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Global pedodiversity, taxonomic distance, and the World Reference Base

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ABSTRACT

This paper discusses the study of taxonomic distance and pedodiversity by (1) deriving taxonomic distances for the World Reference Base for Soil Resources (WRB), (2) calculating pedodiversity indices at the global scale using the soil map of the world at a scale 1:25M, and (3) comparing traditional diversity measures which are based on abundance of soil individuals to measures that are based on taxonomic distance. Based on dominant identifiers in the WRB soil groups, taxonomic distances were derived between the soil groups and plotted in feature space. Using this information the soil's mean taxonomic distance for the world was calculated. The mean taxonomic distance combines the abundance and taxonomic relationship between soil groups and appears to be a useful index of pedodiversity. There is a good relation between mean taxonomic distance and climate or soil classes; areas with extreme temperatures and precipitation have the lowest pedodiversity. It was observed that areas with more detailed soil mapping units exhibit the largest pedodiversity and it was concluded that the measure of pedodiversity depends amongst others on the detail of the soil survey in an area.

1. Introduction

Quantification of soil variation based on soil taxa or classes has prompted the study of pedodiversity. It started with the quantification of the complexity of soil cover or the soil mantle, and coefficients have been proposed for quantifying the soil cover complexity such as the average area of soil individuals (Fridland, 1974, 1976). An early example on the use of Shannon's diversity index for quantifying soil diversity was investigated by Jacuchno (1976), who used Shannon's entropy and relative entropy (evenness) to evaluate soil cover complexity in Russia. Linkeš et al. (1983) used Shannon's entropy to map the complexity of soil cover in Slovakia. The objective of their study was to classify the areas in terms of its soil mantle complexity for the purpose of making larger agricultural plots. This was an important area of study in the 1970s and 1980s in Eastern European, where large collective farms with large fields were established. They mapped the complexity of agricultural areas in Slovakia with soil maps at a 1:50 000 scale. The map was rasterized to a grid of 1 km × 1 km. For each 1 km^2 square, the area of the dominant soil-ecological unit and number of soil-ecological units, the value of Shannon's entropy, and the index of evenness were calculated.

The use of Shannon's entropy as a measure of pedodiversity was revisited by Ibáñez et al. (1990, 1995) as a tool for analyzing soil pattern. Further discussion on the development and concept of pedodiversity is given by Petersen et al. (2010-this issue). While the concept and definition of pedodiversity is debatable, most studies aim to quantify the diversity of soil within an area using a single value, which allows comparison to other areas.

McBratney and Minasny (2007) discussed some alternatives to pedodiversity measures that take into account the taxonomic distance between soil classes. They showed how taxonomic distance can play an important role in determining the soil's diversity in an area. This paper extends the study of taxonomic distance and pedodiversity by:

(1) deriving taxonomic distances for the World Reference Base (WRB) soil groups (IUSS Working Group WRB, 2006),
(2) calculating pedodiversity indices globally using the 1:25 million FAO soil map of the world, and
(3) comparing 'traditional' diversity measures that are based on abundance of soil individuals to measures based on taxonomic distance.

2. Methods

2.1. Taxonomic distance for WRB soil groups

The World Reference Base (WRB) is being used as a soil taxonomic system and to classify soil profiles based on their diagnostic horizons and properties (IUSS Working Group WRB, 2006). The soil-forming factors have been defined for each of the WRB soil reference groups (Bockheim and Gennadiev, 2000), but no formal taxonomic distance has been defined yet. In this study, we attempt to determine the taxonomic distance between the WRB soil reference groups based on their dominant identifiers. The 2006 WRB system has 30 soil reference groups, and the first separation is made between organic soils and

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mineral soils. Mineral soil groups are then determined based on their dominant identifiers, and a list of soil properties that defined the soil classes according to a key (FAO, 2001). Based on the key, 21 soil and environmental conditions were identified to define soil reference groups (Table 1). Each group is matched with the 21 identifier properties, and coded with 0 when the condition cannot be present, and 1 when the condition is likely to be present in the soil group (Table 1). The approach assumes that a soil profile can be described adequately by these identifiers, and that each identifier has an equal weight.

