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Organic carbon and nitrogen losses influenced by vegetation removal in a semiarid mediterranean soil

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Abstract. A reduction in plant cover can lead to an increase in the erosion processes that diminish soil quality. Any rise in temperature resulting from predicted climate changes may aggravate this effect, particularly in semiarid Mediterranean areas. Bearing this in mind, the capacity of a soil to preserve organic matter becomes very important if the soil is to maintain its physical and chemical properties. Soil organic carbon and nitrogen changes were evaluated in a non-disturbed (with natural vegetation) and a disturbed (all vegetation manually clipped to ground level) pine system. Nine years after vegetation removal significant differences ($p < 0.01$) were found in the soil organic carbon content between plots (top 20 cm), but not in total nitrogen. In the disturbed plot 0.0232 Mg ha^{-1} y^{-1} of soil organic carbon were lost through erosion and 4.30 Mg ha^{-1} y^{-1} through mineralization. In the first 48 months after vegetation removal the soil organic carbon content fell from 40.3 to 28.0 g kg^{-1}. In the last 60 months of the experiment the amount of organic carbon in the soil fell from 28.0 to 27.7 g kg^{-1}. This result was mainly attributable to the intense oxidization, which took place during the first 60 months, of organic matter linked to the coarse soil mineral fraction. Up to the 72nd month the losses by erosion were a total of 532.7 g, which rose to 1284.4 g by the end of the experiment (108 months). The effect of vegetation removal in a Mediterranean semiarid area leads to a rapid decline in the amount of organic carbon stored in the soil. Such perturbation is irreversible if left to nature.

Introduction

Soil degradation is one of the greatest environmental problems in the world. In semiarid Mediterranean areas the dry climate leads to a low level of vegetal cover which, in turn, leads to a very scarce organic matter input, and, as a consequence, to a poor development of soil structure (Díaz et al. 1994). In such a conditions the role of plant cover in protecting soil against erosion is crucial (Morgan 1986), since removal of vegetation strongly increases surface runoff and sediment yield (Albaladejo 1990; Castillo et al. 1997) and, as a consequence, soil quality deteriorates (Kaihura et al. 1999).

Vegetation removal is normally followed by a period in which the soil has sufficient organic matter to maintain its physical-chemical properties, enabling it to recover from the damage, according to the concept of soil resilience (Castillo et al. 1997). Soils rich in organic matter, such as those of many rainy regions, are more resilient than soils with a low organic matter content, such as those which predominate in arid and semiarid areas. In this respect the nature of the soil parent material is very important for maintaining soil productivity in erosive situations. When the surface layer, which contains fresh plant remains, is eroded, the subsurface material is exposed and the capacity of this material to hold nutrients becomes crucial (Gregorich et al. 1998).

Although there is general agreement with regard to the role of erosion in soil organic carbon losses (United Nations 1992), some controversy seems to exist with respect to the intensity of soil organic carbon losses caused by mineralization. Yaalon et al. (1990) indicated that mineralization would lead to a reduction in the soil organic matter content within 50 years in the Mediterranean area. Although Squires et al. (1998) pointed out that the carbon stored in dryland soils is a very important deposit, since it has been stabilized over a period of hundreds to thousands of years, Scharpenseel and Pfeiffer et al. (1998) indicated that these areas may be very sensitive to climatic change due to inadequate reserves of water and soil nutrients. Hence, it is important to study the quantity and quality of soil losses by analyzing the nutrients contained in sediments.

The vulnerability of Mediterranean arid and semiarid lands to human-induced changes in soil use means that the effects of climate change upon these environments will be exacerbated (Scharpenseel and Pfeiffer et al. 1998). Reduced precipitation or increased temperature accelerates land degradation through the loss of plant cover, biomass turnover, nutrient cycling and soil organic carbon storage, accompanied by higher greenhouse emissions (Ojima et al. 1995). Moreover, if the projected increase in temperature following global climate change occurs, the degradative processes will be aggravated (Tinker and Imeson 1990; Neilson and Marks 1994; Kimble et al. 1998).

