Discussion Paper

Pedodiversity and global soil patterns at coarse scales (with Discussion)

J.J. Ibáñez , S. De-Alba , A. Lobo , V. Zucarello

Abstract

Several algorithms for analyzing the diversity of the world pedosphere are reviewed and employed. Special emphasis has been laid on indices based on the Theory of Information. We study the diversity and distribution of major soil groups by continents and climatic zones on the basis of data compiled by the FAO at the scale 1 : 5,000,000. Major soil group–distribution model relationships on a world level seem to follow more equitable patterns than those established for biocenoses and soil patterns at fine scales. At a continental level, the pedosphere's diversity is characterized by similarities rather than differences. Differences in diversity by climatic zones are more marked. Evenness (Pielou's index) and diversity (Shannon's index) tend to be greater in the climatic zones of intermediate latitudes than in circumequatorial and circumboreal latitudes. The climatic zones closest to the Poles could be the planet's most uniform soil patterns at small scales. Mountain areas, in general, achieve the highest pedorichness and lowest values of diversity. Global soil pattern distribution was also analyzed using multivariate techniques. At a continental level, it is possible for the structure of the global pedosphere to be determined by the continent's geological, tectonic and climatic histories. Soil patterns of different climatic zones are linked in a very well-defined latitudinal gradient.

Keywords: soil; pedodiversity; global distribution; climate; plate tectonics

1. Introduction

The notion of diversity (e.g. Margalef, 1958; Pielou, 1966, 1975; Hughes, 1986) has been used widely in ecological studies, although almost exclusively for the biotic component (biodiversity) (e.g. McIntosh, 1967; Sugihara, 1980). The notion of diversity applied to the abiotic component (geodiversity) has had little impact on researchers (Ibáñez et al., 1990, 1994, 1995a,b; McBratney, 1992). The characterization and quantification of several aspects of geodiversity (e.g. geomorphological diversity, lithodiversity and pedodiversity) should be taken into account when estimating a territory's ecological value because it refers to non-renewable natural resources that have profound qualitative and quantitative repercussions on the architecture of landscapes, ecosystems and biocenoses (McBratney, 1992, 1995; Ibáñez et al., 1995a,b). At the same time, this may be one of the ways to explore, quantify and compare the complexity of abiotic landscape structures in different areas and environments (Ibáñez et al., 1995b).

Currently, several disciplines within the field of earth sciences have begun to develop new lines of research with the aim of tackling world-scale analyses. Such is the case of the world climatic system (e.g. Huggett, 1991), the megageomorphology (Baker et al., 1993), and the relationships of soils and plate tectonics (Paton et al., 1995). This work could fit within this latter type of approach. In a previous paper (Ibáñez et al., 1995b), we defined the concept of pedodiversity, expounded the main methodological tools for determining it and examined its possible applications in analyzing soil patterns. In this article we show how methods commonly used for estimating biodiversity may also be employed for analyzing the pattern of soil distribution on a world scale. We also analyze and discuss differences between continental and climatic zones in terms of their relative composition of major soil groups (MSG) (FAO, 1993), which, for some authors (Magurran, 1988) is equivalent to an analysis of the β-diversity of the global pedosphere.

The primary purpose of this paper is therefore didactic, to help to teach modern concepts of diversity in soil geography and soil survey at coarse scales. Before we display and interpret the results, some prior considerations must be taken into account. These will help to understand to what extent the conclusions obtained may be generalized.

Firstly, estimates of pedodiversity have been made on information from a very small-scale map (1 : 5,000,000). As a consequence of the map generalization process considerable information is not available. The value of such a map is precisely this synthesis of world soils, which facilitates an understanding of how soils relate to climate, vegetation and the geography of the continents (FAO, 1993). In other words, the results obtained can only be considered as very rough estimates. However, at present there are no more accurate data on a world scale other than those used here. Nevertheless, the aforementioned limitations are also present in other global data-sets (i.e., vegetation maps) and should not be used as an excuse to delay the analysis of the available data. In fact, among the natural resources (geology, vegetation, soils and water) the FAO Soil Map of the World SMW is the most detailed inventory completed on a global level (FAO, 1993).

Analysis of the diversity of the global pedosphere is limited, in this study, by partition of the starting information into continents and climates (FAO, 1993). As we explain in the corresponding section, we consider that both types of partition could be improved. For example, the mountainous climatic zone is highly peculiar, inasmuch as it displays a steep altitudinal gradient. In other words, mountainous environments have many climatic belts in short distances and, therefore, soilscape belts. Mountains do rise above the surrounding landscapes but then all sorts of diversity of soil forming factors and processes take place. In addition, the enormous climatic difference between different mountain regions in the world must also be taken into account.

At present, all soil classifications are substantially limited in their ability to describe the great structural and genetic variability of soils. Obviously, this fact is more marked when working with more general classification categories. Thus, the values obtained for indices of richness and diversity are determined by the maximum number of pedotaxa which the classification used allows. Only 26 MSGs appear in this analysis and, therefore, the magnitudes of these two variables are fairly low (of the 28 MSG the FAO soil keys allow in their 1988 version, only 26 appear, in view of the fact that no difference was made between Acrisols and Alisols, nor were Anthrosols considered due to lack of information available in the FAO–Unesco Soil Map of the World). Would similar trends to those obtained in this study be obtained using the second or third level FAO soil units (FAO, 1988)?

Until recently, most soil work has been done in the temperate climatic zone of Europe and North America, thus the pedologists of these countries have been able to define a greater number of soil types compared to other climatic zones in which fewer detailed studies have been made. We suspect that a similar trend will eventually occur in these other zones as more detailed surveys are undertaken and the data become available for use. This influences current soil classification schemes and available information in world scale maps. Therefore, soil class differentiae are biased towards temperate and, perhaps, Mediterranean climatic zones.

Current soil classification schemes are designed for agricultural purposes, and where agriculture is marginal (e.g. boreal and arid climatic zones) the pedosphere may appear through the classification and soil maps to be less diverse.

Many soils outside glaciated areas are polycyclic and/or have very deep profiles. However, most current classifications do not specify the difference between monocyclic and polycyclic soils. Emphasis on near surface features is common in soil classifications and this tends to minimize the influence of time and past climates on soil classifications and pedodiversity analysis.