Based on this matrix, the distance between the WRB soil groups was calculated:

$$d_{ij} = \sqrt{\left(\mathbf{x}_i - \mathbf{x}_j\right)^{\mathrm{T}}\left(\mathbf{x}_i - \mathbf{x}_j\right)} \tag{1}$$

where d_{ij} is the element of distance matrix **D** with size ($c \times c$), c is the number of soil groups. The value of d_{ij} represents the taxonomic distance between soil group i and group j, and **x** refers to a vector of indicators of the soil identifiers. To visualise the relative position of each soil group, we performed a principal coordinate analysis to transform the distance matrix to principal coordinate axes (Gower, 1966). Principal coordinate analysis, which is a form of multidimensional scaling, is useful for ordination of multivariate data given a distance matrix and provides a low-dimensional plot of soil groups as such that the distances between the groups in the plot are close to the taxonomic distances.

Hereto the distance matrix **D** with elements d_{ij} size ($c \times c$) is transformed into the centered matrix **G**:

$$\mathbf{G} = \left(\mathrm{I} - \frac{1}{n}\mathbf{1}\,\mathbf{1}^{\mathrm{T}}\right)A\left(\mathrm{I} - \frac{1}{n}\mathbf{1}\,\mathbf{1}^{\mathrm{T}}\right) \tag{2}$$

Where **1** is a vector of 1's of length n, **I** is an identity matrix, and $\mathbf{A} = (a_{ij}) = \left(-\frac{1}{2}d_{ij}^2\right)$. Matrix **G** is then decomposed into its component eigenvectors and eigenvalues. The principal coordinate axes are calculated from the eigenvectors, standardised by the standard deviation (square root of the eigenvalues). Fig. 1 shows the WRB soil groups plotted on their first two principal coordinate axes.

Since the first two principal coordinate only explain 38% of the variation, it is difficult to see the relationship between the soil groups. Alternatively, we plotted the soil groups in a minimum spanning tree (Gower and Ross, 1969) where they are represented as a tree spanning the soil groups as points in straight lines segments joining pairs. The tree in Fig. 2 is represented using Sammon's non-linear mapping, which emphasizes structure in the neighbourhood of nodes (Sammon, 1969).

2.2. Pedodiversity of the FAO Soil Map of the World

To quantify pedodiversity globally, we used the FAO Soil Map of the World, at a scale of 1:25 million (FAO, 2003). The map contains 31 soil mapping units, each mapping unit is a combination of 1 to 3 WRB soil reference groups. The mapping units are: Acrisols, Alisols, Plinthosols (AC); Albeluvisols, Luvisols (AB); Andosols (AN); Anthrosols (AT); Arenosols (AR); Calcisols, Cambisols, Luvisols (CL); Calcisols, Regosols, Arenosols (CA); Cambisols (CM); Chernozems, Phaeozems (CH); Cryosols (CR); Durisols (DU); Ferralsols, Acrisols, Nitisols (FR); Fluvisols, Gleysols, Cambisols (FL); Gleysols, Histosols, Fluvisols (GL); Gypsisols, Calcisols (GY); Histosols, Cryosols (HR); Histosols, Gleysols (HS); Kastanozems, Solonetz (KS); Leptosols, Cryosols (LR); Leptosols, Regosols (LP); Lixisols (LX); Luvisols, Cambisols (LV); Nitisols (NT); Phaeozems (PH); Planosols (PL); Plinthosols (PT); Podzols, Histosols (PZ); Regosols (RG); Solonchaks, Solonetz (SC); Umbrisols (UM); Vertisols (VR).

Based on the WRB soil reference group description (Table 1) we redefined a new indicator matrix for the mapping units. The taxonomic distances were calculated between the mapping units using Eq. (1).

The following pedodiversity indices were calculated:

- Richness s, which is the number of soil classes or groups (c) that exist in an area.
- Shannon's entropy or diversity index:

$$H = -\sum_{i=1}^{c} p_i \ln p_i \tag{3}$$

where p_i is the proportional abundance of class i, and c is the number of soil groups.

