SOIL QUALITY AND ORGANIC CARBON RATIOS IN MOUNTAIN AGROECOSYSTEMS OF SOUTH-EAST SPAIN

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ABSTRACT

Soil physical and chemical characteristics as well as climatic and geomorphological factors have been determined in 68 sites of a mountain calcimorphic ecosystem (Sierra María-Los Vélez Natural Park, Almería) in Southeastern Spain. Land use and vegetation were natural pine forest, evergreen oak forest, reforested pine forest of different ages, bush, juniper forest, and olive, almond and cereal crops under conventional tillage. By using multivariate data treatments, 17 soil variables were processed. A large part of the total variability was controlled by local topographical features through their effect on moisture retention and vegetation. Most characteristics were significantly correlated with total organic C (mean= 28.5±4.6 g kg^{-1}), which demonstrates the central role of the organic matter in the functioning of the whole ecosystem. New soil quality descriptors consisting of ratios to soil organic carbon were obtained, informing about the specific activity (per C unit) or performance of the organic matter, independently of its total content. When soil data are directly processed by using principal component analysis, we found a set of high quality soils under natural and old reforested forests, where environmental services provided by soil depend on the high levels of quality descriptors related to organic carbon, e.g. cation exchange capacity (CEC), total porosity, aggregate stability. When variables such as CEC, porosity and aggregate stability are calculated as ratios to the total organic carbon, a new classification pattern is obtained, allowing to detect soils with organic matter of high maturity which in general do not coincide with soils with high organic matter content. The results suggest the assessment of soil quality based on ratios informing on the organic matter performance should be emphasized as an alternative to direct descriptors based on the total organic carbon content.

Keywords: Forest soils, cleared soils, physico-chemical indicators, aggregate stability/C, porosity/C, topographic attributes.

INTRODUCTION

In semi-arid sites, soil degradation associated to inappropriate use is especially critical due to specific climatic constraints, which in mountain ecosystems are also linked to stressing topographical conditions (Sánchez-Marañón et al., 2002; Dunjo et al., 2003; Delgado et al., 2007). In fact, microtopographical features leading to abrupt changes in slope, orientation and exposure of soils have a significant bearing on the hydrological patterns in the geosystem (Brown, 1994; Del Barrio et al., 1997), generating mosaic-like patterns of the vegetation (Campbell, 1989). This chief role of topography, combined with unforeseeable rainfall, typical of most Mediterranean areas, is often associated to erosion processes leading to severe degradation and loss of soil. In addition, certain anthropogenic actions such as agriculture and forest exploitation could accelerate these problems, causing adverse and lasting effects on soil physical, chemical and biological properties (Doran et al., 1998).

The progressive loss of soil quality is associated to decreased productivity and loss of organic matter, resulting in desertification (Nardi et al., 1996; Islam et al., 1999). The assessment of soil quality in mountain sites is of particular importance in order to forecast the resilience of the whole ecosystem, which under the above environmental constraints is especially fragile. Progressive degradation of forest ecosystems in Mediterranean areas results in severe decline of all soil functions such as biological productivity, regulation of the hydrological cycle and water quality, carbon balance, and mitigation of pollution and erosion (Sojka and Upchurch, 1999; Singer and Sojka, 2001).

Previous research works carried out in mountain environments (Powers et al., 1998; Burger and Kelting, 1998; Schoenholtz et al., 2000; Page-Dumroese et al., 2000) have shown the lack of an universal standard on soil quality based on a specific assemblage of soil quality indicators. Most studies focus on individual features of soil quality such as biological productivity or environmental quality, or address them separately (Hajabbasi et al., 1997; Pennock and van Kessel, 1997; Wang and Gong, 1998; Perie and Munson, 2000; Islam and Weil, 2000) because (i) there is no single pure state of soil, and (ii) the status of soil properties and functions is occasionally contradictory, i.e. a soil property could be favourable for biological production and undesirable for an ecological function (Sojka and Upchurch, 1999). Preliminary studies in Mediterranean mountain environments have suggested that the maximum potential and resilience of soils could differ depending on environmental characteristics, hence human activities on these ecosystems resulting into a different ecological impact (Boix-Fayos et al., 2001; Sánchez-Marañón et al., 2002). In consequence, the assessment of soil quality in Mediterranean environment often has a limited value as regards to the agroecosystem performance.

At this point, the conservation and sustainable management of natural resources, as well as the rehabilitation of the forest environment have become priority actions of the Seventh Framework Programme of the European Union. This has led to the imperative of defining objective criteria for the monitoring of soil quality, which is required to implement correction actions to improve the sustainability of managed lands (Acton and Padbury, 1993). Soil quality criteria are often based either on the sustainability of soils under dynamic management practices, or on soil resilience defined in terms of stability against environmental perturbations (Hartemink, 1998). In particular, the reliable assessment of soil quality requires a set of descriptors of rapid determination, precluding problems associated with the exhaustive data collection needed in mosaic-like ecosystems (Fresco and Kroonenberg, 1992) such as the soils developed under Mediterranean mountain conditions (Pieri et al., 1995). Such descriptors should be preferably linked to the functions expected from the soil (Acton and Padbury, 1993), and quality levels need to be established to assign a specific quality degree to a particular soil (Doran and Parkin, 1994). Doran et al. (1994) considered that highest soil quality (reference level) would correspond to natural undisturbed lands, showing a long-term dynamic balance between physical, chemical and biological properties. This idea has also been addressed in several studies comparing cultured with non-cultured soils in order to quantify the loss of quality (de Haan et al., 1993). However, Sojka and

Upchurch (1999) questioned this assumption arguing that well-managed soils do not damage the environment and are much more productive than natural soils, and could consequently be considered as of higher quality.

Despite the fact that soil quality has been subjected to extensive research (Singh and Tripathy, 1992; Jurgensen et al., 1996; Sahani and Behera, 2001, and references therein), most of these studies have been carried out in humid sites where the spatial distribution of vegetation and the associated organic matter tend to be homogeneous. This is not the case with Mediterranean ecosystems, where soil organic matter presents large spatial heterogeneity associated to marked landscape fragmentation in a mosaic of vegetation types resulting from small local variations in climate, topography, soil properties and human colonization (Sánchez-Marañón et al., 2002; Miralles et al., 2007). Finally, only few studies such as that by Franzluebbers (2002) have proposed descriptors for soil quality under different use and vegetation without considering the natural reference.

