter intervals. Long term monitoring of permanent sites should not only considering soil OC, but also all other surrogated soil properties so to allow the understanding of OC dynamics and its influence on other relevant soil functions.

To face the challenges associated to climate change impacts in the soil resources, we need tools allowing to detect changes and to make projections and scenarios in order to develop decission suport systems that may facilitate preventing impacts. Next we suggest selected measures following and completing the suggestions made by The European Strategy for Soil Protection:

– Basic soil information. This information is critical for the applications of predictive models for future scenarios

- Soil map at an appropritae scale, e.g.1:50,000
- Soil profiles data bases linked to the cartography. This will require collecting extant information which is scattered in different institutions.
- Historic temporal series. The collection of data bases may help to identify hitoric soil series that could be useful to characterise changes.

– Improving follow-up

- Existent permanent experimental sites should be maintained, especially those covering longer time periods.
- To identify new sites combining factors that are not sufficiently represented by the existent experimental sites.
- A more ambitious network of sites or plots should be considered for soil OC monitoring. Temporal and spatial scales for detecting changes should be further onsidered
- In areas susceptible to salinisation and sodiufication, the follow-up of the following parameters is recommended:
    - Electrical conductivity as an indicator of salinisation.
    - Sodium absorption ratio (SAR) as an indicator of sodium enrichment.

- Soil erosion monitoring. Given the difficulty and high economic cost of soil erosion monitoring, the proposed approach is base on indicators and modelling.
    - Cartography of the observable evidences of soil erosion in order to produce risk categories by area.
    - Continued measurements of sediment transport in the microcatchment gauging.
    - Measurements of sediment deposition in reservoirs, ponds and lakes. Considering that soil erosion is very variable in time and in space, erosion measurements should be continuous. Long term measurements, for example 10-year periods, can be used to obtain mean values.
    - The area subjected to erosion risk is proposed as an indicator of soil erosion.
    - Callibrating and validating require measurements of the real erosion rates in the field. It is recommended that first utilise the existing experimental stations, and only to raise the number of stations in places where there are insufficient data.
    - Selection of experimental stations (plots and catchments): the areas selected should present a moderate or high risk of erosion and be representative of an agro-ecological zone.
    - Interpolation of results from local measurements to large areas, in order to evaluate the state of soil erosion in areas for which no data are available, while the local factors affecting soil erosion are analysed in detail.
    - Analyses of scenarios aimed at predicting soil erosion under conditions of different land uses and/or of climatic change.

8.9. IMPLICATIONS FOR POLICIES

The soil phsically supports most of human activities. Therefore, it is unavoidable the confrontation of various interests and uses on the soil resources. Dealing with this complexity is not an easy task, however new approches are progressing on the basic recognition of the necessity of integrating environmental elements in the land use policies, in the framework of a sustainable development. This is refelected in the elaboration of The European Strategy for Soil Conservation that would provide the basis for the development of European regulations on soil conservation and sustainable use of soil resources.

According to the preparatory documents for the European Strategy, land planning is a key instrument for soil conservation. The last report emphasises that soil quality should be considered in any development plans or reclassification of land uses. At present, a large amount of our best quality soils are disappearing as a result of sealing (construction) in periurban areas of the big conurbations.

The Common Agricultural Policy (CAP), through agro-ecological measures, promotes sustainable management practices applied to agricultural soils. In the recent past, it has also promoted the abandonment of marginal croplands and the reforestation of these (Reg. 2080/92 and 1257/1999), with an environmental objective in mind (complementary to the primary objective involving the maintenance of profitability in the agriculture sector). The CAP reform offers possibilities to improve the conservation of soils and to increase carbon fixation.

The Spanish Forestry Plan and those of the regional autonomies are incorporating carbon sequestration into their objectives.

8.10. MAIN RESEARCH NEEDS

In Spain, there has been no generalised and continuous activity of soils description and characterisation. This lack of basic information on the geographic variability of soils is particularly evident in any attempt to specify the impacts of climate change. Long-term basic studies should therefore be promoted in order to attempt to detect the evolution tendencies of soils and the responses of these to disturbances and climate change, especially in relation to low-periodicity events. An initial basic need with regard to soil resources is the inventory of soils at an useful management scale (at least 1:50,000), with which to establish an evaluation of their condition, plan management and project change tendencies.

New studies for the survey, evaluation and monitoring of soils would place particular emphasis on selected indicators of soil quality, such as hydric properties (for example, S-theory, Dexter 2004).

With regard to the effects of climate change on soil OC, studies are needed to jointly analyse the effects of increases in atmospheric CO_2 and changes in temperature and rainfall. In relation to mitigation measures, research should be reinforced in the use of organic amendments and the impact of their quality, combined with other soil management techniques, to increase soil OC sequestration, considering the implications and role of soil biological activity and diversity.

Research is needed into computerised systems aimed at facilitating the transfer of information and knowledge of soil resources to politicians and direct users of the territory, both for present scenarios and for those of climate change. Support decision systems in the planning of land uses, along with the formulation of management practices adjusted to each soil type (for example MicroLEIS DSS, de la Rosa *et al*. 2004), are now a reality, and offer extraordinary possibilities for application and adaptation.

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