- Gini–Simpson's diversity index:

$$G = 1 - \sum_{i=1}^{c} p_i^2 \tag{4}$$

with $0 \le G \le 1$, with values near 1 corresponding to highly diverse systems, and values near zero corresponding to more homogeneous systems.

- Quadratic entropy (Q) or mean taxonomic distance that considers information on the species' relative abundances and the taxonomic distances (Rao, 1982). It is defined as the expected distance between two randomly selected individuals:

$$Q = \sum_{i=1}^{c}\sum_{j=1}^{c} d_{ij}\, p_i p_j \tag{5}$$

In terms of the mean taxonomic distance of the data, it can be written as:

$$Q = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=i}^{n} d_{ij} \tag{6}$$

where n is the number of soil individuals, and d_{ij} the distance calculated by Eq. (1).

We calculated these indices in two ways:

- Based on continents, or climatic zones (Ibáñez et al., 1998).
- Mapping pedodiversity indices, similar to the method of Linkeš et al. (1983). First the soil map was rasterized to 0.5°×0.5°. Then for each pixel, pedodiversity indices were calculated from a square window with radius 1.5°, or approximately an area of 128 000 km^2 (which varies according to latitude).

In addition, we used the global climate and elevation surfaces. The Climatic Research Unit (CRU www.cru.uea.ac.uk/) global climate dataset, was supplied by the Utrecht Centre of Geosciences (Prof. Marc Bierkens and Dr Rens van Beek), and has a resolution of 0.5° latitude by 0.5° longitude with mean monthly climatic variables for all global land areas. It includes temperature, rainfall, solar radiation, and evapotranspiration calculated with the Penman formula. In addition, we used a global surface of Holdridge life zone classification, and a simplified global lithology map (Dürr et al., 2005).

3. Results and discussion

3.1. Pedodiversity by land area and climatic regions

Fig. 3 shows the relation between land area (by continent) and Shannon's diversity index. There is a linear relationship between increasing land area and diversity which was also observed by Ibáñez et al. (1998). Soils in South-east Asia, Oceania and the Middle-East appear to be the least diverse, whereas North America has the largest diversity. However, when the mean taxonomic distance is plotted against land area (Fig. 4), no clear relationship can

Table 1
Key attributes for characterising WRB soil groups, 1 represents possible presence of the properties, and 0 is absence of the defined properties.

	Histosols	Anthrosols	Cryosols	Leptosols	Vertisols	Fluvisols	Solonetz	Solonchaks	Gleysols	Andosols	Podzols	Plinthosols	Nitisols	Ferralsols
Soils with thick organic layers	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Strong human influence	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Ice-affected soil	1	0	1	1	0	0	0	0	0	0	0	0	0	0
Shallow or extremely gravelly soils	0	0	0	1	0	0	0	0	0	0	1	1	0	0
Cracks and slickensides	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Floodplains, tidal marshes	1	0	0	0	0	1	0	1	1	0	1	0	0	0
Alkaline soils	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Salt enrichment	0	0	0	0	1	0	0	1	0	0	0	0	0	0
Groundwater affected soils	1	0	1	0	0	1	0	1	1	0	0	1	0	0
Allophanes or Al-humus complexes	0	0	0	1	0	0	0	0	0	1	1	0	1	0
Cheluviation and chilluviation	1	0	1	1	0	0	0	0	0	0	1	0	0	0
Accumulation of Fe under hydromorphic conditions	0	0	0	1	0	0	0	0	0	0	1	1	0	0
Dominance of kaolinite and sesquioxides	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Abrupt textural contrast	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Accumulation of organic matter	1	1	0	0	1	0	1	0	0	0	0	0	0	0
Calcareous	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Accumulation of Silica	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Soils with a clay-enriched subsoil	0	0	0	0	0	0	1	0	0	0	0	1	1	1
Relatively young soils with an acidic dark topsoil	0	0	0	1	0	0	0	0	0	1	0	0	0	0
Sandy soils	0	1	0	0	0	1	0	0	0	0	1	0	0	0
Moderately or poorly developed soils	0	0	0	1	0	1	0	0	0	0	0	0	0	0

For definition of the properties, see IUSS Working Group WRB (2006).

be observed. There are three groupings of diversity and South-east Asia and Oceania appear to be the least diverse areas. The analysis suggests that Shannon's entropy is closely related to the number of soil classes.