Assuming the above limitations, the main objective of the present research is establishing suitable quantitative soil quality descriptors of general application irrespective to the main types of soil use and management in forest and agricultural areas, using the natural park Sierra María-Los Vélez, (Southern Spain) as a model scenario for mountainous Mediterranean environments.

MATERIALS AND METHODS

Study area

Sierra María-Los Vélez Natural Park lays in the Southern Iberian Peninsula, in the

Northern part of Almería province (Figure 1). The Mediterranean-type climate has marked continental features, ranging from semi-arid to sub-humid, displaying mild temperatures, and irregular and torrential rainfall (erosivity K-factor 1000–1500 MJ mm ha^{-1} h^{-1} yr^{-1}, which is strongly influenced by the topography). The annual temperature is between 12 and 18 ºC and the rainfall is between 300 and 500 mm. Altitude ranges between 800 and 2045 m.a.s.l., and slopes show frequent abrupt changes in their gradient, shape and direction (Table 1). Above 1800 m.a.s.l. high-mountain scrub occurs consisting of *Vella spinosa* Boiss., *Erinacea anthyllis* Link. and *Lygeum spartum* L. Between 1800 and 1400 m.a.s.l. there is a more developed vegetation, in addition to natural forests with *Pinus nigra* Arnold., *Quercus ilex* L. and *Juniperus phoenicea* L. associated to old pine reforestations (between 60–90 years) with *Pinus halepenis* Mill. This vegetation is accompanied by abundant brushwood of *Quercus coccifera* L., *Juniperus oxycedrus* L., *Cistus laurifolius* L.*, Rosmarinus officinalis* L., *E. anthyllis*, *Festuca* sp., *Helianthemum* sp., *V. spinosa*, *Genista scorpius* (L.) DC, *Teucrium* sp. Below 1400 m.a.s.l. there are recent pine reforestations (<60 years) of *P. halepensis* and natural communities represented by thyme and grasslands (*R. officinalis*, *G. scorpius*, *Artemisia* sp., *Stipa tenacissima* L., *L. spartum*, *Thymus* sp., *Lavandula latifolia* Medic., *Teucrium* sp., and *Salvia* sp.). These areas are also occupied by agricultural crops, mainly cereal, almond trees and olive trees under conventional tillage (with ploughing, harrowing and addition of synthetic fertilizers and pesticides).

Soil sampling and analysis

The soil samples (30 uppermost cm) were collected from 68 soil plots (19 in Leptosols, 18 in Calcisols, Vertisols and Luvisols, and 31 in Kastanozems and Chernozems) representative for different topography, vegetation and use (pine tree, evergreen oak, Spanish juniper, bush, olive tree, almond tree and cereal under conventional tillage) and with different age of the forested areas (natural pine, pine reforestation between 60 and 90 years, and reforested pines of less than 60 years). Up to 15 quantitative characteristics of the soils associated with its ecological functions of environmental protection were selected as indicators to assess soil quality (Doran and Parkin, 1996; Brejda et al., 2000; Sánchez-Marañón et al., 2002). Free Fe and $CaCO_3$ were included as relevant variables in Mediterranean calcimorphic soils (Miralles, 2007).

Soil particle-size distribution (sand, silt and clay) was determined with the Robinson’s pipette method (Gee and Bauder, 1986), and the organic C content according to Nelson and Sommers (1996). The $CaCO_3$ was measured with Bernard’s calcimeter (Loeppert and Suarez, 1996). Water holding capacity was calculated at -33 and -1500 kPa with the Richard’s pressure-membrane extractor (Richards, 1954) and total N with the method of Kjeldahl (Bremner, 1996). The pH was determined in soil-water suspensions at 1:1 in weight (Thomas, 1996). The cation exchange capacity (CEC) and base saturation were measured after extraction with ammonia acetate solutions (Sumner and Miller, 1996). Free Fe was determined by colorimetry in extracts of sodium citrate–dithionite (Holgrem, 1967). Bulk density was measured from undisturbed soil cores of known volume, and the real density with a pycnometer (Blake and Hartge, 1986). The total porosity was calculated from the real and bulk densities, and the macroporosity (defined as pores with equivalent diameter >75 micrometers) was obtained by difference between total porosity and microporosity (water volume to -33 kPa). The erodibility (USLE *K* factor) was estimated with the method of Wischmeier and Smith (1978). Aggregate stability was determined by wet sieving (Kemper and Rosenau, 1986).

Topographical attributes

Slope and altitude of the study area were recorded during field sampling and a set of additional topographical attributes were calculated with the Geographic Information System ArcGIS 9.0 and Solar Analyst 1.0 from a digital terrain model with a cell size of 20 m. The data obtained were: topographic distance to the nearest stream, wetness index as related to the spatial distribution and size of zones of saturation or variable source areas for runoff generation (Beven and Kirkby, 1979), length slope factor i.e. the effect of topography on the sediment transport processes of water flow at a given point of the landscape (Moore and Burch, 1985), slope profile curvature (speed changes in runoff and sediment transport processes), plan curvature i.e. a measure of convergence/divergence topography and the extent of landscape water concentration (Moore et al., 1991), and global solar radiation calculated as the sum of the values of direct and diffuse solar radiation (Pearcy et al., 1989) in the summer and winter solstices and equinoxes.

Statistical analyses

The variables under study were subjected to a descriptive statistical study and tested in terms of their normality prior to their processing using one-way analysis of variance (ANOVA) with multiple range test, Pearson correlation analysis, multidimensional scaling, principal components analysis, discriminant analysis and canonical regression. The factor *R*-mode analysis was designed using Kaiser ortogonal varimax rotation to find out the main components better fitting the experimental variables (Johnson and Wichern, 1992). The analyses were performed using Statgraphics Plus v.5.1 for Windows (2001) and Statistica v.6.0 (2001).

RESULTS

General and topographical features

It was determined that slopes are higher than 55% in the 39% of the total area of Sierra María–Los Vélez Natural Park, between 13 and 55% in a 51%, and lower than 13% in the remaining 10%. The wetness index values are high in areas with slopes lower than 5%, and the values of length slope factor are generally high (46% of the area with values above 20). This bears into a high potential for the transport of sediments, including organic matter, and hence into high erosion rates (up to 100 Mg ha^{-1} yr^{-1}) in local areas. The contrasting patterns of incident solar radiation, which have an important role on humification processes, also reflect the abrupt topography. Global irradiation in the overall study area ranges between 335 and 3845 W m^{-2} at the winter solstice, between 888 and 6518 W m^{-2} in the spring and autumn equinoxes, and between 3000 and 8730 W m^{-2} at the summer solstice (Table 1).