In short, the conclusions obtained should be understood within the context of the data used, and therefore, at best, may serve to formulate a hypothesis which will require subsequent verification when more reliable and detailed information is available.

2. Material

We used data compiled by the FAO (1993) on the basis of the Revised Legend of the FAO–UNESCO Soil Map of the World (FAO, 1988). The FAO Report has two data tables which present the world distribution of the MSG. The

Table 1
Area (percentages) occupied by the major soil groups in accordance with FAO (1988) nomenclature for each continent, and global data in thousands ha (FAO, 1993)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Leptosols	5.8	26.8	5.9	4.8	13.7	8.3	12.0	13.1
Cambisols	14.1	17.1	9.8	9.7	13.2	14.7	6.6	12.5
Acrisols	0.4	5.6	3.9	6.6	3.3	18.3	16.6	7.9
Arenosols	0.3	0.1	23.4	1.4	16.5	6.6	5.8	7.1
Calcisols	5.1	3.6	13.8	6.6	6.1	15.3	1.2	6.3
Ferralsols	0.0	0.0	0.0	0.0	11.4	0.0	20.6	5.9
Gleysols	1.6	12.2	0.1	7.5	4.4	2.6	4.2	5.7
Luvisols	12.8	3.8	15.4	10.2	0.6	2.9	2.0	5.1
Regosols	2.4	1.3	0.1	16.2	5.0	4.5	1.4	4.6
Podzols	19.2	0.8	1.0	12.6	0.4	0.4	0.3	3.9
Kastanozems	5.0	6.5	0.2	8.8	0.1	0.0	3.9	3.7
Lixisols	0.0	0.0	0.0	0.0	8.8	6.0	5.1	3.5
Fluvisols	3.6	2.8	1.1	0.6	3.5	4.0	3.3	2.8
Vertisols	0.5	0.4	10.9	0.5	3.8	5.3	1.9	2.7
Podzoluvisols	14.5	5.8	0.0	0.3	0.0	0.0	0.0	2.5
Histosols	2.9	3.8	0.1	5.3	0.4	1.7	0.4	2.2
Chernozems	8.8	3.4	0.0	2.3	0.0	0.0	0.0	1.8
Nitisols	0.0	0.0	1.2	0.0	3.5	3.4	2.3	1.6
Solonchaks	0.3	1.8	2.0	0.1	1.7	3.4	1.2	1.5
Phaeozems	0.8	0.8	0.4	4.0	0.1	0.1	2.4	1.2
Solonetz	0.7	1.1	4.6	0.6	0.5	0.0	1.7	1.1
Planosols	0.2	0.1	4.7	0.4	0.7	0.3	2.7	1.0
Andosols	0.4	0.7	0.8	1.0	0.2	0.6	2.2	0.8
Gypsisols	0.1	0.6	0.0	0.0	1.8	1.5	0.0	0.7
Plinthosols	0.0	0.0	0.6	0.2	0.3	0.1	2.2	0.5
Greyzems	0.5	0.9	0.0	0.3	0.0	0.0	0.0	0.3
Total	1114.1	2648.2	826.6	1747.2	2797.9	1435.6	2055.8	12652.4

(1) Europe; (2) N-C. Asia; (3) Australasia; (4) N. America; (5) Africa; (6) S-SE. Asia; (7) S-C. America; (8) Percent of total.

Table 2
Area (percentages) occupied by the major soil groups in accordance with FAO (1988) nomenclature for each climatic zone, and global data in thousands ha (FAO, 1993)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Histosols	0.4	0.9	8.2	7.1	0.1	0.1	0.5	1.8
Leptosols	7.2	2.5	2.2	19.5	14.6	57.6	8.0	3.4
Vertisols	3.6	1.3	0.0	0.0	1.8	0.4	9.0	1.5
Fluvisols	3.4	2.5	2.9	1.7	3.1	0.5	3.4	3.4
Solonchaks	2.6	0.5	0.1	0.0	4.9	0.4	0.8	0.2
Gleysols	1.2	5.2	2.9	16.9	1.2	1.2	4.5	8.7
Andosols	0.4	0.7	1.3	0.8	0.3	2.2	0.7	1.1
Arenosols	5.5	1.5	1.1	0.0	13.8	0.7	13.0	6.6
Regosols	4.3	0.1	1.3	15.7	5.9	3.8	2.1	0.5
Podzols	1.6	5.1	20.3	10.1	0.1	0.3	0.5	0.6
Plinthosols	0.0	0.2	0.0	0.0	0.1	0.1	0.6	2.2
Ferralsols	0.0	0.0	0.0	0.0	0.0	0.4	9.3	26.3
Planosols	3.7	2.3	0.1	0.1	0.1	0.3	3.0	0.3
Solonetz	1.9	0.5	2.1	0.0	2.0	0.6	1.5	0.1
Greyzems	0.0	0.2	1.9	0.3	0.1	0.5	0.0	0.0
Chernozems	0.1	5.7	13.4	0.5	0.4	0.2	0.0	0.0
Kastanozems	6.5	11.4	8.8	0.6	5.0	1.8	1.8	0.1
Phaeozems	2.2	8.6	1.1	0.3	0.1	0.9	0.6	0.1
Podzoluvisols	0.0	3.8	14.6	6.0	0.0	1.8	0.0	0.0
Gypsisols	0.4	0.0	0.0	0.0	3.0	0.2	0.1	0.0
Calcisols	20.3	3.7	1.5	0.1	19.2	4.7	1.9	0.3
Nitisols	0.2	0.3	0.0	0.0	0.1	1.1	4.1	4.5
Acrisols	2.7	12.4	0.0	0.0	0.1	1.4	9.6	30.6
Luvisols	15.6	16.3	10.6	1.2	5.6	1.4	2.5	1.1
Lixisols	0.0	0.1	0.0	0.0	0.9	1.2	14.8	1.6
Cambisols	16.2	14.2	5.6	19.1	17.5	16.2	7.7	5.0
Total	422.3	1147.4	1050.4	1768.8	2875.2	945.8	2481.3	1926.0

(1) Mediterranean; (2) temperate; (3) cold; (4) boreal; (5) arid; (6) mountainous; (7) seasonally dry tropics and subtropics; (8) humid tropics and subtropics.

first gives MSG distribution by continents and the second by climatic zones (FAO, 1993). We used the information given in these tables to draw up two data matrices (Tables 1 and 2) to which the diversity analyses and multivariate statistical analyses were applied.

