C sequestration issues in the Mediterranean soils

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Summary

The Mediterranean region has distinct characteristics resulting from its climate, land use history and landforms that may largely affect soil C balances. In this paper we present data on C storage in Mediterranean soils and how it can be affected by changes in land use and fire. We also discuss the sensitivity of organic matter levels in Mediterranean soils to land use and management in order to set the basis for increasing C sequestration in the Mediterranean.

Introduction

The Mediterranean region has suffered a long and secular exploitation of its natural resources and consequently human pressure has intensely changed plant cover and soils since ancient times. Drought periods and heavy rainfall events are typical in the Mediterranean area since before the glatiation times. Low ecosystem productivity is another generalised characteristic of the Mediterranean areas, with a potential productivity often below 4,5 m^3/ha/year (Gandullo and Serrada, 1977). These climatic characteristics combined with the complex geomorphology of the Mediterranean area and with the millenary and intensive land occupation have given to the Mediterranean soils and landforms a high diversity (Ibànez et al., 1995) and have resulted in widespread reduction of soil organic matter content. However, the large scale agricultural land abandonment, afforestation plans, and natural plant regrowth that have been taking place since the second half of the XXth century may have partly offset the former SOC losses. The great diversity of soil types and land use histories of the Mediterranean area will make difficult to predict the soil GHG balances in the near future.

The forecasted climate change for the Mediterranean area (IPCC, 2007) indicates that the Mediterranean area is among the most sensible ones to climate change and has forecasted large increases in temperature, drought periods and heavy rainfall events. Losses in soil organic carbon associated to increases in soil temperature have already been demonstrated in temperate Europe (Bellamy et al., 2005). In the Mediterranean area, increases in temperature, drought periods and heavy rainfall events will likely result in further reductions in soil organic C and will favour land degradation specially in the most sensitive areas to land erosion (e.g. mountain slopes and semiarid areas). In this context, regional land management issues associated to the land use change must be given special attention in order to prevent further losses of organic C from soils, land degradation and potential losses in soil productivity.

In this paper we present data on carbon storage of Mediterranean soils and how they can be affected by changes in land use, land management and by fire. We aim to show the resilience of organic matter in Mediterranean soils in front of changes in climate, land use and management in order to set the basis for increasing C sequestration in the Mediterranean.

Soil organic matter and climate

In temperate and Boreal areas pine forests litter fall increases when latitude decreases. This relationship is not maintained in the Mediterranean area, where litter fall is lower that in adjacent Atlantic areas and