In general, soils at Natural Park are strongly carbonated, with $CaCO_3$ concentrations ranging between 175 and 590 g kg^{-1}. However, active $CaCO_3$ leaching processes are especially marked in soils with natural vegetation, located at the uppermost areas with strong rainfall. The dominant soil granulometric fraction is clay, its content amounting between 219 and 483 g kg^{-1}. The highest percentage of sand was found in the southern slopes of the mountain ranges, in the most degraded soils. The organic C values ranged from 12 g kg^{-1} in crop areas to 51 g kg^{-1} in natural forest areas (Table 2), with an overall mean value of 28.5 ± 4.6 g kg^{-1} (95% confidence). Soil humus is usually of a high degree of transformation (*mull* or calcic *moder*). The pH values in water suspension were slightly alkaline and the CEC ranged between 17 and 34 $cmol_c$ kg^{-1} (Table 2).

Soil quality indicators under different vegetation and use types

The soils under natural pine forests, evergreen oak forests and juniper forests showed the highest values for organic matter content, clay, total porosity, macroporosity, aggregate stability and CEC, and the lowest ones for erodibility, pH and bulk density (Table 2). On the contrary, cultured soils (conventional tillage), bush and pine forests of recent reforestations (< 60 years) showed the opposite behaviour. The soils under old reforested pine forests (90–60 years) showed intermediate values in most soil properties between natural forest soils and degraded soils (cultured, scrublands or recently reforested soils).

The higher total N values were found in soils under juniper forest (4.2 g kg^{-1}), followed by soils under natural pine forest (2.6 g kg^{-1}), evergreen oak forest (2.2 g kg^{-1}), old pine-reforested soils (2.2 g kg^{-1}), secondary bush (1.6 g kg^{-1}), recently reforested soils (1.4 g kg^{-1}),and cultured soils (1.1 g kg^{-1}). Soils under natural pine forest had the highest C/N ratio, suggesting low transformation of plant litter, and reaching suboptimal values (C/N between 15 and 20) in soils reforested with pine (< 60 years) and under evergreen oak. The soils under juniper, the old pine-reforested soils and the cultured soils also showed C/N ratios (C/N= 13, 14 and 14, respectively) frequently found in active soils with favourable agrochemical characteristics, although somewhat lower than the previous ones. The soils under secondary bush showed the lower C/N ratios (Table 2).

The content of organic matter and clay, as well as the macroporosity and total porosity, progressively decreased from the soil under natural pine forest to the old-reforested pine soils, and to the more recently pine-reforested soils (Table 2). All these features are connected with the parallel increase of surface runoff and erodibility (USLE *K* factor= 0.1 in pines of 60–90 years, and 0.2 in pines less than 60 years). In addition, the recently reforested soils showed high pH and bulk density, and low CEC, compared to the soils under natural pine forests (Table 2).

The soils under bush showed high erodibility (USLE *K* factor= 0.3), as well as lower organic matter content (15.4 g kg^{-1}), total porosity, macroporosity and aggregate stability than the other soils. The CEC was also reduced after bush encroachment (19.0 $cmol_c$ kg^{-1}), although it is still higher than those in reforested and cultured soils (17.4 and 17.8 $cmol_c$ kg^{-1}, respectively). These soils also showed higher values of $CaCO_3$ compared to natural pine forests, evergreen oak and juniper forests (Table 2).

The cultured soils presented concentrations of N, and particularly of organic C, much lower than the rest of the soils, as well as lower aggregate stability (Table 2). Furthermore, the bulk density show a very high value (1.3 g cm^{-3}), which is connected with very low total porosity (0.5 cm^3 cm^{-3}) and macroporosity (0.1 cm^3 cm^{-3}), which are associated to low infiltration rates and high erodibility (USLE *K* factor 0.3). The high concentration of carbonates, in addition to the low content of organic matter, lead to a higher pH and a lower CEC than in the other soil use classes (Table 2).

The soils under juniper, natural pine and evergreen oak forest showed lower available water (0.8, 0.8, and 1.0 mm cm^{-1}, respectively) than recent pine reforestations (1.1 mm cm^{-1}), old pine-reforested soils (1.2 mm cm^{-1}), secondary bush (1.4 mm cm^{-1}) and crops (1.5 mm cm^{-1}).

According to the analysis of variance and multiple range test, the soils under natural pine, evergreen oak and juniper forest (Table 2) showed significant ($P< 0.05$) differences with the rest of the soil groups in most quality descriptors, with weak significant differences between them. The soils reforested with pines between 60–90 years showed significant differences with natural pine forest in C content, pH, water content at -1500 kPa, total porosity, macroporosity and bulk density; with evergreen oak forest in $CaCO_3$ content, pH and water content at -1500 kPa; and with juniper forest in N content, pH, free Fe, water content at -1500 kPa, total porosity and bulk density (Table 2). There were no significant differences between old pine reforestations and recent pine reforestations, and only small significant differences of the former soils with the ones with scrubland for erodibility, and with crops for erodibility and aggregate stability. Significant ($P< 0.05$) differences between soils under bush and crops were found only for aggregate stability, the latter group displaying slightly less favourable values in most of the quality indicators studied.

DISCUSSION

The quality of soils

Soils developed under natural pine forest, evergreen oak forest and—to a lesser extent—the undisturbed soils under juniper showed comparatively high quality levels, compared with soils under reforested pine forests, crops and secondary bush. This suggests that the favourable conditions associated with the original vegetation cover in these soils are reflected in a high organic matter content, which favours the formation of stable aggregates (Smith et al., 2000; Schoenholtz et al., 2000), and the consequent increase in total porosity, macroporosity (Table 2), aeration and percolation of water into the soil. The dense undisturbed vegetation on these soils and their organic matter richness contribute to a slow surface runoff, promote infiltration and reduce erodibility (Bulygin and Lisetskty, 1991). All these characteristics point to the proper functioning of the nutrient cycling, drainage, water storage, and resistance to erosion, which are soil functions with an outstanding role on the environment conservation (Guilley et al., 1997).