The climatic zones are distinguished on the basis of the present-day atmospheric climate (FAO, 1993). As such, they do not necessarily accurately reflect the soil climate in the sense used in the USDA Soil Taxonomy (Soil Survey Staff, 1975), nor do they always show a direct link with the major soil-forming processes (zonalistic approach), as they may have been determined to a greater or lesser extent by climates that prevailed in the past (FAO, 1993). As a basis for the definition of the eight climatic zones three primary parameters have been used: the length of the growing period, the length of the frost-free season and other temperature characteristics, and the seasonal rainfall concentration and variability (FAO, 1993).

3. Methods

3.1. Diversity

From a methodological point of view, the different ways of measuring diversity may be grouped into the following three categories (Magurran, 1988).

(1) Indices of richness: number of categories (e.g. biological species, communities, pedotaxa, soilscapes ...) known to occur in a defined sampling area.

(2) Indices based on proportional abundance of categories: not only the number but also their relative abundance (in our case, the relative area occupied by each pedotaxa) are taken into account.

(3) Models of the distribution of abundance of categories: these provide the most complete description but also the least abridged.

When there exists a possibility of delimiting the study area in space and time, as well as recognizing all the objects present, estimating richness proves to be extremely useful. If, on the contrary, only a sample and not the entire population can be obtained, it is necessary to distinguish between numerical richness (Kempton, 1979) and object density (Hurlbert, 1971). In the case of a soil survey, the former would be defined as the ratio between the number of different pedotaxa found and that of the pedons analyzed. The latter refers to the number of pedotaxa per sampling area.

Although there are numerous abundance models or distributions in the literature, most studies are based on only four (Magurran, 1988; Ibáñez et al., 1995b). These are the geometric series, the logarithmic series, the lognormal distribution and the broken-stick model (Magurran, 1988). Only the last one is original to the literature on biodiversity. According to this model, splitting or subdividing the pedosphere space into pedotaxa would be similar to a stick broken randomly and simultaneously into S fragments (Macarthur, 1957). There is a sequential order of distributions starting with the geometric series which is the least equitable (a few objects are dominant whilst the rest are very rare or infrequent), continuing with the logarithmic series and the lognormal distribution (where objects with intermediate abundance are most common) and ends with the broken-stick model (the most equitable) (Magurran, 1988).

Indices based on the proportional abundance of objects comprise the most frequent way of estimating diversity and may be classified according to the importance or to the weight each gives to richness and evenness. The most commonly used in ecology come from the Theory of Information. These are the

Shannon index (H', Shannon and Weaver, 1948) and the Brillouin index (BH, Brillouin, 1956). Only Shannon's algorithm will be utilised in this study:

$$H' = -\Sigma p_i \ln p_i \tag{1}$$

p_i is estimated by means of n_i/N where n_i is the area covered by the ith category (MSG) and N the total area studied. Relationships between entropy and information (Schrödinger, 1944; Brillouin, 1956) and between both and diversity (Margalef, 1958) have been postulated (Schneider, 1988). The relationship between the observed value of H' and its maximum value (for a given richness occurs when all MSG are equiprobable) is used as a measure of evenness (E) (Pielou, 1969):

$$E = H'/H\max = H'/\ln S \tag{2}$$

where S is the richness or number of categories and E takes values in the interval $|0,1|$.

Despite the high variety of proportional abundance of objects indices and evenness indices, with their respective virtues and defects, Magurran (1981, 1988) shows how most of them give highly correlated figures. The α, λ and Brillouin (BH) proportional abundance of object indices, maximum relative diversity (Hmaxr) and evenness Brillouin index (E^*) (Tables 3 and 4) are given with the purpose of providing information for those readers interested in studying the properties, potential and utility of other indices.

Table 3

Richness (S index), diversity indices (Hmax, Hmaxr, H', BH, α and λ indices), and evenness (E and E^* indices) with respect to the major soil group distribution (FAO, 1993) by continents and global data

	S	Hmax	Hmaxr	H'	BH	E	E^*	α	λ
Europe	22	3.09	0.95	2.42	2.37	0.78	0.78	1.66	7.6
N. and C. Asia	22	3.09	0.95	2.40	2.35	0.78	0.77	1.58	8.5
Australasia	20	3.00	0.92	2.30	2.26	0.77	0.77	1.56	6.6
North America	22	3.09	0.95	2.57	2.52	0.83	0.83	1.56	8.0
Africa	23	3.13	0.96	2.55	2.50	0.81	0.81	1.67	8.5
South and SE Asia	20	3.00	0.92	2.50	2.46	0.83	0.83	1.45	8.3
South and C. America	22	3.09	0.95	2.62	2.56	0.85	0.84	1.59	10.1
Global pedosphere	26	3.26	1.00	2.92	2.86	0.90	0.90	1.51	14.8

S = richness in mayor soil groups (MSGs).
H' = Shannon's diversity index. $H' = -\Sigma\ p_i \times \ln\ p_i$.
Hmax = maximum diversity. $H\max = \ln\ S$.
Hmaxr = maximum relative diversity. $H\text{maxr} = \ln\ S/\ln\ N\text{TOT}$.
BH = Brillouin's diversity index. $BH = (\ln\ N! - \ln\ p_i!)/N$.
E = Pielou's evenness index. $E = H'/H\max$.
E^* = Brillouin's evenness index. $E^* = BH/BH\max$.
α = index of the logarithmic distribution.
λ = index of the normal-logarithmic distribution.