An understanding of the dynamics of soil organic carbon is required to better appreciate the ability of soils to stabilize carbon and any implications for global change (Bajracharya et al. 1998). Although many studies have been performed to quantify nutrient losses under controlled conditions using rainfall simulators (e.g. Sharpley (1985); Ghadiri and Rose (1991)), there have been few studies based on long term data series under natural rainfall conditions (e.g. Fullen et al. (1996)). Furthermore, most of the data refer to nutrient losses under tillage (e.g. Moyo et al. (1998); Palis et al. (1997)) and not to losses in natural conditions in semiarid environments (e.g. Alías et al. (1997)).

Long term data series from natural rainfall events in semiarid environments are crucial for studying nutrient dynamics because: i) the soil's response within a few months of vegetation removal may not be sufficient for estimating its long-term behavior, caution should be used in extrapolating results from short-term experiments to predict longer-term responses to environmental perturbations (Rustad

2001); and ii) it is difficult to produce data comparable to natural storms using rainfall simulators (Flanagan and Foster 1989).

The aim of this study was to evaluate the changes of organic carbon and nitrogen under natural rainfall conditions in a semiarid Mediterranean soil affected by vegetation removal. The paper reports data obtained over a nine-year period (1988–1998) concerning changes in soil and sediment organic carbon and nitrogen contents in a non-disturbed vegetated area and an area from which vegetation had been removed and therefore exposed to erosion processes.

Study site and methods

The study was conducted in two field plots (disturbed plot, Plot D, and non-disturbed plot, Plot ND) located at the Experimental Field Station of the Centro de Edafología y Biología Aplicada del Segura (CEBAS) (Murcia, SE Spain). The area is characterized by a semiarid Mediterranean climate, with a mean annual rainfall of about 300 mm, most of which falls in irregular and intense storms in autumn and spring. The mean annual temperature of 17 °C is accompanied by a very high mean evapotranspiration rate of 850 mm year^{-1}, which, in consequence, leads to a pronounced soil moisture deficit. The soil is a Lithic Xeric Haploxeroll (Soil Survey Staff 1998), with a top 20 cm mollic epipedon, silty clay loam to clay loam (22% sand, 43% silt and 35% clay). The bulk density is 1.57 Mg m^{-3} in plot ND and 1.6 Mg m^{-3} in plot D. More detailed data on the soil characteristics appear in Albaladejo et al. (1998). The natural vegetal cover consists of planted *Pinus halepensis* Miller (Aleppo pine) and shrub formations including *Rhamnus lycioides* L. (black buckthorn), *Thymus hyemalis* Lange (winter thyme) and *Sideritis leucantha* Cav. (ironwort). The study area is very representative of semiarid regions of the world and, in particular, of the whole Mediterranean region. A large number of target areas for large scale multinational projects on desertification share the characteristics of our study and are located in the province of Murcia (Vandekerckove et al. 1998; Nachtergaele et al. 2001).

In December 1988 two adjacent plots (5 m wide by 15 m long) were installed on the North face of a low-crested ridge with 23% slope. Each plot was bordered by 200 mm wide cement blocks driven 100 mm into the ground. At the beginning of the experiment all the aerial vegetation was removed from one of the plots (plot D) to simulate human disturbance. The plants were manually clipped at ground level using grass clippers and pruning shears before being removed from the plot. No attempt was made to remove protruding, root crowns or stumps. Only one clipping was carried out and no further treatments were imposed. This plot was compared with the adjacent natural non-disturbed plot (plot ND).

These plots are part of a broader study in which soil loss, runoff, and physical and biological soil properties have been recorded since December of 1988 (Castillo et al. 1997; Albaladejo et al. 1998; Martínez-Mena et al. 1999). Since the aim of this trial was to study the long term evolution of erosion and soil properties under

Table 1. Mean (± standard error) soil organic carbon (OCs), total nitrogen (TNs), Ocs/TNs ratio from disturbed (D) and non-disturbed (ND) plots measured over a 9 year period (n = 18, twice a year).