Pedodiversity was also analysed according to the Holdridge Life Zone Classifications, which is based on mean annual biotemperature, annual precipitation, and ratio of annual potential evapotranspiration to mean total annual precipitation. Fig. 5 shows Shannon's entropy of the bioclimatic groups as a function of mean annual temperature and precipitation, showing areas of tundra and polar to be the least diverse (dominated by Cryosols) followed by the desert, tropical seasonal and rain forests. The highest diversity is in the tropical semi-arid dry forest zones. Overall pedodiversity seems to increase with increasing mean annual temperatures with the exception of soils in the desert and tropical seasonal rain forest.

Fig. 6 shows the mean taxonomic distance as a function of mean annual temperature and precipitation. Areas with either lowest or highest temperature (tundra/polar and tropical forests) have the lowest pedodiversity. Low pedodiversity is also found in the areas with the lowest and highest rainfall. The tropical seasonal rainforests have the lowest pedodiversity because such areas are often dominated by Acrisols (AC) and Ferrasols (FR) (59%). These two major soil groupings are taxonomically close (see Fig. 2) and both are old, highly weathered soils.

3.2. Mapping pedodiversity

Fig. 7 shows the map of Shannon's entropy across the world, as mapped with a radius of 1.5° whereas Fig. 8 shows map of mean taxonomic distance. Both maps appear inconsistent, and mainly show soil class boundaries.

Fig. 9 shows the relationship between conventional diversity measures (*H* and *G*) with mean taxonomic distance *Q*. It shows that a value of entropy (*H*) can translate into a high to low mean taxonomic distance (depending on the soil classes). Shannon's entropy is more related to the number of soil classes found within an area.

3.3. Pedodiversity and map quality

Soil mapping units and pedodiversity index were correlated with environmental attributes. This include global data with raster size $0.5° \times 0.5°$: total annual precipitation (TAP), mean annual temperature (MAT), mean annual solar radiation (MAR), and mean annual evapotranspiration (MAET). In addition, a digital elevation model and a global lithology map were available. No clear relationship between pedodiversity indices and the environmental variables was found at this scale. The index mainly reflects the coverage or the intensity of the map. This can be observed for example, the whole island of Kalimantan (Borneo) appears to have low pedodiversity as it

Planosols	Chernozems	Kastanozems	Phaeozems	Gypsisols	Durisols	Calcisols	Albeluvisols	Alisols	Acrisols	Luvisols	Lixisols	Umbrisols	Arenosols	Cambisols	Regosols
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1
0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0
0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	1	0	1	0	0	0	0	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0
0	0	1	0	1	1	1	0	0	0	1	0	0	0	0	1
0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
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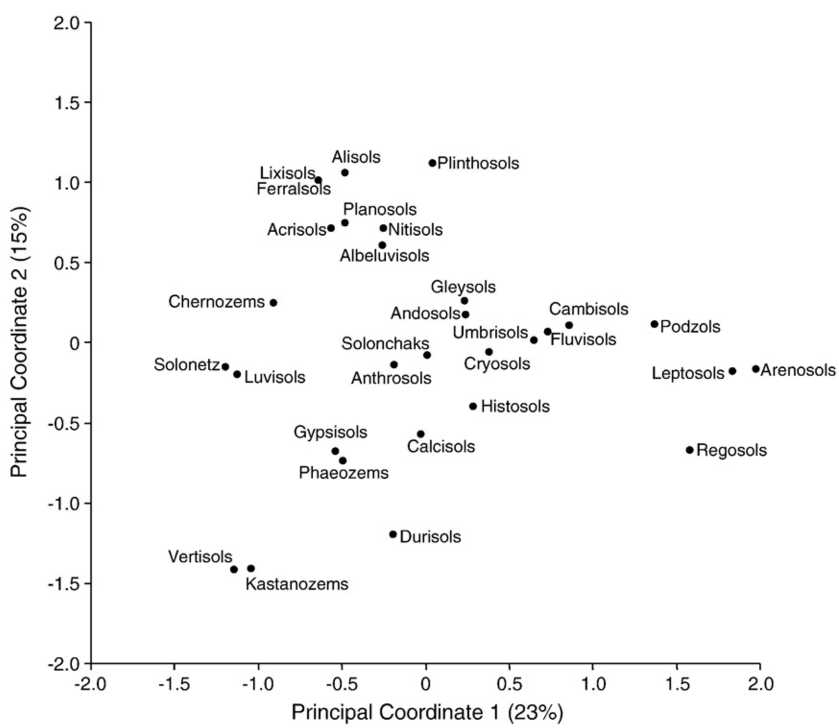