Table 4
Richness (S index), diversity indices (Hmax, Hmaxr, H', BH, α and λ indices), and evenness (E and E^* indices) with respect to the major soil group distribution (FAO, 1993) by climatic zones (legend in Table 3)

	S	Hmax	Hmaxr	H'	BH	E	E^*	α	λ
Mediterranean	21	3.04	0.93	2.48	2.43	0.81	0.81	1.69	9.4
Temperate	24	3.18	0.97	2.58	2.53	0.81	0.81	1.78	8.7
Cold	19	2.94	0.90	2.43	2.38	0.82	0.82	1.38	9.6
Boreal	16	2.77	0.85	2.08	2.05	0.75	0.75	1.16	6.7
Arid	24	3.18	0.97	2.36	2.31	0.74	0.74	1.71	7.6
Mountainous	26	3.26	1.00	1.69	2.64	0.52	0.51	1.97	7.8
Dry tropics[a]	23	3.13	0.96	2.68	2.63	0.85	0.85	1.63	10.7
Humid tropics[b]	22	3.09	0.95	2.13	2.09	0.69	0.69	1.61	6.1

[a] Seasonally dry tropics and subtropics.
[b] Humid tropics and subtropics.

Computer programs developed by the International Center for Theoretical and Applied Ecology, Gorizia, Italy (CETA) (Ganis, 1991) were used for diversity analysis.

3.2. *Multivariate analysis of major soil group compositions*

The previous analysis of diversity does not consider the variation of MSG composition between different continents or climatic zones, which would be an analysis of 'differentiation diversity' in the terminology of Whittaker (1977). According to Magurran (1988) such an analysis could be considered as an analysis of the β-diversity of the global pedosphere, but other authors tend to restrict the concept of β-diversity to the degree of change of diversity indices across different areas. Beyond the terminology, it is clear that the analysis of the similarity of geographical units (continents or climatic zones in our case) in terms of their MSG composition complements their diversity analysis.

The following conventional multivariate statistical methods were applied.

(1) Cluster analysis was applied to a matrix of continents (elements) × MSG (variables) (Table 1) and to a matrix of climatic zones (elements) × MSG (variables) (Table 2), plotting dendrograms to show the patterns of similarity between the elements (continents and climatic zones) in terms of their relative abundance of MSG. Two square-distance matrices (chord distance) were computed from these data matrices. Cluster analysis was conducted by complete linkage based on the chord distance matrices (Anderberg, 1973; Orloci, 1978; Legendre and Legendre, 1983).

(2) Minimum spanning tree: simplifies the dendrogram by plotting the clusters according to a criterion of maximal intersection between the clusters (Gower and Ross, 1969; Westhoff and Van der Maarel, 1978; Feoli and Lagonegro, 1979).

(3) Principal coordinate analysis was conducted by the eigen analysis of both chord distance matrices (Feoli, 1977; Orloci, 1978; Legendre and Legendre, 1983). MSG and geographical units (continents and climatic zones) were plotted in the axis of the two first principal coordinates. These plots help to distinguish between the relative ordination of MSG and geographical units.

All analyses were performed using the SYNTAX IV package of programs (Podani, 1991).

4. Results and discussion

4.1. Diversity of global soilscapes

4.1.1. Pedosphere richness

Ibáñez et al. (1995a,b) showed how the richness of pedotaxa increases as the area sampled increases (Fig. 1). This trend has also been observed when analyzing the biodiversity–area ratio (Magurran, 1988). In contrast to these last studies carried out on more detailed scales (Ibáñez et al., 1995a,b), the existence of a clear relationship between pedorichness and area is not demonstrated at coarse scales.

The MSG richness (*S* values) is very similar in all continents (Table 3). Most MSG are represented in all continental units considered.

Differences in MSG richness by climatic zones (Table 4) are more marked. The mountainous climatic zone has the smallest area after the Mediterranean climatic zone, but also the greatest pedosphere richness. The Mediterranean climatic zone also has an average type global richness. Thus, Mediterranean and mountainous climatic zones have a MSG density far higher than that of the remaining types considered. Ibáñez et al. (1995a) also showed that in the European Union, soil richness of countries in the Mediterranean Basin is higher than in temperate and cold environments in central and northern Europe. Mancini (1966), Ibáñez et al. (1995c, 1996) and Yaalon (1997) demonstrate and try to find cause–effect relationships to explain the high soil richness of the Mediterranean climatic zone.

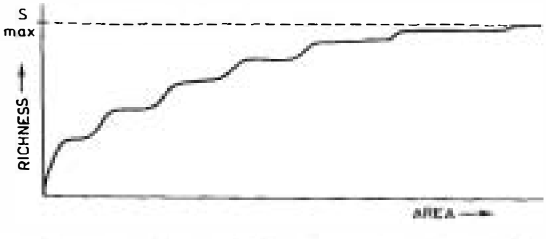

Fig. 1. Hypothetical curve of object richness saturation as the sampling area increases.

The climatic zones closest to the Poles (boreal and cold) also have the lowest pedorichnesses. This is particularly true for the boreal climate, where, in addition, MSG density reaches the second lowest figure. It is worth bearing in mind that pre-Pleistocene soil cover in boreal and cold climatic zones largely disappeared as a result of Quaternary glacial erosion. This could explain why present soilscapes are more recent and uniform. An alternative explanation is that information density in these climatic zones is sparse, which may account for

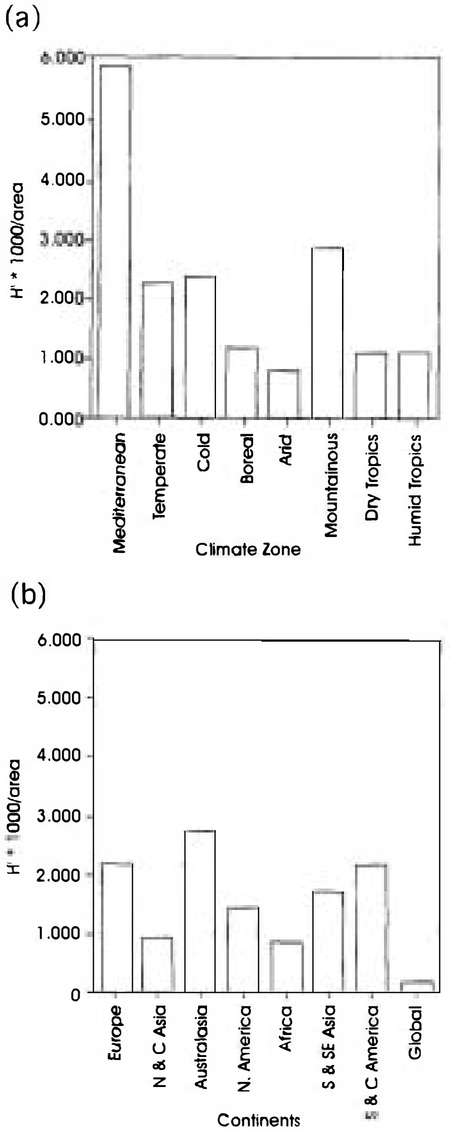

Fig. 2. Histograms of the ratio of Shannon's index (H') and the area of climatic zones (a) and continents (b)

their apparent uniformity. The arid climatic zone has a relatively high richness, but MSG density is the lowest of all those estimated.