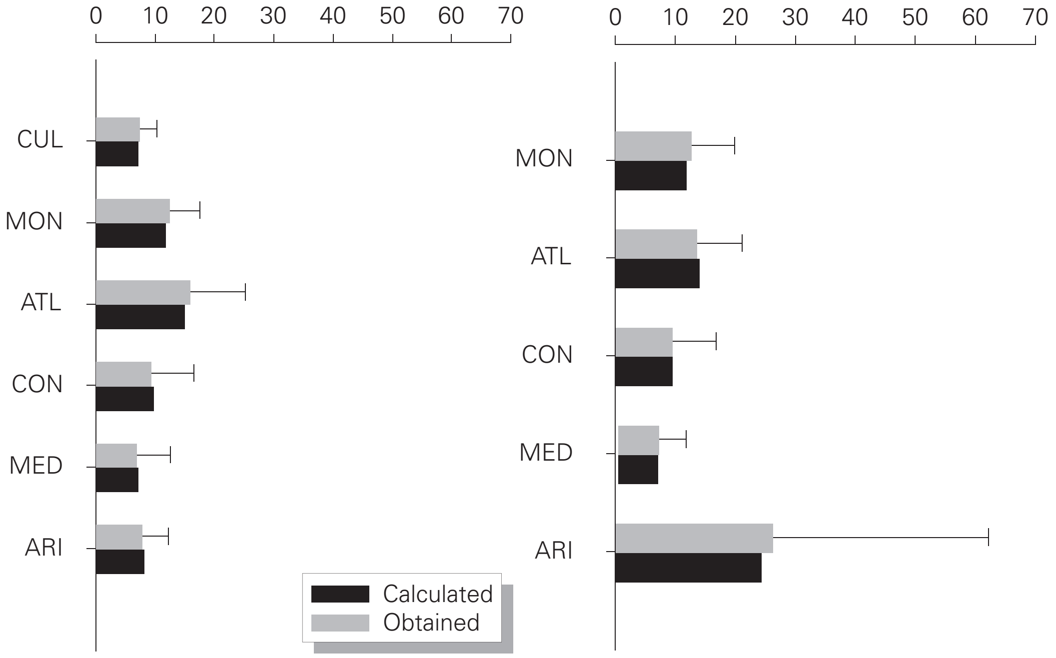

Figure 2.
Carbon content (kg m^{-2}) in soil profiles of conifer and hardwood forests soils in different climatic areas of Spain (ARI refer to Semiarid; MED to Mediterranean; CON to Continental; ATL to Atlantic; MON to Mountain; CUL to Culminal). The number of sampled soils is 626 for the conifer and 466 for the hardwood. *'Obtained'* refers only to the complete soil profiles (down to the parent material) while calculated data has also included the incomplete soil profiles: in these, total C was calculated by means of a probabilistic approach.

show a large variability irrespective of latitude (Berg *et al.* 1999). In contrast, litter fall in Spanish Mediterranean *Pinus radiata* plantations was higher than litter fall of Spanish Atlantic *Pinus radiata* (Romanyà and Vallejo, 2005). In spite of this fact the Mediterranean soils showed lower C content than the Atlantic suggesting that organic matter decomposition is faster in the Mediterranean soils.

By analysing a large data set of soil C content of the Spanish conifer and hardwood forests soils we can see that Mediterranean soils showed lower C content than Atlantic and Mountain soils. However, somewhat surprisingly soil organic matter content of semiarid hardwood forests showed unexpected high amounts that did not occur in conifer soils. This observation may have resulted from the fact that the conifer forests of the semiarid area have been established quite recently (less than 50-60 years ago) while the age of the hardwood forests is much greater. Consequently, hardwood forests may have accumulated higher amounts of carbon in the soil. Indeed soil carbon concentration of the soil surface horizon is larger in the hardwood forest that in conifers for all studied climates and the largest difference occurs in semiarid soils (data not shown).

The main limitation of decomposition in Mediterranean environments is drought. However, drought could be less limiting for microbial activity than often supposed. The effects of drought decrease with soil depth (Rovira and Vallejo, 1997). Casals et al. (2000) observed that CO_2 effluxes from a *Pinus halepensis* forest soil under Mediterranean semiarid conditions did not decrease in spite of the strong summer drought. Biological activity at the soil surface was very low in summer, and it was suggested that high soil CO_2 effluxes during drought may have originated from soil deep horizons. They also discussed that soil microbia can be still active down to a limit of -8 MPa for bacteria and to -10 MPa for fungi.

Plants are generally more sensitive to drought than microbia. The increased effects of drought experienced over the last decades has resulted in reductions of tree biomass or even on the die back of some forests stands. It has been stated that Mediterranean forest will likely become sources of CO_2 when affected with severe droughts (Sabaté et al., 2002).

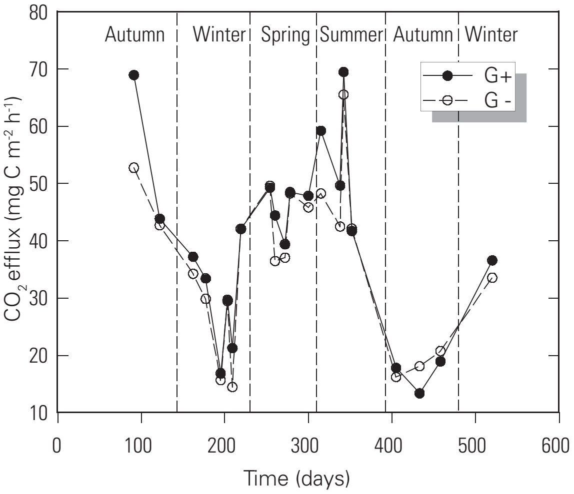

Figure 3.
Seasonality of soil CO_2 effluxes in soils with gravel and without gravel (Casals et al. 2000).