Fig. 1. WRB soil groups plotted along the first two principal coordinates, inset shows the first three principal coordinates.

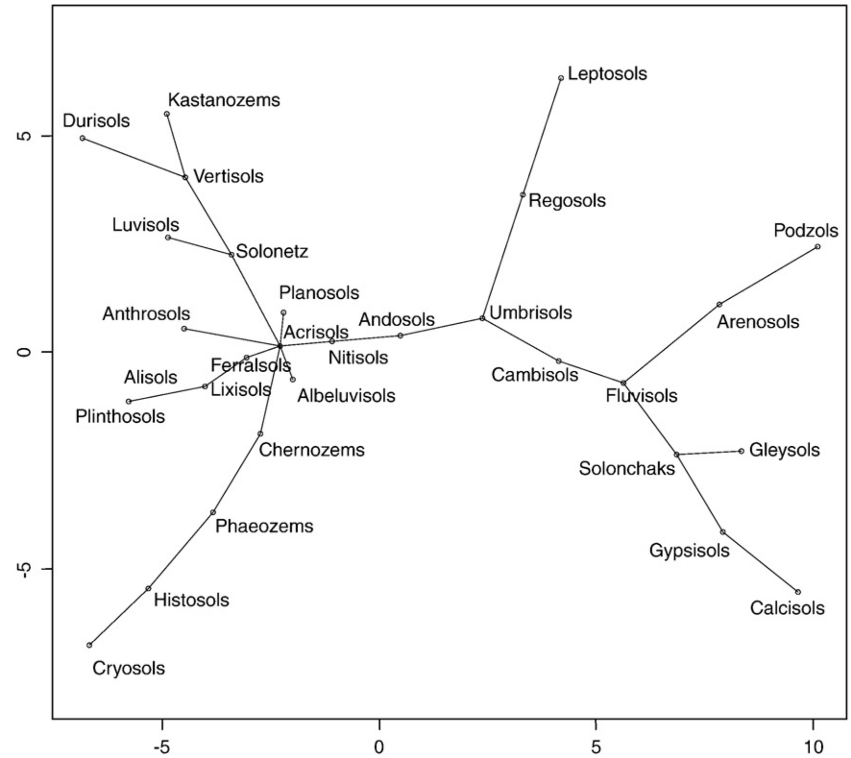

Fig. 2. A minimum spanning tree of the WRB soil groups.

is dominated by Acrisols (AC). The soils in Papua New Guinea appear to be less diverse than in West Papua. Petersen et al. (2010-this issue) argues that direct comparison of pedodiversity measures between studies is not possible as it depends on the type of classification used, scale and the soil survey intensity.

It can also be observed that areas with more soil mapping units exhibit the largest pedodiversity. Therefore the measure of pedodiversity depends on the coverage or density of the soil map. Fig. 10 shows richness and Shannon's entropy (H) as a function of land area for Western European countries. The linear relationship (Fig. 3) between land area and H is absent. France appears to have the highest number of mapping units (10); this is also observed in Fig. 7 with areas in France exhibiting high entropy. Meanwhile, the UK which only has 5 mapping units, exhibits the largest entropy.

Fig. 11a shows richness measures in South America and Africa. Argentina has more mapping units than Brazil and a study conducted by ITC (Enschede, The Netherlands) showed that Argentina has a 10% coverage for large scale mapping (<1:25 000) (Zinck, 1995); Brazil has only 5% coverage at this scale. In Africa, Sudan has 20% of the area surveyed at scales greater than 1:25 000. This is demonstrated in Fig. 11b, where Sudan has the largest number of mapping units. Chad, Mozambique, and Cameroon have more mapping units than other countries despite of their land area.