When comparing soils under pines of different ages (Table 2), it was observed that soils reforested with pines between 60–90 years tend to show levels of organic matter similar to those of the undisturbed soils under natural pine forest, which is associated to improved aeration, drainage, water holding capacity, and stability against erosion. Therefore, and despite some soil quality indicators such as organic matter, N, CEC, water retention at -33 and -1500 kPa, erodibility, total porosity and macroporosity are lower than in native forest soils, it is observed a trend of these soils to recover the initial quality level of undisturbed soils (Table 2). Similar patterns have been described by several researchers in different climatic conditions (Islam and Weil, 2000; Lemenih et al., 2005; Nogueira et al., 2006). However, the environmental quality of recent pine-reforested soils (< 60 years) and bush is still far from the original levels found in the corresponding undisturbed forest soils.

The cultured soils (conventional tillage) had the lower organic matter and N levels, as a result of the loss of plant cover and the culture practices applied. This is a typical situation in calcimorphic soils where encapsulated organic matter in soil microcompartments is temporarily protected against biodegradation, but periodic tillage causes aggregate breakdown, exposing to enzymatic attack previously protected organic matter (Nardi et al., 1996; Almendros, 2008). Due to the compaction caused by the agricultural practices and grazing, soil bulk density increases and the porosity significantly decreases (Islam and Weil, 2000), affecting negatively and specifically water circulation, drainage within the pores and infiltration, and increasing the risk of soil erosion (Islam and Weil, 2000).

Low levels of available water in natural pine forests, evergreen oak and juniper as regards to cleared soils under bush and crops, although not statistically significant, (Table 2) could possibly be associated with the emergence of hydrophobicity phenomena. Pine litter decomposition favours the accumulation of aliphatic substances associated with the hydrophobicity of the soil (Walter, 2002), a fact which has also been noted by Savage et al. (1972) for certain soils under evergreen oak and pine forests, which showed a resistance to water percolation between low to severe after the water drop penetration time hydrophobicity test. The lowest values of available water were observed in soils with high organic matter content, usually with *mor* humus (Imenson et al., 1992) as well as in sites under climacic pine and evergreen oak forests, with a developed O horizon (Crockford et al., 1991). The decline of available water in soil under pine with increased age could also be explained by the accumulation of strongly hydrophobic organic matter, which has also been noted by other authors (Teramura, 1980; Walter, 2002).

The granulometric composition showed differences between soils under different vegetation types; the soils under natural pine forest showed higher clay values (mean= 343 g kg^{-1})—although not statistically significant—than pine-reforested soils (323 g kg^{-1}

for pines 90–60 yr and 219 g kg^{-1} for pines with less than 60 yr) and bush (mean= 310 g kg^{-1}). As pointed by Lal (1989) and Narain et al. (1990) soil erosion, which generally increases with deforestation, lead to selective loss of clay during the wettest months. This agrees with our results, where clay content decreases in the soils lacking of vegetation cover. In fact, many researchers have studied the loss of clay associated with the conversion of forest soils into other uses (Prasad et al., 1994; Hajabbasi et al., 1997). The major clay fraction also favours the formation of stable aggregates in areas with pronounced slope (between 13–19%, Table 1), thus reducing the denudation of these soils (Sahani and Behera, 2001). Crops are located in topographically more favourable positions and areas with sediment accumulation; hence, despite agricultural practices these soils have a high content of clay (358 g kg^{-1}).

Relationships between soil quality indicators

Organic C, N and CEC were the soil quality indicators showing higher correlation indexes ($P < 0.05$). The content of organic C presents correlation indices greater than 0.8 ($P < 0.001$) with N, CEC, water retention at -33 and -1500 kPa, total porosity, macroporosity, bulk density and erodibility (Table 3), and was positive for aggregate stability ($r = 0.40$). These correlations confirm the chief role played by organic matter in sustaining the physical, chemical and biological properties of Mediterranean ecosystems (Stevenson, 1994; Sánchez-Marañón et al., 2002). On the other hand, the organic C showed negative correlations with the pH measured in water ($r = -0.67$), the $CaCO_3$ content ($r = -0.42$) and the available water ($r = -0.37$). The negative correlation with the $CaCO_3$ content (Table 3) is expected from the preferential accumulation of organic matter in acid humus types. The negative correlation between organic matter and available water (Table 3) was also expected from the primary biomass production (Walter, 2002). The contents of clay, free Fe, N and aggregate stability show a pattern of correlations similar to that for the organic carbon (Table 3), also reflecting the impact of soil use and management practices.

The $CaCO_3$ content also correlates positively with the percentage of sand, pH, bulk density and erodibility, and negatively with the content of N, clay, Fe, total porosity, macroporosity, and water retention at -33 and -1500 kPa (Table 3). Such correlations showed that the soils with higher carbonate content would be more skeletal and less evolved, with lower porosity (r= -0.51) and increased bulk density (r= 0.53), and therefore more prone to erosion (r= 0.57) due to the reduced infiltration and the favoured runoff. This leads to decreased fine fractions by erosion (r= -0.60) and consequent increased sand content (r= 0.47). A low clay content is also associated with the depletion of the exchangeable complex (r= -0.73) and water retention at -1500 kPa (r= -0.60), whereas the positive relationship with the pH (r= 0.57) is also expected from the effect of $CaCO_3$ on the soil reaction.

The pattern of correlations observed for soil pH (Table 3) is consistent with the relative concentrations of organic matter and carbonates, whereas the correlations between the water retention at -33 and -1500 KPa, total porosity, macroporosity, bulk density and soil erodibility also agree with the above considerations.

Relationships between soil quality indicators and topographical features

In general, individual topographic characteristics presented significant but low correlations (P<0.5) with the rest of the variables analyzed (Table 4). This may be due to the fact that their effect on soil chracterstics is essentially indirect and there are several factors implicated (Uset and Borroto, 2001). It could be highlighted the positive correlation between altitude, organic matter and N content, which could be mainly attributed to the coincidence of the main forests in the higher part of the study area, where increased precipitation and comparatively low temperatures slow down the mineralization of organic matter (Table 4). The increase of organic matter content with altitude is also associated with the increase in CEC (*r*= 0.42), aggregate stability (*r*= 0.36) and soil water retention at -1500 kPa (*r*= 0.33). This favours water infiltration and reduces erodibility (*r*= 0.40). The inverse correlation between altitude, $CaCO_3$ and pH (Table 4) could be explained by the accumulation of $CaCO_3$ at lower altitude. Also climate presents a clear altitudinal gradient, the precipitation increasing with altitude, favouring the leaching of carbonates and exchangeable bases, with a concomitant decrease in pH. The inverse relationship between altitude and available water (*r*= -0.26) could be explained by hydrophobicity phenomena occurring in very productive sites at high altitudes with large amount of organic matter mainly derived from the slow decomposition of the pine biomass (Miralles et al., 2007).