Dynamics of carbonates

The Soil Inorganic Carbon pool is important in soils of arid and semi-arid climate (Schlesinger, 1997). Dissolution and redistribution of carbonates has been considered an important soil process in Mediterranean soils (Yaalon, 1996). The formation of secondary carbonates and carbonate exports into the groundwater can be important mechanism of soil Carbon sequestration. Lal, (2007) in a recent review has reported C sequestration rates in the carbonates between 10-1000 kg ha^{-1} yr^{-1}. However, these rates are restricted in areas with high abundance of Ca (or Ca+Mg) and with high pH soils. The amount of carbonates in soils depends on soil-forming factors such as slope and aspect (Carter and Ciolkosz, 1991), as well as vegetation, human and natural disturbance, time and climate. In Mediterranean conditions decarbonation would occur during rainy winter season (with minimum water losses for evapotranspiration) causes slow dissolution and redistribution of carbonates. However, Mediterranean summer droughts prevent carbonates from completely disappearing from the soil profile. A recent study based on large data base of Spanish forest soils has quantified the relationship between the intensity and the probability of dissolution of calcium carbonate at the soil surface and several soil forming factors under Mediterranean forest soils (Rubio and Escudero, 2005). In this study, the decarbonation probability in the soil surface has been found to inversely relate to potential evapotranspiration and to be enhanced in areas with low insulation (North facing slopes). Thus, the intensity of the decarbonation process appears to depend fundamentally on altitude and on the annual moisture surplus. Another result of this study is that the formation of calcium carbonate is positively correlated with pH and negatively with organic matter content. Both high pH and low CO_2 concentrations are factors that favour the formation of secondary calcium carbonate.

The role of soil inorganic Carbon sequestration on soil Carbon dynamics in relation to the climate change is less understood than that of Soil Organic Carbon sequestration (Lal, 2007). Thus, there is a need to conduct studies on secondary carbonates formation and leaching rates in the Mediterranean soils mainly in areas with high Ca or Ca+Mg abundances.

Soil carbon and land use change

Cultivation produces large and quick losses of organic matter from the soil. The magnitude of the losses is related to the type of cultivation associated to a given crop and mainly to the organic matter inputs. Arable soils show much lower levels of soil organic carbon at the soil surface than forest or grassland soils (Figure 4). In Spain, most arable soils show less that 2% of organic C. Changes in soil C among climates are much larger in forest and grassland soils than in arable soils. In soils with low organic matter content small losses of soil C can result in large losses of soil quality that may greatly affect soil function. Loveland and Webb (2003) proposed a threshold of 2% bellow which soil quality can be largely decreased. However, soil degradation thresholds can depend on soil and climatic conditions. Benito and Díaz-Fierros (1992) found that in Atlantic grasslands soil erosion largely diminished in soils with more than 3 % of OC. In cereal fields of Australia it has been observed important losses of soil when SOC is below 1.6% (Malinda 1995). Considering the role of SOM in terms of soil fertility (N availability), Loveland and Webb (2003) suggested that under the 1% threshold crop production would decline, even when applying synthetic fertilisers due to the low content on mineralizable N. This conclusion however was inferred from data of temperate soils. In figure 4 we can observe that most arable soils in Spain are bellow the three higher thresholds although many of them would be under the fertility threshold of 1%.

Forest ecosystems are those having the lowest intensity of management. For that reason we have taken forest soils as a reference of the level of organic C typical of a given climatic area. The difference between forest and arable soils in a given climate has been taken as a deficit in soil organic C. This deficit was always highest for wet (nemoral) soils, medium for Mediterranean and low for semiarid soils. Differences between forest and grasslands were no significant in any case. From this analysis we can state that losses of soil organic matter resulting from cultivating forest soils would be greater in wet areas and lowest in semiarid. Similarly, we could also infer that after abandoning agricultural lands the capacity of C sequestration would be greater in wet areas and lowest in semiarid. However, low levels of organic C in semiarid and Mediterranean soils (Figure 4) suggest that the recovery of C after the abandonment of arable may not take place mainly as a result of ecological and soil constraints existing in dry and semiarid areas. This fact would suggest higher resilience of SOC in abandoned wet areas and low in semiarid and dry Mediterranean areas.