The pedodiversity measures for the world soil map are related to the detail of survey and map coverage of the area. Countries that have detailed soil maps have more mapping units in the 1:25 million FAO map and thus have a higher diversity. Smaller countries have more

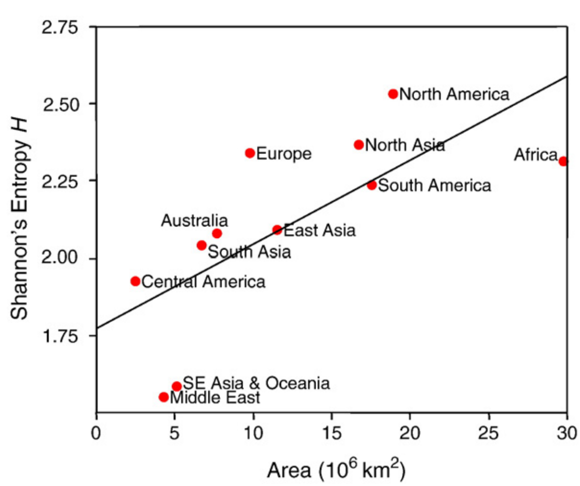

Fig. 3. The relationship between land area and Shannon's entropy based on continents.

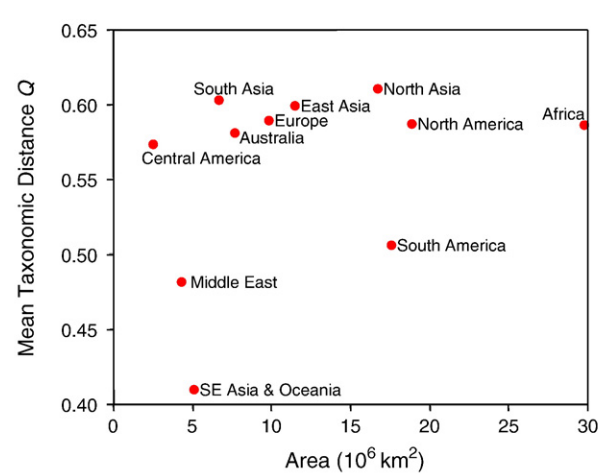

Fig. 4. The relationship between land area and mean taxonomic distance based on continents.

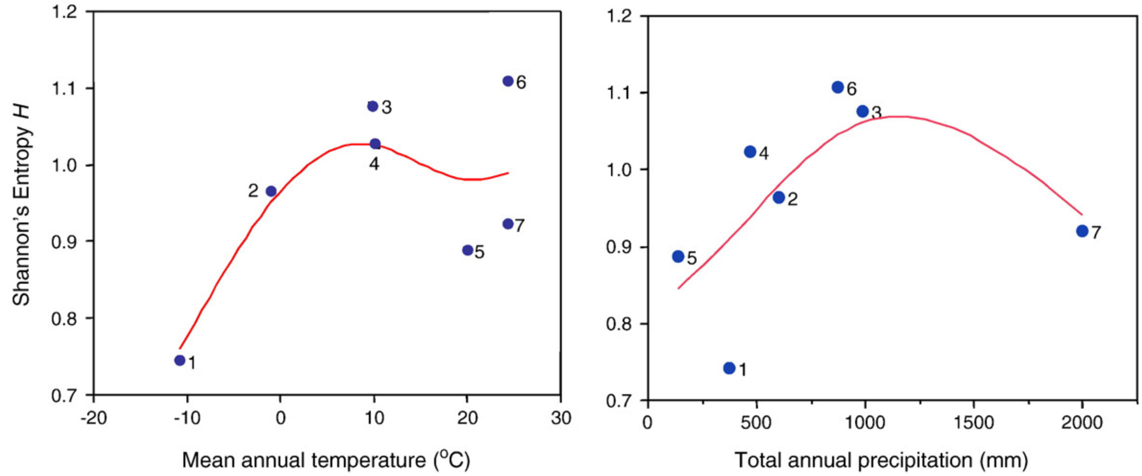

Fig. 5. The relationship between mean annual temperature and mean annual precipitation with Shannon's entropy index based on climatic zones. 1 – Tundra/polar; 2 – Forest tundra, boreal; 3 – temperate, warm temperate forest, 4 – Steppe, chapparal; 5 – cool desert, hot desert; 6 – tropical semi-arid, tropical dry forest; 7 – tropical seasonal forest, tropical rain forest.