	Plot D	Plot ND	Differences (D-ND)	P(z)[a]
OCs (g kg^{-1})	30.5 ± 3.96	40.5 ± 0.96	−10.0 ± 0.92	< 0.01
TNs (g kg^{-1})	2.26 ± 0.08	2.40 ± 0.16	−0.14 ± 0.14	0.504
OCs/TNs	14.0 ± 0.67	18.1 ± 1.48	−4.1 ± 1.05	< 0.01

[a] P(z) Probability values for Wilcoxon signed-rank test based on paired differences

natural conditions, large plots (> 10 m long) were deemed to be preferable to smaller replicate plots with rainfall simulation. Nearing et al. (1999) showed that soil erosion variances between replicated plots decreased with soil loss regardless of the time over which the data were collected. In the case where erosion is expected to be low, it might be preferable to measure soil loss over a longer period of time to reduce variance instead of using a large number of replicates. On the other hand, many studies have highlighted that plots must be at least 10 m long to develop surface runoff with sufficient flow energy (Morgan 1986; Mutchler et al. 1988).

A tank with a five-slot divisor was installed at the bottom of each plot to measure runoff and sediment yield. Total runoff was measured using a stage recorder in the tank connected to a data logger. Sediment from the tanks was sampled immediately after each storm event. Five 1-liter aliquots were taken from different depths while the content of the tanks was being stirred. The five sub-samples were immediately taken to the laboratory, oven dried at 105 °C and weighed to determine the suspended sediment concentration. The sediment concentrations were averaged and multiplied by the total runoff volume to calculate total soil loss. The five sediment sub-samples were then mixed to constitute a sample and analyzed for organic carbon and total nitrogen. When the quantity of sediment was too small for organic carbon and nitrogen to be analyzed, the organic carbon was prioritized. In consequence, the total number of samples was different for both variables.

Between December 1988 and January 1998 soil samples were also taken from the two plots twice a year (one in winter and one in summer). At each sampling date one soil sub-sample (top 20 cm) was collected from the upper third of both plots, one from the middle third and one from the lower third. The sub-samples from each zone were mixed in order to obtain one representative sample of each plot, and their organic carbon and total nitrogen content was ascertained. Sand (> 50μm) and silt + clay (< 50μm) fractions were isolated in the soil samples taken from both plots at the end of the experiment and organic carbon and total nitrogen were determined in each fraction.

Organic carbon and total nitrogen in soils and sediments were determined in a Carlo Erba 1500 Automatic Nitrogen and Carbon Analyzer, after preteatment with HCl to eliminate carbonates (Colombo and Baccanti 1989) and combustion at 1020 °C.

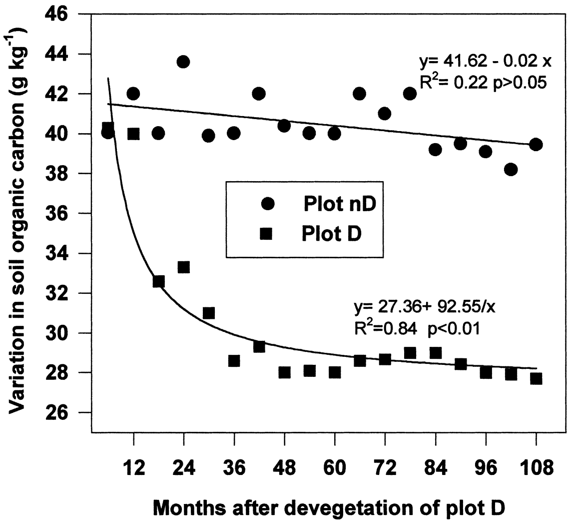


Figure 1. Variations in soil organic carbon in disturbed (plot D) and non-disturbed (plot ND) plots in a 9-year period after vegetation removal.

The sand and silt + clay fractions in soil samples were separated using the siphoning technique after dispersion using ultrasound. The settling was allowed at 20 °C applying Stokes' law and a particle density of 2.675 g cm^{-3}.