Romanyà et al., (2000) analysed the organic matter changes that occurred as a result of cultivation and afforestation under Mediterranean climate with moderately acid sandy soils over granodiorites (Figure 5). We can see that organic matter in vineyards dropped to one third of the original levels in the forest soils while in cereal fields the loss of organic matter was much lower. Before converting the agricultural soils to fast growing *Pinus radiata* forest plantations levels of SOC were 0.68 % for vineyards and 0.97 % for the cereal fields. In spite of the low levels of organic matter recorded we can see a good recovery in both cases. However, the recovery in the cereal fields soils is faster than in the vineyards. High N availability in former cereal fields may have accelerated the process of organic matter recovery. We can also see in the case of *Pinus radiata* growing on former the cereal fields that soil organic matter can increase beyond the levels of the less productive native forest.

Land use in the dehesa

The *dehesa* represents an agroforestry system unique in the world; almost exclusive to the Iberian Peninsule it covers more than 3 millions of hectares in Spain and Portugal. The dynamics and function of this ecosystem has not been widely studied (Dupraz and Newman, 1997). The traditional *dehesa* of *Quercus ilex* subs. *ballota* (Holm oak) and *Q. suber* (cork oak) comes from the original Mediterranean forest that has been thinned as a result of traditional human activities related mainly to the sylvopastoral use (pigs, lambs and

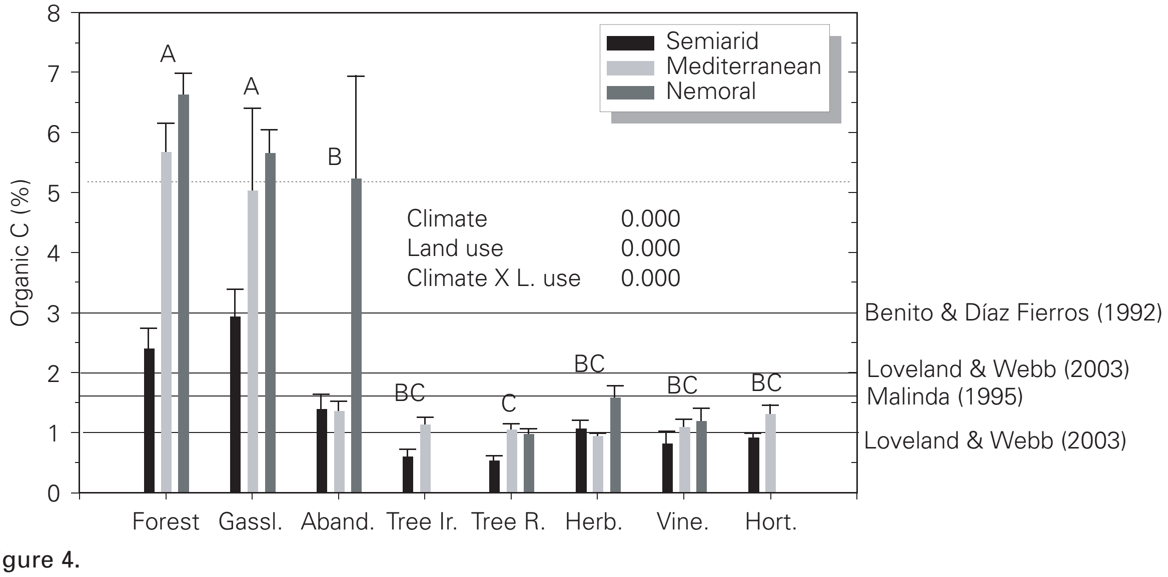

Figure 4.
Percentage of C in the soil surface horizon of the Spanish soils. Letters refer to significant differences between different land uses. Solid lines refer to the land degradation thresholds proposed by several authors in different contexts (see text). Dotted line refers to the maximum stabilisation capacity of OC of Mediterranean forest soils of the Ebro Depression (Rovira and Vallejo, 2003). *Forest* refers to forest and shrublands, *Grassl.* to grasslands. *Aband.* to abandoned croplands, *Tree Ir.* to irrigated tree crops, *Tree. R.* rainfed tree crops, *Herb.* herbaceous crops, *Vine*, to vineyards, *Hort.* to vegetable orchards.