4.1.2. Pedodiversity indices

Evenness index is very similar over the whole continent, as is the case of richness (Table 3). In view of the fact that Shannon's index is based on the proportional abundance of MSGs taking both richness and evenness into account, it is not surprising that the values obtained are very similar. Thus, on a

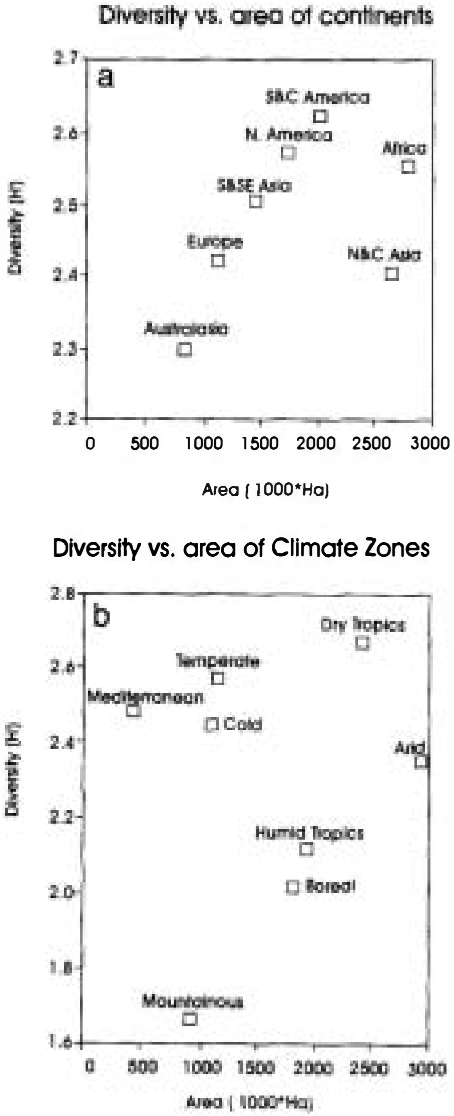

Fig. 3. Plots of pedodiversity as measured by the Shannon's index (H') and the area of continents (a) and climatic zones (b)

continental level, the pedosphere's diversity is characterized by similarities rather than differences. *E* figures prove to be abnormally high if compared with those usually occurring in biocenoses at any scale (Magurran, 1988), MSG at 1 : 1M scale (Ibáñez et al., 1995a), soilscapes at 1 : 20,000 scale (Ibáñez et al., 1990) and pedogeomorphological landscapes at fine scales (Ibáñez et al., 1995b).

Differences in evenness and Shannon's index of climatic zones are more marked (Table 4). In general, evenness and Shannon's index tend to be higher in the climatic zones of intermediate latitudes (Mediterranean, temperate) than in circumequatorial and circumboreal latitude extremes (boreal, cold, humid tropics and subtropics). Despite notable richness, the mountainous climatic zone has a lower Shannon index in view of its low evenness. This is, therefore, the most singular climatic zone since, although all MSG occur there, they do so in the least equitable manner. As for richness, the value of H' of the arid climatic zone is relatively high.

When the ratio between H' and land unit areas ('density of diversity') is determined, the Mediterranean stands out from the other climatic zones (Fig. 2a) and South and Southeast Asia from the other continents (Fig. 2b) for their high values. Fig. 3a shows a weak relationship between H' and area of continents. The relationship of H' to area completely vanishes if the area of climatic zones is considered (Fig. 3b).

4.1.3. Pedodiversity and abundance models

Most communities studied by ecologists display lognormal species abundance distribution (Sugihara, 1980). Preliminary studies would also seem to demonstrate that the diversity of soilscapes, pedotaxa and pedogeomorphological landscapes as well as some aspects of the internal diversity of soil map units (SMU) also preferably adjust to this model (Ibáñez et al., 1995a,b). However, results obtained on a very coarse scale would not seem to follow the same patterns.

If the degree of fit of MSG abundance distributions to the four models considered is simultaneously heeded, the type of pedosphere fragmentation between the different continents and climates may be divided into four groups placed in order of decreasing evenness (Table 5).

In general, MSG distribution by continents and climatic zones are very equitable. In fact, data only seem to fit two of the four models tested (lognormal distribution and broken-stick model) which was not the case in those showing less equitable distribution patterns (geometric and logarithmic distributions). Furthermore, fragmentation in the pedosphere's major soil groups fit the broken-stick model perfectly, although the distribution of MSGs is more equitable when analyzing by continental units than by climatic zones. In this latter case, the most equitable distribution models occur in mid-latitudes whilst as we approach the Poles or the Equator, the opposite happens.