Results

Soil nutrients

A statistic summary of the analysed soil nutrients of plots D and ND and of their paired differences using the Wilcoxon signed-rank test is shown in Table 1. The mean soil organic carbon content was 1.33 times higher ($p < 0.001$) in plot ND than in plot D while the mean soil organic carbon/total nitrogen ratio was 1.30 times higher in plot D than in plot ND ($p < 0.001$). No statistically significant differences were found in the soil total nitrogen content between plots. After nine years, the change in soil organic carbon content with time was significant ($r = 0.91$, $p < 0.001$) in plot D (from 40.3 g kg^{-1} in December 88 to 27.7 g kg^{-1} in January 1998, Figure 1), leading to a total quantity of 350.7 kg of organic carbon lost in this plot (calculated on the basis of a bulk density of 1.6 g cm^{-3} in the upper 20 cm of soil). In plot ND, on the other hand, there was no statistically significant ($r = 0.44$, p: 0.07) variation in the soil organic carbon content with time (from 40.0 g kg^{-1} in December 1988 to 39.5 g kg^{-1} in January 1998, Figure 1).

A more detailed analysis showed two tendencies for organic carbon losses recorded in plot D. In the first 4 years (up to month 48) of the experiment the soil organic carbon content decreased by 12.3 g kg^{-1} (from 40.3 to 28.0 g kg^{-1}, repre-

Table 2. Mean (± standard error) of sediment organic carbon (OCsed), total nitrogen (TNsed) from disturbed (D) and non-disturbed (ND) plots measured over a 9 year period.

	Plot D				P(z)[a]
	n[b]		n		
OCsed (g m^{-2})	46	0.454 ± 0.096	38	0.097 ± 0.033	< 0.001
TNsed (g m^{-2})	40	0.050 ± 0.013	31	0.007 ± 0.003	< 0.001
OCsed / TNsed	40	11.10 ± 0.66	31	11.71 ± 0.66	0.469

[a] P(z) Probability values for Wilcoxon signed-rank test based on paired differences (n = 38 for sediment organic carbon, and n = 31 for sediment total nitrogen)
[b] n; The number of available observations is reduced when there was no runoff or when samples had no measurable content of some constituents.

senting a total quantity of 342.4 kg). In the following 5 years (months 48 to 108) the concentration of soil organic carbon decreased by 0.3 g kg^{-1} (from 28.0 to 27.7 g kg^{-1}, representing a total of 8.3 kg). No such pattern was observed in plot ND (Figure 1).

The variation of soil total nitrogen content with time was not significant during the nine years of the experiment in either plot (from 2.4 g kg^{-1} in December 1988 to 2.1 g kg^{-1} in January 1998, in plot D, and from 2.8 g kg^{-1} in December 1988 to 3.0 g kg^{-1} in Jan 1998, in plot ND).

Sediment nutrients

Table 2 shows a statistic summary for the analysed sediment nutrients of plots D and ND and their paired differences using the Wilcoxon signed-rank test. The total organic carbon and total nitrogen contents in the sediments of plot D was significantly higher ($p < 0.001$) than those in the sediments of plot ND during the nine year period. The mean sediment organic carbon content was 4.70 times higher in plot D than in plot ND and the mean sediment nitrogen content was 7.14 times higher. These results were in accordance with the higher soil loss induced by vegetation removal in plot D compared to plot ND (Figure 2).

Two periods were identified in the evolution of the organic carbon and nitrogen content in the sediments of plot D during the nine years: in the first 6 years (up to month 72), a total of 532.7 g of organic carbon was found in the sediment and during the following 3 years (months 72 to 108) this quantity reached 1284.4 g (Figure 3a). The quantity of total nitrogen recorded in the sediment was 4.3 g in the first period and 13.1 g in the second one (Figure 3b).

In spite of the marked differences in the total amounts of organic carbon and total nitrogen in the sediments, no significant differences between plots were found when expressing the concentration in grams of organic carbon and total nitrogen per kilogram of soil lost (mean value of 38.4 ± 1.6 g kg^{-1} in plot D and 36.8 ± 1.6 g kg^{-1} in plot ND).