With regard to the relationships between the slope and soil variables, the results suggest high values of organic C, N, aggregate stability and CEC in sites with pronounced slope (Table 4), generally found at comparatively higher altitude with greatest density of vegetation cover. It was observed that, in general, areas characterized by low slope (< 5%) and altitude (< 1200 m.a.s.l.), which have been cleared and cultured, showed a decline of the original soil properties. Nevertheless, despite the steep slopes, the increased density of the vegetation cover reduces surface runoff, and therefore erodibility of soils (*r*= -0.29).

The correlation between the slope profile curvature and organic C, N, free Fe and water retention at -33 kPa (Table 4), indicate that these variables increased with the pronounced concavity in the direction of the longitudinal slope. Thus, in the study area, and irrespective to altitude, concave areas have greater organic C and N contents, which are indicative of soil evolution. This agrees with Walter (2002), which found that concave areas are the most stable sites from the geomorphological point of view.

The correlations between direct and global solar radiation and the amounts of sand and silt (Table 4) indicate that the soils more directly exposed to solar irradiation also presented thicker textures. This is in agreement with the above set of correlations, and is also associated to soils with comparatively lower evolution which, in general, present low content of organic matter, and therefore low CEC (r= -0.26).

Wetness index was positively correlated with bulk density, and negatively correlated with total porosity (Table 4); suggesting soil compaction in areas of accumulation of runoff water. The positive correlation (r= 0.33) between this variable and pH could indicate that water runoff saturated in carbonates concentrates in areas with a higher tendency to water accumulation, i.e. with higher values of wetness index. It was also observed that soils located at a higher distance to the nearest stream tend to have significantly (P<0.05) higher concentrations of N, and lower values of available water and pH (Table 4).

Overall interpretation of the soil quality descriptors

Preliminary data analysis based on multiple regressions, cluster analysis and multidimensional scaling were applied to reduce the number of variables for further data treatments and to minimize the degree of intrinsic redundancy of the data matrix. These analysis suggested that the set of classical soil quality descriptors examined in the site under study show large colinearity, the soil organic C embracing most of the total variance of the whole set of quality descriptors. For this reason, the number of quality descriptors were reduced based on numerical taxonomy criteria i.e., clusters of variables showing the most significant reciprocal correlations. The independent application of discriminant analyses with classification factors consisting of vegetation and use types, topographic attributes, etc., was also useful to remove redundant variables after processing the whole set of variables using the automatic backward variable selection. This treatment failed in showing sharp sample clusters with any of the above classification factors, hence suggesting that samples could be classified in terms of a gradient of soil quality to a large extent controlled by soil variables with a more intense effect than that of the mineralogical and vegetation characteristics. For this reason, after the previous variable assessment, principal component analysis was carried out using a reduced set of 10 variables including soil physical and chemical characteristics as descriptors.

Figure 2 showed a classification of sample points in the space defined by the two first axes calculated by principal component analysis. The direction of the eigenvalues illustrates that strong correlation remains between total organic matter with variables such as CEC, water holding capacity at -1500 kPa, aggregate stability, C/N and total porosity. Concerning sample classification, this Figure suggests a sample cluster where the favourable properties of soils are but side-effects of the accumulation of soil organic matter. To some extent, the soil quality defined by this set of variables mainly reflects the difference between forest and cleared soils.

The pattern is different when those soil descriptors more strongly correlated with soil C are expressed as ratios to total soil C. The new descriptors are expected to inform on soil organic matter quality (or activity), i.e., total cation exchange positions per kg of soil organic carbon or the aggregation capacity of soil organic carbon. In fact, this is a classical strategy to refer data for microbiological and enzymatic activities of the soils, which it is assumed to depend on the amount of substrates in the soil (Gil-Sotres et al., 2005). The new sample arrangement obtained with these ratios (Figure 3) clearly illustrates neat differentiation between forest soils with raw humus but high concentration of organic matter, and cleared soils with low C amounts and enhanced physico-chemical characteristics and stable structure reflected by e.g. high water holding capacity per unit of soil C. Such a new cluster of soils is defined by resilient or matured organic matter and mainly includes crops, bush and some recent pine forests (<60 years). In this new scenario, the organic matter in the second group of samples, in comparatively lower amount, could be considered as less influenced by the effects of climatic change than the litter-based humus formations represented in the other cluster, which consisted of samples where the soil C sequestration processes could be considered as not sustainable.

Figure 3 also illustrates the above-indicated fact that humus quality does not primarily depend on the impact of vegetation type, this scatter diagram suggesting that organic matter quality depends on the accelerated biogeochemical cycle in cleared sites. In this cluster there was also a series of pine forests (mainly recent reforestations) where favourable physico-chemical properties per unit of soil C are associated with the previously mentioned geomorphological constraints favouring advanced humification processes.

CONCLUSIONS

Soil quality indicators (hydrophysical and agrochemical soil descriptors) examined in calcimorphic soils developed in the continental Mediterranean site under study were found highly responsive to forest age, forest conservation and topographical constraints.

The bearing of topographical constraints on soil quality descriptors has been quantified, yielding useful information to separate homogeneous soil environments and reference levels of soil quality.

The analysis of the original data set led to a selection of environmental proxies useful for Mediterranean soils in a scenario where large proportion of the total variability in soil characteristics depends (or at least is conspicuously reflected by) the total quantity and the quality of the soil organic matter.

Classical soil quality descriptors showed large mutual redundancy. Soil organic C is involved in the most significant ($P< 0.05$) correlations between soil variables.

The proposed new indicators consist of ratios with the organic C content, with potential usefulness as surrogate indicators of soil resilience. In the area under study these indicators show a contrasting behaviour as regards the previous indicators (conventional or previously described raw soil variables).