Table 5
Degree of fit of MSG abundance distributions to the four models considered for continental units and climatic zones (groups have been placed in order of decreasing evenness criteria)

Continental units
- (broken-stick model): global pedosphere, South and C. America
- (broken-stick model > lognormal): North and C. Asia, South and SE Asia
- (lognormal > broken-stick model): Europe, Australasia, Africa
- (lognormal): North America

Climatic zones
- (broken-stick model): global pedosphere
- (broken-stick model > lognormal): Mediterranean, cold
- (lognormal > broken-stick model): temperate
- (lognormal): boreal, arid, mountainous, seasonally dry tropics and subtropics, humid tropics and subtropics

Margalef (1974) indicates that the type of distribution of a population continuously varies as the sampling area is increased. It should come as no surprise that an increase in sample area can change the pattern of species and pedotaxa abundance models from less equitable to more equitable models (Magurran, 1988; Ibáñez et al., 1995b). In any event, what would seem obvious is that when large geographic areas (continents and climatic zones) are considered on coarse scales (e.g. 1 : 4,000,000) most of the major soil groups considered appear and all tend to occupy a considerable space. It would seem plausible to consider the following:

(a) the use of classifications gives rise to a low number of pedotaxa (especially using the first level of hierarchical classifications);

(b) the fact that when increasing a continent's area, a higher number of climatic zones and regions which underwent different paleoclimates in the past tend to be captured (which gives rise to the presence of polycyclical soils and paleosols);

(c) conversely, when a certain climatic zone covers large areas and/or is widely dispersed over the globe, it is natural for it to capture a greater variety of lithologies, morphostructural units and areas with different geological histories;

(d) the probable existence (at least as suggested by some theoretical inferences) of richness–area saturation curves at this scale (Fig. 1).

4.2. Per-continent and per-climatic zone composition of major soil groups (β-diversity analysis)

The hierarchical clustering run with data from Tables 1 and 2 produces two dendrograms in which continents and climatic zones are grouped according to their similarity in terms of the abundance of MSG (Fig. 4). Australasia, South and C. America, Africa and South and SE Asia pedospheres are akin. The same

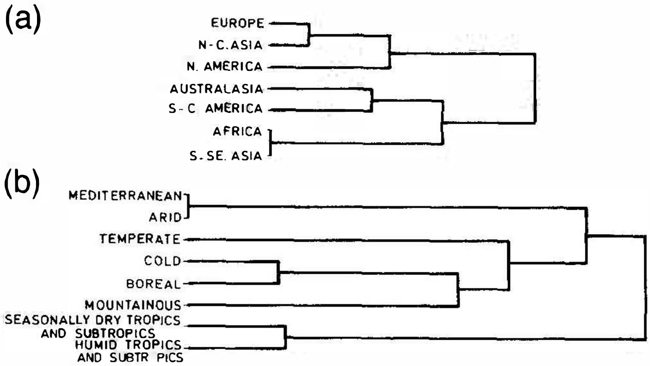

Fig. 4. Dendrograms grouping continents (a) and climatic zones (b), with respect to the number and extension of their mayor soil groups (MSGs).

is true for Europe, North America and North and C. Asia (Fig. 4a). Mediterranean and arid climatic zones are almost indistinguishable in terms of MSG composition. The temperate climatic zone is much more similar to the cold-boreal cluster than to the Mediterranean climatic zone (Fig. 4b). In addition, the extreme climate and physiographic conditions of mountainous environments lead to their pedosphere being similar to those of high latitudes.

The 'minimum spanning tree' helps to clarify the relations between MSGs and the different climate and continental units (Fig. 5) and ratify results obtained by cluster analysis. The minimum spanning tree for climatic zones (Fig. 5a) clearly reflects how regional pedospheres (pedomes) link in a very well defined latitudinal gradient. In other words, as was to be expected, there are marked similarities between bordering climatic zones.

Principal coordinate analysis confirms clustering results and enables one to make additional considerations (Fig. 6). For example, each continent also has its characteristic pedosphere features. Such is the case of the association of Andosols with South and C. America, probably as a consequence of high volcanic activity plate tectonics in this continental unit (Fig. 6a).

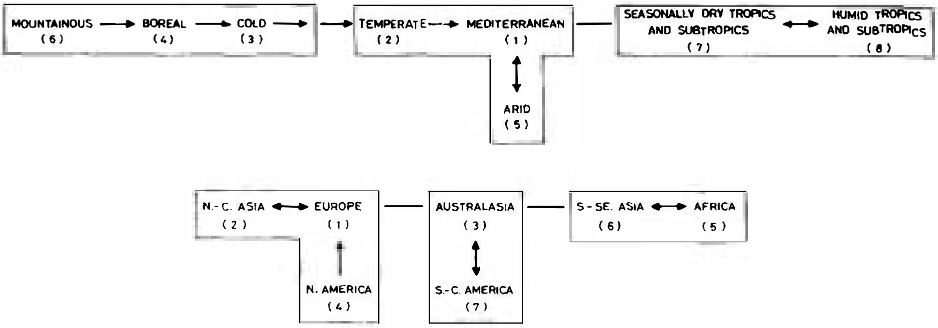

Fig. 5. Minimum spanning tree analysis for climatic zones (a) and continents (b).