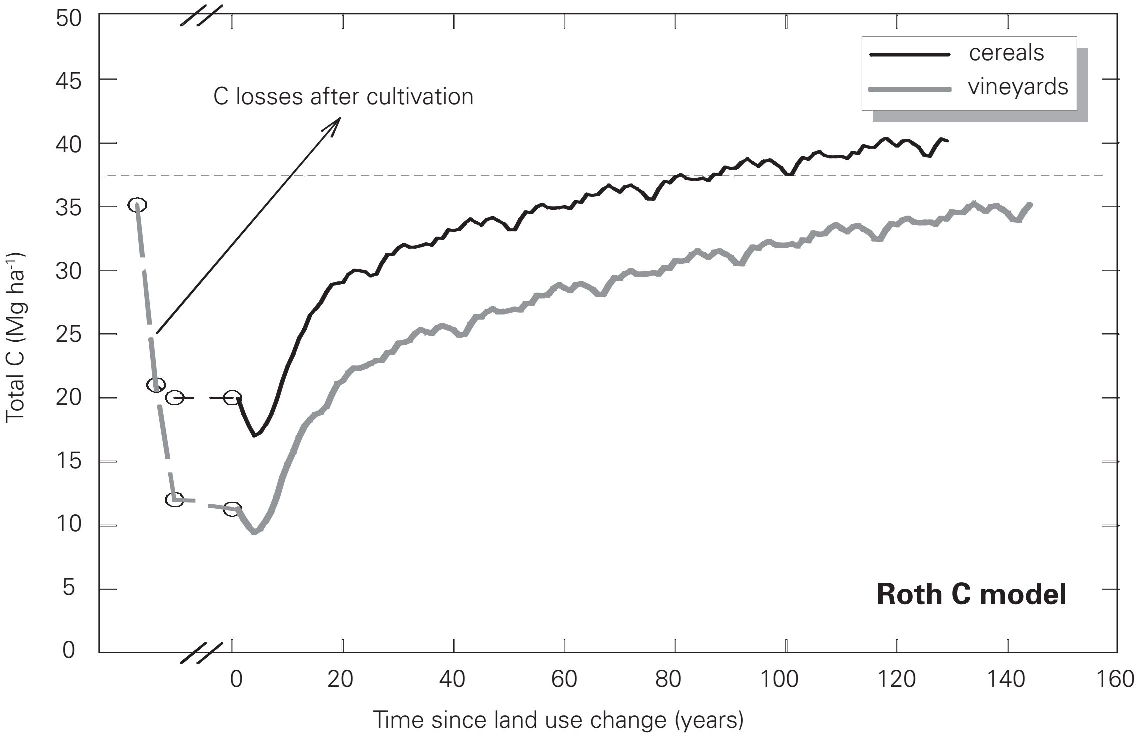

Figure 5.
Changes in soil C after cultivation and after afforestation with *Pinus radiata* under Mediterranean conditions as modelled with Roth C model. The dashed line refers to the levels of C of the native holm oak forest.

goats). The *dehesa* has also been used for charcoal production and occasionally it has been also cultivated with dryland crops (mainly small grains). Thus, the *dehesa* can be considered a paradigmatic case of continuous and intensive land use that may be adapted to the harsh climatic conditions of the Mediterranean area. However, nowadays the sustainability of the *dehesa* is being questioned due to recent changes in land management and perhaps also due to the climate change. For instance, some data shows that tree regeneration of *dehesa* is threatened (Plieninger *et al.* 2003) by a more intense agricultural use and livestock practices and tree ageing (Pulido *et al.* 2001). Within this context there is a need to study how this agro-sylvocultural system would contribute to Carbon sequestration in response to different management practices and to climate change (Nair *et al.* 2006).

Fire as a constraint

Wildfires are an important feature of Mediterranean terrestrial ecosystems. While it is accepted that they were already important before massive human disturbance, there is no doubt that human impact has strongly increased its relevance as a determinant factor for many of the landscape's characteristics.