Some soils (such as ancient forest and those at the uppermost areas of the mountain system) could be considered as representative for the highest levels of soil quality because of their favourable physical and chemical properties exclusively associated to the high concentration of organic matter. Nevertheless, these soils display organic matter with low degree of humification. When using the ratios between the soil quality indicators to the organic C content, the cleared soils under bush and crops—in stable geomorphological systems with comparatively lower amount and more transformed organic matter—, showed the most favourable values. This suggests the sustainable improvement of soil properties in these comparatively resilient biogeochemical scenarios.

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Table 1. Topographical features of the study area, Sierra de Maria-Los Velez Natural Park.

Soils under	**Altitude**	**Slope**	**PLC**	**SPC**	**DIST**	**LSF**	**W**	**RUNN**	**DIF_S**	**DIR_S**	**GLOB_S**
Natural pine forest	1314	17 (10)	-0.0005	0.0005	2.4	49.6	8.8	6.8	618	852	1470
	(272)		(0.0042)	(0.0053)	(1.4)	(52.4)	(1.0)	(8.9)	(26)	(686)	(675)
Reforested pine forest (60–90 yr)	1126	19 (11)	0.0011	-0.0024	2.8	51.6	9.5	9.4	578	805	1383
	(173)		(0.0066)	(0.1000)	(1.9)	(30.7)	(2.6)	(7.6)	(37)	(597)	(615)
Reforested pine forest (< 60 yr)	1206	16 (8)	0.0017	-0.0023	3.0	59.8	9.7	49.9	610	1201	1812
	(197)		(0.0032)	(0.0062)	(2.2)	(43.4)	(1.6)	(134.0)	(31)	(686)	(693)
Evergreen oak forest	1217	13 (5)	0.0018	-0.0012	2.0	45.4	9.9	16.7	610	871	1481
	(154)		(0.0030)	(0.0060)	(0.8)	(33.5)	(1.1)	(14.9)	(28)	(339)	(331)
Juniper forest	1040	14 (5)	-0.0059	0.0026	4.3	18.2	7.6	1.4	607	1321	1929
	(216)		(0.0071)	(0.0024)	(1.9)	(7.7)	(0.7)	(0.9)	(29)	(488)	(494)
Bush	1179	14 (8)	0.0006	-0.0025	4.0	48.3	9.2	13.6	597	1216	1813
	(267)		(0.0022)	(0.0042)	(2.7)	(56.5)	(1.1)	(20.8)	(57)	(434)	(476)
Crops	1068	6 (3)	-0.0005	0.0002	2.0	11.8	10.9	15.1	629	1061	1690
	(147)		(0.0024)	(0.0023)	(1.8)	(9.1)	(4.3)	(22.4)	(12)	(193)	(194)

Altitude (m.a.s.l.); Slope (%); PLC: Plan curvature; SPC: Slope profile curvature; DIST: Distance to the nearest stream (m); LSF: Length slope factor; W: Wetness index; RUNN: Runoff (m^2); DIF_S: Diffuse solar radiation in the winter solstice (W m^{-2}); DIR_S: Direct solar radiation in the winter solstice (W m^{-2}); GLOB_S: Global solar radiation in the winter solstice (W m^{-2}). Mean and standard deviation (in parenthesis) in soil groups with different vegetation and use.

Table 2. Analysis of variance for soil quality indicators using vegetation and land use as classification factors

Indicator	**F-ratio**	***P***	**Mean and standard deviation (in parenthesis) for each group (†)**							**Multiple range test(‡)**
			Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5**	**Group 7**	**Group 8**	
Total C (g kg^{-1})	12.9	0.0000	51.2	27.9	18.6	37.8	15.4	48.4	11.5	1–2, 1–3, 1–5, 1–8, 3–4, 3–7, 4–5, 4–8, 5–7, 7–8.
			(19.9)	(9.0)	(12.0)	(16.7)	(7.3)	(19.5)	(5.8)	
Total N (g kg^{-1})	5.9	0.0001	2.6	2.2	1.4	2.2	1.6	4.2	1.1	2–7, 3–7, 4–7, 5–7, 7–8.
			(2.4)	(1.1)	(1.0)	(0.7)	(0.7)	(2.1)	(0.7)	
C/N	1.4	0.2391	37.4	13.9	19.5	18.6	10.8	12.6	13.5	–
			(55.4)	(5.0)	(22.2)	(8.2)	(2.9)	(4.0)	(9.8)	
Sand (g kg^{-1})	5.5	0.0001	275.2	337.7	464.7	225.3	292.7	170.7	292.0	1–3, 3–4, 3–7, 3–8.
			(102.7)	(114.9)	(121.0)	(119.8)	(160.6)	(124.7)	(112.3)	
Clay (g kg^{-1})	5.2	0.0002	343.1	323.0	219.1	461.4	309.9	482.8	357.8	3–4, 3–7.
			(137.1)	(97.9)	(63.9)	(165.3)	(94.9)	(139.1)	(122.1)	
Fe (g kg^{-1})	3.8	0,0025	8.3	4.8	4.7	10.8	4.4	14.1	4.8	2–7, 3–7, 5–7, 7–8.
			(4.1)	(2.8)	(3.2)	(9.1)	(2.7)	(9.8)	(3.9)	
CaCO$_3$ (g kg^{-1})	7.7	0.0000	258.8	554.0	625.1	172.4	584.8	212.4	589.9	1–3, 1–8, 2–4, 3–4, 3–7, 4–5, 4–8.
			(228.4)	(217.5)	(305.3)	(179.1)	(126.6)	(270.2)	(171.1)	
pH (H$_2$O)	4.4	0.0010	8.1	8.4	8.4	8.1	8.3	8.1	8.5	1–2, 1–3, 1–8, 2–4, 2–7, 3–4, 3–7, 4–6, 7–8
			(0.3)	(0.2)	(0.3)	(0.3)	(0.3)	(0.2)	(0.2)	
CEC (cmol$_c$ kg^{-1})	11.3	0.0000	32.9	23.8	17.4	32.7	19.0	34.3	17.8	1–3, 1–5, 1–8, 3–4, 3–7.