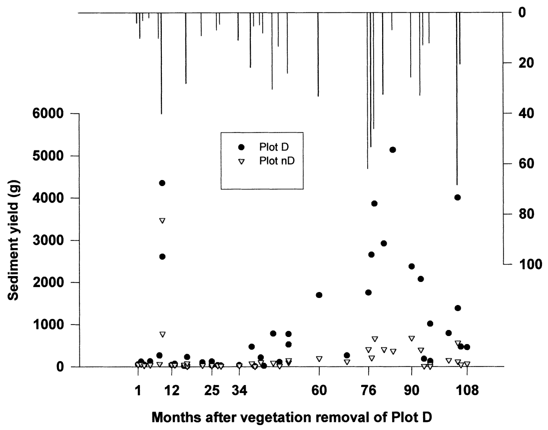


Figure 2. Sediment yield and maximum 30-minute rainfall intensity (I_{30}) per single event in the 9-year period after vegetation removal in plot D.

The ratio of organic carbon/total nitrogen in the sediments did not significantly differ between plots (Table 2).

Nutrient enrichment ratio

Soil nutrient losses can be assessed by reference to enrichment ratio (ER) (Gachene et al. 1997), which is calculated as the relation between the nutrient concentration in sediment and the same parameter measured in the source soil.

The organic carbon and total nitrogen enrichment ratios (EROC and ERTN, respectively) significantly increased ($r = 0.60$, $p < 0.001$ for EROC and $r = 0.75$, $p < 0.001$ for ERTN) with time as a consequence of vegetation removal in plot D (Figures 4a and 4b). In contrast, in plot ND there was no significant change with time in either enrichment ratio during the nine year period which the study lasted.

In plot D there was a positive correlation between both EROC (Spearman's rank correlation coefficient $rs = 0.4750$; $p \leqslant 0.001$) and ERTN ($rs = 0.4777$; $p \leqslant 0.003$) and the kilograms of sediment lost, reflecting the progressive increase in nutrient enrichment of the sediments with increasing erosion rates. In plot ND no significant correlation was observed between soil loss and EROC or ERTN ($p > 0.1$).

Discussion

Nine years after vegetation removal the soil organic carbon content of plot D had fallen by 30.7% (equivalent to 4.51 Mg ha^{-1} y^{-1}). Since losses from erosion represented only 0.0232 Mg ha^{-1} y^{-1} in the overall study period, we assume than the main cause of carbon losses was mineralization (about 4.49 Mg ha^{-1} y^{-1}). This assumption was supported by two facts: i) the mean higher maximum soil temperature reached in the soil of plot D (29.5 °C) compared to plot ND (25 °C) in the

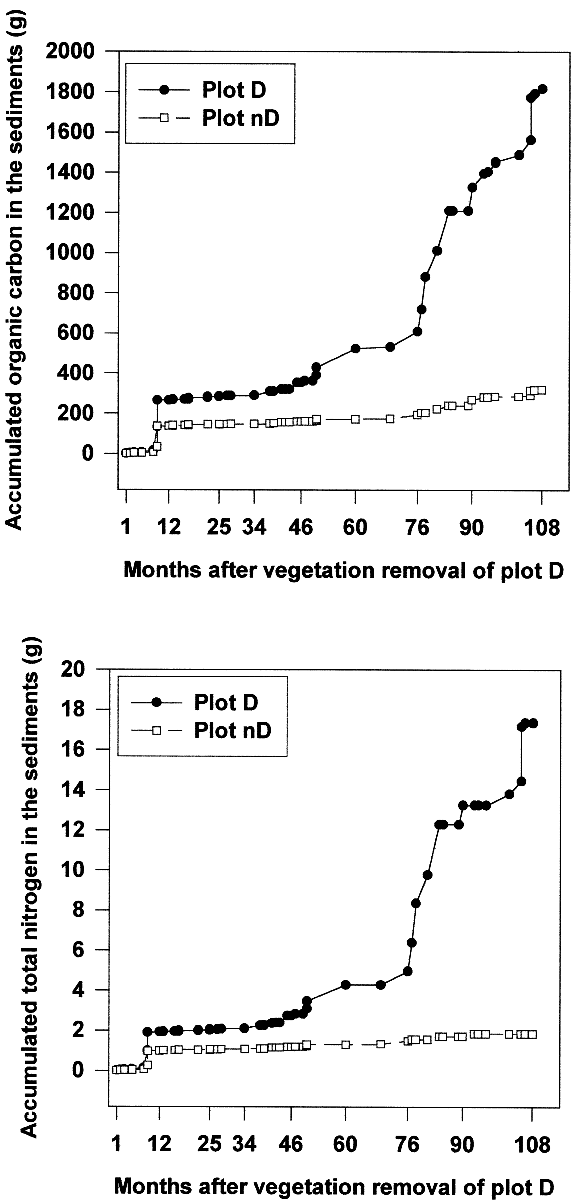
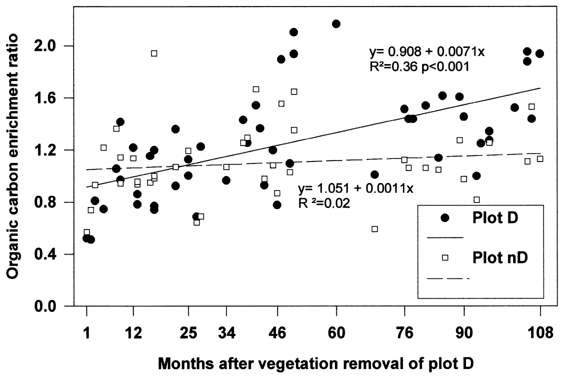