Mediterranean plant communities often have a high resilience against a single fire event. For instance, Ferran & Vallejo (1992) studied the recovery of vegetation and litterfall after fires, in a chronosequence of *Quercus ilex* forests of Catalonia. Two years after the fire, plant cover had already reached 100%. At the first phases most of the plant cover were shrubs and herbs (*Rosmarinus officinalis, Ulex parviflorus, Cistus albidus, Coriaria myrtiifolia*), colonizing by seed. The relative importance of them decreased with time, as trees (*Quercus ilex*) recovered. This was reflected in the composition of the L horizon, mostly made of shrub litter until 18 years after fire, and dominated by *Quercus ilex* litter thereafter.

Nevertheless, the situation may be less optimistic when aridity does not allow rapid understory regeneration, or when the frequency of wildfires is high. Destruction of the vegetation by a wildfire involves a great increase in the risk of soil erosion, which by itself means that a portion (often substantial) of soil carbon is lost.

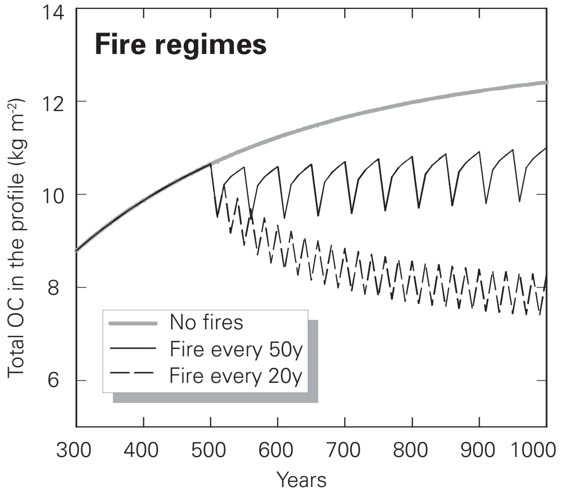

Figure 7.
Evolution of total OC in a soil profile, obtained by computer simulation (model PERFIL: Rovira, 2001). It was assumed that soil receives continuously aports? (litter and roots) during 500 years (aggradation phase); then, 3 fire regimes were introduced: (a) Control, with no fires, (b) Fire every 50 years, and (c) Fire every 20 years.

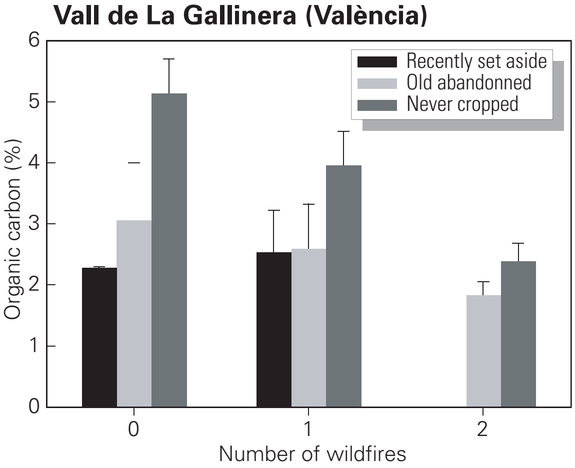

Figure 8.
Carbon concentration in the uppermost 5 cm of mineral soil, in shrubland communities of Vall de la Gallinera (València, E Spain) growing on old, set aside fields, *vs.* never cropped sites. For recently abandoned croplands, having suffered 2 wildfires, no plots were available.

A wildfire implies, first, an interruption of the carbon inputs to soil. Even though vegetation can recover, such an interruption results in a decrease in the total OC in the soil and, if repeated periodically - as common in many Mediterranean forests, due to human frequentation - the natural process of aggradation of the soil OC can be stopped or even reverted. In the computer simulations shown in Fig. 7 it was assumed that vegetation can regrow in 20 years, i.e. there is always time enough between two fire events to recover. As a consequence, soil OC evolution results from the interruption of OC inputs, not from changes in vegetation type (from forest to shrubland, for instance). Under natural conditions the degradation of the soil OC reserve may be worse than that illustrated in Fig. 7, if the frequency of wildfires increases. The most common tree species in subspontaneous forests of S Spain, *Pinus halepensis*, needs about 15 years to develop enough to produce cons; hence if wildfires are intense enough to kill all the trees, and if the interval between two wildfires is short enough (< 15 years), a *Pinus halepensis* stand may disappear. In such a case, forest is usually replaced by shrublands, which in general less produce litter and/or fine roots. In addition shrublands are often highly pyrophytic, hence the recurrence of fires can become increased. By such a process the drop in the total soil OC content can be accelerated.