			(8.4)	(5.9)	(7.1)	(6.4)	(8.0)	(6.7)	(5.5)	
pF (-33 kPa)	4.8	0.0004	33.7	30.6	24.6	32.9	24.6	38.7	26.7	1–3, 3–7, 5–7, 7–8.
			(8.3)	(6.2)	(5.8)	(7.7)	(7.8)	(3.7)	(5.4)	
pF (-1500 kPa)	13.0	0.0000	26.5	16.8	11.2	25.1	15.1	28.9	15.7	1–2, 1–3, 1–5, 1–8, 2–4, 2–7, 3–4,
			(7.3)	(5.3)	(3.5)	(5.5)	(4.6)	(10.4)	(3.6)	3–7, 4–5, 4–8, 5–7, 7–8.
Total porosity (cm^3 cm^{-3})	9.3	0.0000	0.6	0.5	0.5	0.6	0.5	0.6	0.5	1–2, 1–3, 1–5, 1–8, 2–7, 3–4, 3–7,
			(0.1)	(0.0)	(0.0)	(0.1)	(0.0)	(0.1)	(0.1)	4–5, 4–8, 5–7, 7–8.
Macroporosity (cm^3 cm^{-3})	6.4	0.0000	0.3	0.1	0.1	0.3	0.1	0.3	0.1	1–2, 1–3, 1–5, 1–8, 4–5, 5–7.
			(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)	(0.1)	
Bulk density (g cm^{-3})	10.9	0.0000	0.9	1.2	1.3	0.9	1.3	0.9	1.3	1–2, 1–3, 1–5, 1–8, 2–7, 3–4, 3–7,
			(0.3)	(0.1)	(0.1)	(0.2)	(0.1)	(0.3)	(0.1)	4–5, 4–8, 5–7, 7–8.
Available water (mm cm^{-1})	2.4	0.0399	0.8	1.2	1.1	1.0	1.4	0.8	1.5	–
			(0.3)	(0.3)	(0.6)	(0.5)	(0.4)	(0.5)	(0.6)	
Aggregate stability	14.38	0.0000	0.9	0.9	0.9	0.9	0.8	0.9	0.7	1–8, 2–8, 3–8, 4–8, 5–8, 7–8.
			(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	
Erodibility, USLE *K* factor	12.7	0.0000	0.1	0.1	0.2	0.1	0.3	0.1	0.3	1–3, 1–5, 1–8, 2–5, 2–8, 3–4, 3–7,
			(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	4–5, 4–8, 5–7, 7–8.

† Group 1= Natural pine forest (*n*= 10); Group 2= Reforested pine forest (between 60–90 yr) (*n*= 12); Group 3= Reforested pine forest (< 60 yr) (*n*= 12); Group 4= Evergreen oak (*n*= 10); Group 5= Bush (*n*= 8); Group 7= Juniper forest (*n*= 5); Group 8= Crops (*n*= 11).

‡Only significant ($P< 0.05$) differences after Bonferroni's test are shown.

Table 3. Correlations between soil variables (n= 68)

	Total C	**Total N**	**Sand**	**Clay**	**Fe**	**$CaCO_3$**	**pH (H_2O)**	**CEC**	**pF (-33 kPa)**	**pF (-1500 kPa)**	**Tp**	**Mp**	**BD**	**AW**
Total N	**0.902**													
Sand	**-0.315‡**	**-0.314‡**												
Clay	**0.257***	0.207	**-0.801**											
Fe	0.129	0.117	**-0.434**	**0.532**										
$CaCO_3$	**-0.423**	**-0.401**	**0.471**	**-0.598**	**-0.605**									
pH (H_2O)	**-0.675**	**-0.641**	**0.435**	**-0.510**	**-0.266***	**0.565**								
CEC	**0.801**	**0.735**	**-0.501**	**0.536**	**0.435**	**-0.728**	**-0.752**							
pF (-33 kPa)	**0.831**	**0.801**	**-0.430**	**0.354‡**	0.174	**-0.405**	**-0.613**	**0.731**						
pF (-1500 kPa)	**0.894**	**0.849**	**-0.518**	**0.496**	0.217	**-0.600**	**-0.716**	**0.849**	**0.784**					
Tp	**0.803**	**0.634**	**-0.516**	**0.505**	**0.290#**	**-0.507**	**-0.666**	**0.767**	**0.694**	**0.758**				
Mp	**0.808**	**0.615**	**-0.240***	**0.285#**	0.173	**-0.396**	**-0.583**	**0.676**	**0.623**	**0.692**	**0.939**			
BD	**-0.831**	**-0.667**	**0.455**	**-0.470**	**-0.302#**	**0.527**	**0.731**	**-0.815**	**-0.706**	**-0.767**	**-0.976**	**-0.940**		
AW	**-0.372**	**-0.334**	-0.047	-0.099	-0.174	0.141	**0.500**	**-0.321‡**	**-0.294#**	**-0.308‡**	**-0.416**	**-0.529**	**0.489**	
AS	**0,403**	**0,334**	-0,007	0,024	0,150	-0,173	**-0,442**	**0,423**	**0,277#**	**0,277#**	**0,359‡**	**0,363‡**	**-0,463**	**-0,328‡**
Erod	**-0.914**	**-0.826**	**0.277#**	**-0.356‡**	-0.195	**0.556**	**0.635**	**-0.834**	**-0.768**	**-0.862**	**-0.700**	**-0.692**	**0.746**	**0.313‡**

Bold characters indicate significant correlations to $P< 0.001$, ‡ indicates significant correlations to $P< 0.01$, # indicates significant correlations to $P< 0.02$, and * indicates significant correlations to $P< 0.05$.

CEC: Cation exchange capacity; Tp: Total porosity; Mp: Macropores; BD: Bulk density; AW: Available water; AS: Aggregate stability; Erod: Erodibility.

Table 4. Correlations between soil characteristics and topographical attributes (*n*= 68)