Figure 3. Accumulated grams of organic carbon and total nitrogen in the sediments of disturbed (plot D) and non-disturbed (plot ND) plots in a 9-year period after vegetation removal in plot D.

hottest months (Albaladejo et al. 1998), since other authors (West et al. 1994) have estimated that the steady state organic matter content of a soil would decrease by 12.4% as a result of a 2 °C increase in mean annual temperature and ii) the very low percentage of water soluble carbon, less than 1% in the eroded soil of Murcia



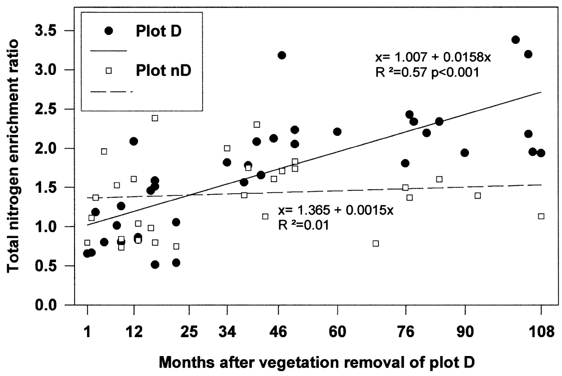


Figure 4. Organic carbon and total nitrogen enrichment ratios per single event in the sediments of disturbed (plot D) and non-disturbed (plot ND) plots in a 9-year period after vegetation removal in plot D.

region (García et al. 1997), meaning that the organic carbon losses in runoff water are practically null. Furthermore, García et al. (1997) pointed to the lack of any difference between these two plots as regards the water soluble carbon content of soils. It is, reasonable to expect, then, that if a great quantity of water soluble carbon had been lost in the runoff water, differences would have been observed between the plots due to the higher runoff observed in plot D than in plot ND.

Although it seems evident than the main cause of soil carbon loss in plot D was mineralization, it was also seen than soil carbon losses due to erosion increased with time. Thus, in the first 6 years (up to month 72) following vegetation removal, the organic carbon found in the sediment represented 0.16% (532.7 g) of the total organic carbon lost from the soil, while in the last 3 years (from months 72 to 108) it reached 5.99% (1284.4 g) of the total organic carbon lost. The increase of the maximum 30-minutes rainfall intensity values (I_{30}) in the last 36 months of the experiment (Figure 2) and the progressive increase in soil erodibility (Castillo et al. 1997) might have contributed to these results. Furthermore, the large decrease in soil organic carbon observed up to 4th year (48 month, Figure 1) was in agreement with the smaller contribution of erosion to these losses in the overall study period.

Similar results have been found in the literature. For example, Fullen (1991) observed a sharp fall organic matter after vegetation had been removed from loamy sand soils with an average slope of 12%. Gregorich et al. (1998) indicated that mineralization was the predominant process in the decrease in organic carbon in the first years after devegetation of a cultivated Black Chernosem in Saskatchewan, while erosion was the main process in later years. These authors indicated that 3.1 Mg ha^{-1} y^{-1} of organic carbon were lost by mineralization and 0.5 Mg ha^{-1} y^{-1} by erosion during a 23-year period.