Data obtained in old, set-aside fields of La Vall de la Gallinera (Valencia, E Spain) suggests that the effects of even a single wildfire can be detectable sometimes, both in never cropped shrublands and in shrublands growing in old fields (Duguy et al., 2007). Only for recently abandoned fields changes due to wildfires may be not relevant (Fig. 8).

Trends and perspectives

The Spanish National Forest Inventory (1998) indicates that the maximum extension for agricultural land (including natural meadows and pastures) in Spain was achieved in 1972 and represented a 44.8 % of the territory. In 1994 the agricultural lands had decreased to 39.4 % of the surface while forest soils (including woodlands and shrublands) had increased and represented 51.4 % of the land. Despite of the recurrent forest fires there is a general tendency of forest recuperation, so that the land covered by trees does not diminish. Nowadays, cultivation of forest lands does not occur widely in Spain. On the other hand, changes in agricultural management such as tillage reduction and the reintroduction of manure as fertiliser can increase the carbon content of soils. In this context it appears that C in Spanish soils may increase. However, as soils with higher capacity to sequestrate C are agricultural lands converted to forest soils, probably the greatest uncertainty to estimate C sequestration would be associated to this process. Plant growth and belowground biomass allocation of the species growing on afforested lands and/or on abandoned agricultural lands can be relevant to determine the rate of C sequestration in the soil.

In lands with severe limitations to plant growth, such as degraded lands and/or semiarid areas, the potential for C sequestration will be lower. Under these conditions small increases in soil C may be relevant to stop desertification processes. Organic matter additions to mitigate desertification may also enhance carbon sequestration.

C losses associated to fire are highly dependent on the type of ecosystem that is burnt. In degraded ecosystems soil C losses resulting from fire are small while in mature ecosystems C losses may be much greater.

Many wild grassland and pasture soils contain similar amounts of C that forests. Unlike forest soils, these soils show C decreases after reducing the cattle pressure. The extend to which soil C content in these systems is sensitive to management is an uncertainty as well as the changes in soil C that may occur when these soils are converted to forests.

In summary, the long history of human occupation of the Mediterranean countries and the conventional methods of cultivation associated to the extensive agriculture may have depleted the natural abundance of organic matter of Spanish soils. Nowadays Spanish soils can potentially increase its C content mainly by managing land set aside and agricultural lands.

References

Bellamy, P. H., Loveland, P. J., R., Bradley, I., Lark, R. M. & Kirk, G.J.D. (2005). Carbon losses from all soils across England and Wales 1978-2003. *Nature* 437: 245 - 248.

Benito, E. & Díaz-Fierros, F., 1992. Effects of cropping on the structural stability of soils rich in organic matter. Soil Tillage Research. 23: 153-161.

Berg B., Albrektson A., Berg M.P., Cortina J., Johanson M.B., Gallardo A., Madeira M., Pausas J., Kratz W., Vallejo V.R. & McClaugherty C. 1999. Amounts of litter fall in some pine forests in a European transect, in particular Scots pine. Ann, For. Sci. 56: 625-639.

Carter, B.J. & Ciolkosz, E.J., 1991. Slope gradient and aspect effects on soil developed from sandstone in Pennsylvania. Geoderma, 49: 199-213.

Casals P., Romanyà J., Cortina J., Bottner P., Coûteaux M.M. & Vallejo V.R. 2000. CO_2 efflux from a Mediterranean semiarid forest soil. I. Seasonality and effects of stoniness. Biogeochemistry 48: 261-281.