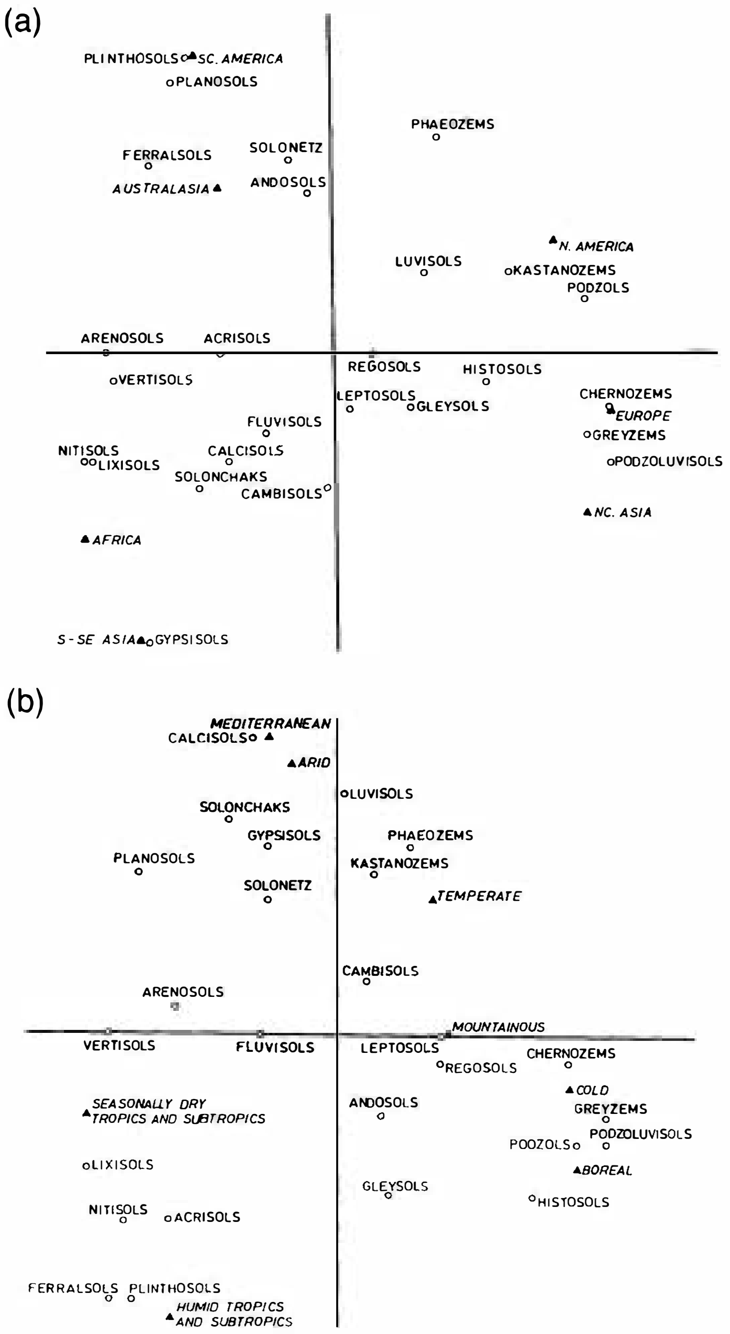

Fig. 6. Principal coordinate analysis to determine the relationship between the major soil groups (MSGs) and continents (a) and climatic zones (b).

Connections between pedosphere and climatic zones (Fig. 6b) are more evident. For example, the association between Andosols and Leptosols and mountainous climatic zone. Mediterranean and arid climatic zones share their connection with Calcisols. However, these latter two climatic zones are separated by the greater abundance of saline soils in arid environments and by that of other leached ones in Mediterranean environments (Luvisols and Planosols). It can also be seen (Fig. 6b) that the pedosphere of the temperate climatic zone is differentiated mainly by MSG representative of areas with highly climatic continentality (e.g. Kastanozems, Phaeozems). Tropical and subtropical environments (dry and wet) have the most differentiated pedosphere (e.g. Lixisols, Nitisols, Acrisols, Ferralsols, Plinthosols).

4.3. β-diversity analysis and plate tectonics

According to Paton et al. (1995), primary factors controlling the global distribution of soils are lithospheric materials and topography. In turn, the nature of these factors is controlled by plate tectonics (Paton, 1986). It is possible to consider any emerged continental lithospheric plate as being made up of three segments, a plate centre (old cratons of granitic nature), a compressive continental plate margin (circum-Pacific, Asian and Mediterranean mountain belts, which are peripherical to old cratons) and an emerged tensional margin (of a basaltic nature and reduced spatial dimensions), within each of which lithospheric material, topography, volcanism, and seismicity are very similar (Paton et al., 1995). Is it possible to explain the distribution of MSG by continental units within this framework? Obviously, in the first instance, the resemblance between them must depend on the percentage cover by each plate segment in each continental unit.

In fact, MSG composition tends to group continents in patterns that resemble paleoecological patterns originated by the dynamics of plate tectonics. This hypothetical relation may be traced to fragmentation of the supercontinent Pangea 2 at the beginning of the Mesozoic (Sengör, 1985; Paton et al., 1995).

Since the beginning of the Mesozoic (250–300 Myr) plate centres have maintained themselves as land areas exposed to pedogenetic processes, except for interruptions by marine transgressions (mid-Cretaceous) and the more recent Pleistocene glaciations. By this time, all the continents were assembled in one supercontinent, Pangea, and after that, in two closely associated continents, Laurasia in the Northern Hemisphere and Gondwana in the south, which have since fragmented and dispersed (Sengör, 1985).

Gondwana segments were not exposed to Pleistocene glaciations so pedogenetic processes have been operating over immense periods of time. This has led to the accumulation on each of the continental fragments of considerable amounts of inert end products. For this reason, their characteristic MSG has very deep and evolved solum. Cluster analysis by continents show that all Gondwana fragments are very akin in terms of MSG composition. Likewise, ancestral links in the flora of all Gondwana fragments are recognized at the family level (Tallis, 1991).

Laurasia has had much the same history of fragmentation as Gondwana and consist of equally homogeneous broad areas of granite bedrock and gentle topography typical of continental plate centres (Paton et al., 1995). However, paleoenvironmental history of continental plate centres of northern Laurasia in both Eurasia and North America, is different from that of Gondwana fragments (Tallis, 1991; Paton et al., 1995). Thus, a large area of the former (currently under boreal and cold climatic zones) was subject to Pleistocene glaciations, and, therefore, great areas of previous soil materials have been eroded or covered by the products of glacial and periglacial depositions (e.g. loess, moraine complexes, boulder clay plains). These materials have not been exposed to pedogenesis for longer than about 10,000 years. Within such a time period, not a great deal of pedogenesis is to be expected. Furthermore, since this last event, these areas has been subject to continuous or discontinuous frost action (e.g. cryoturbation, permafrost) and other non-pedologic processes. Thus, currently, these areas present totally different pedological landscapes from those of the Gondwana plate centres (Paton et al., 1995). Could this explain the low pedorichness and pedodiversity of the boreal and cold climatic zones?

The short time over which pedogenesis has been operating on this glaciated derived lithospheric material is reflected in the MSG composition (e.g. Podzols, Podzoluvisols, Chernozems, Kastanozems, Phaeozems) (Fig. 6a) for which the characteristic pedogenetic processes needs a very short time to develop.

At the southern limits of glaciated plate centres of Laurasia fragments (currently under temperate, Mediterranean, arid and subtropical climatic zones) lithospheric materials and topography are akin to those of Gondwana plate centres. Thus soilscapes, in some aspects, are similar in both regions (Paton et al., 1995). In other words, in these areas pedogenesis was able to continue for an extended period of time explaining why these contain pre-Pleistocene variated paleosoils.