	Altitude	**Slope**	**SPC**	**DIST**	**LSF**	**W**	**DIR_S**	**GLOB_S**
Total C	**0.357‡**	**0.272***	**-0.243***	0.091	0,103	-0.196	-0.223	-0.212
Total N	**0.436**	**0.252***	**-0.310‡**	**0.244***	0,065	-0.198	-0.179	-0.166
Sand	-0.034	-0.096	-0.140	-0.054	0,044	0.186	**0.244***	**0.246***
Clay	-0.030	-0.020	0.161	0.057	-0,154	-0.139	-0.081	-0.087
Silt	0.102	0.186	-0.023	0.000	0,167	-0.086	**-0.268***	**-0.263***
Fe	-0.003	-0.056	**0.246***	-0.034	-0,092	-0.115	-0.003	-0.001
$CaCO_3$	**-0.247***	0.038	-0.015	-0.001	0,173	0.161	0.049	0.040
pH (H_2O)	**-0.449**	-0.180	0.103	**-0.261***	0,060	**0.326‡**	0.016	0.006
CEC	**0.420**	**0.261***	-0.134	0.050	0,087	-0.217	**-0.255***	**-0.246***
pF (-33 kPa)	0.170	0.145	**-0.245***	0.057	0,042	-0.207	**-0.321‡**	**-0.310‡**
pF (-1500 kPa)	**0.325‡**	0.150	-0.214	0.111	-0,024	-0.118	-0.233	-0.221
TP	0.110	0.183	-0.059	-0.047	-0,014	**-0.262***	-0.223	-0.220
Mp	0.106	0.138	-0.102	-0.069	-0,004	-0.195	-0.182	-0.176
BD	-0.201	-0.226	0.057	0.002	-0,028	**0.269***	0.205	0.201
AW	**-0.258***	-0.111	-0.048	**-0.277**#	-0,005	0.210	-0.018	-0.033
AS	**0,357‡**	**0,449**	-0,044	0,097	**0,358‡**	-0,233	-0,080	-0,084
Erod.	**-0.396**	**-0.285**#	0.225	-0.075	-0,106	0.165	0.180	0.172

Bold characters indicates significant correlations at $P < 0.001$, ‡ indicates significant correlations at $P < 0.01$, # indicates significant correlations at $P < 0.02$, and * indicates significant correlations to $P < 0.05$.

CEC: Cation exchange capacity; TP: Total porosity; Mp: Macropores; BD: Bulk density; AW: Available water; AS: Aggregate stability; Erod: Erodibility; SPC: Slope profile curvature; DIST: Distance to the nearest stream; LSF: Length slope factor; W: Wetness index; DIR_S: Direct solar radiation in the winter solstice; GLOB_S: Global solar radiation in the winter solstice.

FIGURES

Figure 1. Location of the site under study.

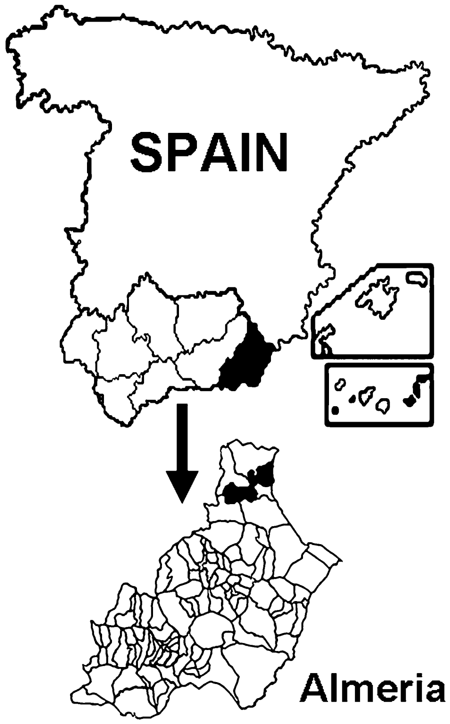

Figure 2. Scatter diagram of the scores for the samples in the space defined by the two first axes calculated by principal component analysis using soil physical and chemical variables as descriptors. Lines are also drawn for each of the original variables, representing their location in the components space. CEC: cation exchange capacity.

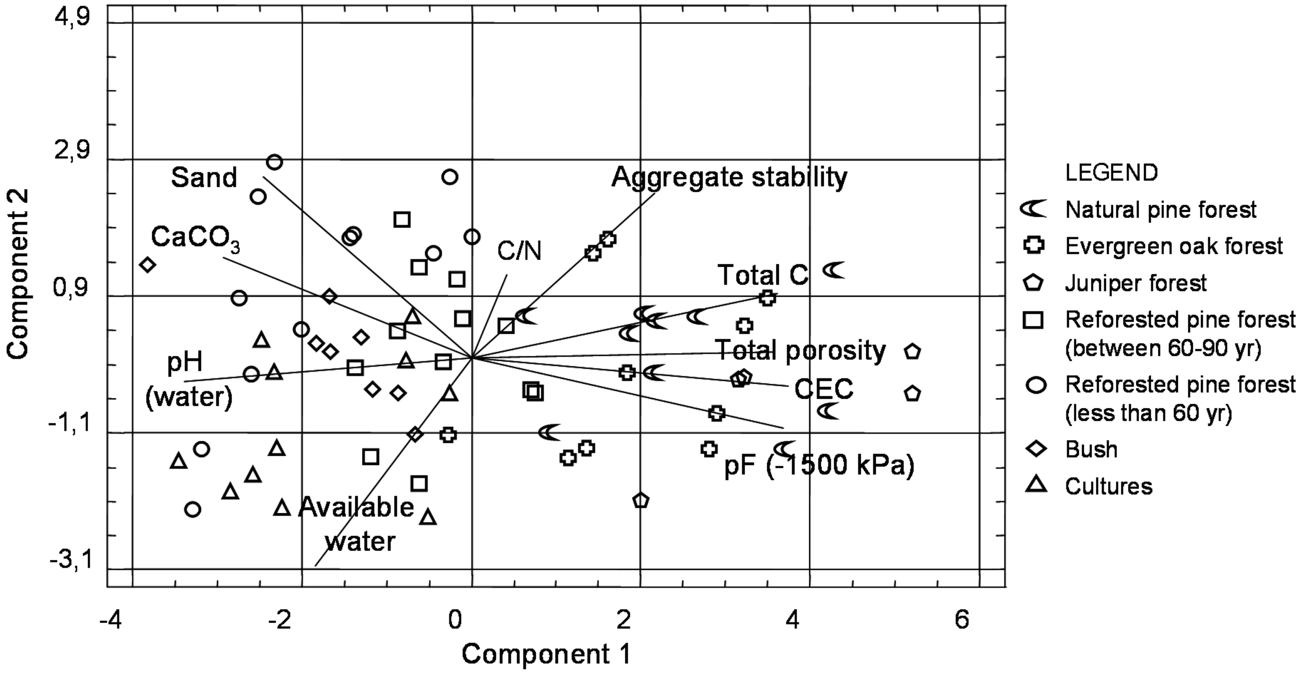

Figure 3. Scatter diagram of the scores for the samples in the space defined by the two first axes calculated by principal component analysis using soil physical and chemical variables as descriptors, in most cases calculated as ratios to total C. Lines are also drawn for each of the original variables, representing their location in the components space. CEC/C: cation exchange capacity to total C.