Duguy B., Rovira P. & Vallejo V.R. (2007). Land-use history and fire effects on soil fertility in eastern Spain. European Journal of Soil Science 58: 83-91.

Dupraz C., Newman S.M. 1997. Temperate Agroforestry: the European way. En: Gordon A.M., Newman S.M. (Eds). Temperate agroforestry systems. CABI. Pp: 181-236.

Ferran A. & Vallejo V.R. 1992. Litter dynamics in post-fire successional forests of *Quercus ilex*. Vegetatio 99-100: 239-246.

Gandullo, J.M., Serrada, R. 1977. Mapa de productividad potencial forestal de la España peninsular. Instituto Nacional de Investigaciones Agrarias. Madrid.

Ibáñez, J.J., de Alba, S., Boixadera, J., 1995. The Pedodiversity Concept and its Measurement: Application to Soil Information System. In: D. King, R.J.A. Jone, A. J. Thomasson (Eds.), European Land Information Systems For Agro-Environmental Monitoring. Joint Research Centre, European Commission, Brussels, pp. 181-195.

Lal R. 2007. Carbon management in agricultural soils. Mitigation and Adaptation Strategies for Global Change 12: 303-322.

Loveland P. & Webb J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil & Tillage Research 70: 1-18.

Malinda, D.K. 1995. Factors in conservation farming that reduce erosion. Aust. J. Expl. Agric. 35: 969-978.

Nair P.K.R., Bannister M.E., Nari V.D., Alavalapati J.R.R., Ellis E.A., Jose S., Long A.J. 2006. Silvopasture in south-eastern United States: more than just a new name for an old practice. En: Mosquera-Losada R., McAdam J., Riguiero A. (Eds) Silvopastoralism and Sustainable Land Management. CABI. Pp: 72-82.

Plieninger T., Pulido F.J., Konold W. 2003. Effects of land-use history on size structure of holm oak stands in Spanish dehesas: implications for conservation and restoration. Environmental Conservation 30 (1): 61-70.

Pulido F.J., Diaz M., Hidalgo S.J. 2001. Size-structure and regenetartion of hola oak (Quercus ilex) forests and dehesas: effects of agroforestry use on their long-term sustainability. Forest Ecology and Management 146: 1-13.

Romanyà J., Cortina J., Falloon P., Coleman K. & Smith P. 2000. Modelling changes in soil organic matter after planting fast-growing *Pinus radiata* on Mediterranean agricultural soils. European Journal of Soil Science 51: 627-641.

Romanyà J. & Vallejo V.R. 2005. Productivity of *Pinus radiata* in spain in response to climate and soil. Forest Ecology and Management 195: 177-189.

Rovira P, & Vallejo V.R. 1997. Organic carbon and nitrogen mineralization under Mediterranean climatic conditions: The effects of incubation depth. Soil Biol. Biochem 29: 1509-1520.

Rovira P. 2001. Decomposition and stabilisation of organic matter in Mediterranean forest soils: quality, physical protection, and depth effects. Ph. D. Thesis, Universitat de Barcelona.

Rovira P. & Vallejo V.R. 2003. Physical protection and biochemical quality of organic matter in Mediterranean calcareous forest soils: a density fractionation approach. Soil Biology and Biochemistry 35: 245-261.

Rubio, A. & Escudero, A. 2005. Effect of climate and physiography on occurrence and intensity of decarbonatation in Mediterranean forest soils of Spain. *Geoderma*, 125(3-4): 309-319.

Sabaté S., Gracia C. & Sánchez A. 2002. Likely effects of Climate Change on growth of *Quercus ilex*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean Region. Forest Ecology and Management. 5906: 1-15.

Several authors. 1998. Segundo Inventario Forestal Nacional, 1986-1996. Dirección General de Conservación de la Naturaleza, Ministerio de Medio Ambiente.

Schlesinger, W.H. 1997. Biogeochemistry: An analysis of global change. Second edition, San Diego, Academic Press.

Yaalon, D.H., 1996. Causes of pedogenic diversity in the Mediterranean hill regions of Israel. In: J. Bech (Ed.), Abstracts of 6th International Meeting on Soils with Mediterranean Type of Climate, Barcelona, p. 514.

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