Taken together could these facts explain the affinity between pedospheres of Europe, north-central Asia and North America (Fig. 4a)? It is worth bearing in mind that ancestral links in the flora of all Laurasian fragments are also visible at the family and genus level (Tallis, 1991). Moreover, could their large extension, the presence of all the three continental plate segments, the existence of glaciated and unglaciated plate segments throughout the Pleistocene, the great differences between soil forming factors and MSG in continental (e.g. Kastanozems, Chernozems, Phaeozems) and oceanic (e.g. Luvisols, Cambisols) temperate climatic subtypes (not taken into account in the FAO climatic zones) explain the high soil richness and pedodiversity of the temperate climatic zone?

Lithospheric materials and topography of the compressive continental plate margins are very diverse. They form the world's great mountain ranges (mountainous climatic zone) and others of lower altitude (e.g. numerous small mountain ranges bordering the Mediterranean Basin) (Paton et al., 1995). Furthermore, this type of plate segment is associated with seismicity disturbances, explosive volcanism and mass movements (e.g. landslides, debris flows, rock falls). The most important pedological implication of such geological activity and instability is that lithospheric materials are moved at such a rate that there is not enough time for long-term pedogenesis to occur. Thus, many characteristics of the resulting soils resemble those of its parent materials. Therefore, the high richness of MSG of the mountainous climatic zone could be associated with the high richness of the mountainous bioclimatic belts, topography and lithospheric materials.

Mediterranean Basin and Mediterranean regions of California and Chile (non glaciated compressive lithospheric margins) make up more than 90% of the Mediterranean climatic zone. In contrast, South African and Australian Mediterranean regions (mainly non-glaciated plate centres) are of minor importance. The affinity of soilscapes and ecosystems between these individual regions is very unequal. The greatest degrees of affinity exist between California, Chile and the Mediterranean Basin, as well as between South Africa and Southern Australia (Schultz, 1995; Ibáñez et al., 1996). Furthermore, the Mediterranean climatic zone has the highest diversity of bioclimatic types of the world (Rivas-Martínez, 1993). Thus, it is natural that this climatic zone has a high soil richness, pedodiversity and biodiversity (Ibáñez et al., 1995a).

However, the low richness of the arid climatic zone is more difficult to explain. This could be due to the fewer detailed studies existing in this climatic zone and/or the shortcomings of FAO classification for describing the possible considerable structural and genetic variability of arid soils.

5. Conclusions

This paper attempts to explain how the concepts of diversity and its measurement already used by biologists in ecological research could be applicable to soil maps and geo-referenced soil databases. The units used were soil classes (FAO Major Soil Groups). In other words, this exercise might be termed taxonomic pedodiversity (where elements are pedons and the categories different pedotaxa). However, there are other ways of looking at and measuring pedodiversity. Thus, like in ecological research, we could study several different aspects of the soil system: soilscape structural diversity, morphological diversity of pedons (e.g. in terms of soil horizons), genetic pedodiversity (e.g. using genetic horizons and/or another pedogenetic features), ecological pedodiversity (e.g. number and abundance of species living in the soils), functional pedodiversity (e.g. in terms of land capability or land versatility) (Ibáñez et al., 1990, 1995b; Ibáñez, 1995; McBratney, 1992; Odeh, 1995), etc. The soil system is polystructural and multivariate in space and time. Thus, the way in which we measure diversity will depend on our intended application of the results, scale, etc.

Biodiversity has been used to describe a system's structure and dynamics of biocenoses since it is the result of the interaction of its elements or subsystems. Could pedodiversity play the same role in pedology?

Ecological methods are not the only way to quantify pedodiversity. In fact, potentially, there are other alternatives. For example, geostatistics provides useful tools for quantifying pedodiversity (McBratney, 1995).

Pedodiversity measurements could be useful in a number of practical applications. For example, McBratney (1995) and Ibáñez (1995) concurred that pedodiversity measurements could be used for delineation of soil reserves and identification of hot spots of pedodiversity on a national or global scale.

In respect to taxonomic pedodiversity, the authors recognize that the shortcomings of the data severely affect the veracity of the results. Thus, compilation of higher-quality data is necessary, the analysis of which will provide further insight into the global pedosphere pattern, although, the FAO experts consider it unlikely that this task could be tackled in the next few years (FAO, 1993). However, the results are relatively comprehensive and give one hope in future developments, especially if we take into consideration the philosophy and limitations of current soil classifications systems, and the limited knowledge of soil distribution on a global level. Furthermore, many of the results given here are in agreement with a number of studies on soil geography (e.g. Duchaufour, 1975; Bridges, 1978; Schultz, 1995; Paton et al., 1995). For example, results show that the structure of the pedosphere could be explained in the framework of plate tectonics. In order to carry out this task we need know the percentage covered for each plate segment in each continental unit and climatic zone. Moreover, the high richness in pedotaxa and pedodiversity of the Mediterranean climatic zone corroborates the conclusions previously reached by other pedologists. Other results are more difficult to explain and could be used as preliminary hypotheses which would need to be tested. This applies, for example, to the low pedodiversity and pedorichness of the boreal, cold and arid climatic zones. In any case, further work on taxonomic pedodiversity requires more complete data-sets at finer scales.

Being able to determine the diversity of the different ecosphere subsystems using the same methodologies will enable their respective patterns to be studied and compared. The authors are not aware of the existence of complete biological data bases on a world level which could be used to compare pedodiversity and biodiversity on a global scale. However, the fact that the patterns of biodiversity, geomorphological diversity, diversity of pedotaxa, diversity of soilscapes and pedogeomorphological diversity are very similar on more detailed scales suggests that these could possibly be universal regularities common to self-organization processes of biotic and abiotic ecosphere structures. Extensive focused research work is, therefore, necessary to corroborate or refute these preliminary results. We recognize, like Tallis said in the preface of his monograph on Plant Community History that: ''this synthesis must be an imperfect one. My justification for attempting it at this point in time is that any account is better than none at all'' (Tallis, 1991).

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