The difference in the soil organic carbon/total nitrogen ratio between plots was due to the decrease in the soil organic carbon content of plot D, since the total nitrogen content did not significantly differ between plots (2.27 g kg^{-1} in plot D and 2.39 g kg^{-1} in plot ND). The lower values observed for the soil organic carbon content linked to the sand fraction in plot D (17.1 grams of organic carbon per kilogram of sand) than in plot ND (25.9 grams of organic carbon per kilogram of sand) suggested that vegetation removal mainly affected losses of the organic carbon linked to coarse particles. According to several authors (Quiroga et al. 1996) the organic carbon fraction linked to coarse particles is less protected against oxidation, while the organic compounds linked to the clay and silt fractions are better protected. As the mineralization process was more rapid during the first four years (Figure 1), intense oxidation of the organic carbon from the fresh remains would have occurred in plot D, after which time the carbon losses would have stabilized.

In the soil of the studied plots the fine fraction was by far the most abundant and organic carbon was mainly linked to this fraction (43.5 grams of organic carbon per kilogram of silt + clay in plot D and 45.8 grams of organic carbon per kilogram of silt + clay in plot ND). Hassink (1997) described the mechanisms by which the humic substances linked to the fine silt and clay form stable organic-mineral complexes, and indicated that the net rate of accumulation depends not on the protective capacity of a soil *per se* but on the extent to which this capacity is already occupied by organic matter. Since the most abundant particles in the sediments were fine silt and clay in both plots (Martínez-Mena et al. 1999), no differences in the concentration of organic carbon associated with the sediment were to be expected. Obviously, since a greater quantity of sediment was lost from plot D than from plot ND in each storm (Figure 2), a greater total quantity of organic carbon and total nitrogen were lost each year in the former plot.

Vegetation removal led to an increase in the sediment enrichment ratios of organic carbon and total nitrogen with time. This was supported by the significant correlation found between the quantity of sediment lost and EROC and ERTN in plot D. Although in plot ND the total nitrogen measured in the sediment increased, the lack of correlation between ERTN and the quantity of sediment produced by this plot suggests that, when the vegetal cover is not disturbed, other mechanisms besides erosion, such as volatilization, might be involved in such losses. Several authors (e.g. Sharpley (1985)) have pointed to the fact that although the transport of nitrogen and other nutrients is primarily associated with fine-sized mineral and organic particles, nutrient enrichment in runoff sediment can exceed that associated with the selective erosion of fines. The results obtained in plot ND were in accordance with those of Flanagan and Foster (1989) who found no difference between ERTN and the quantity of sediment lost in a silty loam soil. The difficulty of identifying the main causes of soil nitrogen losses was pointed out by Ghadiri and Rose (1991), indicated that nitrogen loss, even if largely in organic forms, does not have to exactly follow the losses of organic matter.

Furthermore the necessity of long-term data to establish plausible answer to an environmental perturbation, in the natural recovery of a disturbed land the precipitation in the following months to the perturbation have influence. In the wet years the probability of recuperation will be higher than in the driest years. In our study, the two years just after vegetation removal can be classified as very wet (529 mm; $p = 0.97$) and wet (351 mm; $p = 0.69$). So, in most years the pluviometric conditions for a natural recuperation of vegetal cover would be worse than in our study.

Conclusions

The mineralization process was much more influential than erosion in the soil organic carbon losses recorded during the 9 years following vegetation removal in a semiarid Mediterranean soil. Two periods were identified in the pattern of soil organic carbon decreases following disturbance. In the first 6 years rapid mineralization was the main cause of the soil organic carbon decreases measured, while in the next 3 years the soil organic carbon losses were mainly due to erosion. Vegetation removal led to a progressive increment in enrichment of the sediments in organic carbon and nitrogen with time.

These results point to the importance of preserving the vegetal cover in semiarid areas, where it is a crucial factor for maintaining the soil organic carbon stock. This aspect becomes even more important in the light of predicted increases in soil temperature in these areas.

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