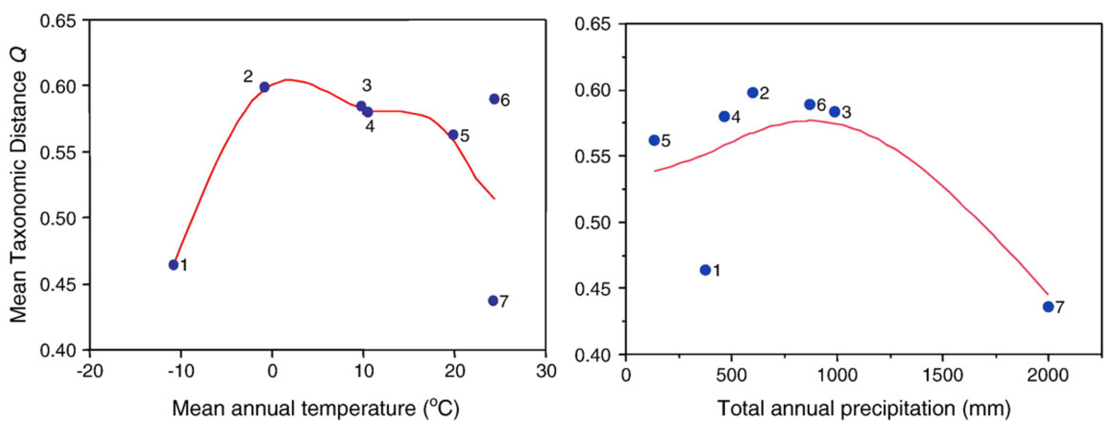

Fig. 6. The relations between mean annual temperature and mean annual precipitation with mean taxonomic distance based on climatic zones.

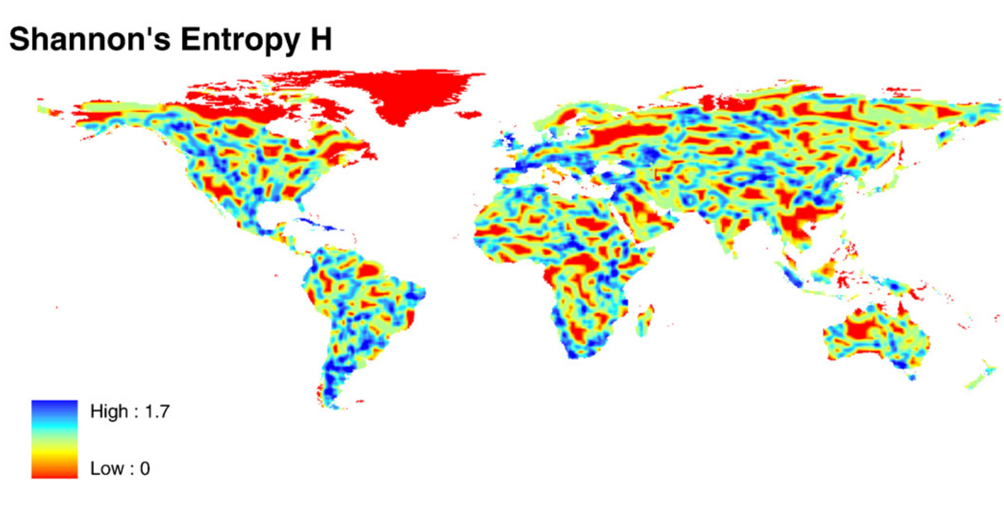

Fig. 7. The map of Shannon's diversity index across the world based on a 1.5° radius window.

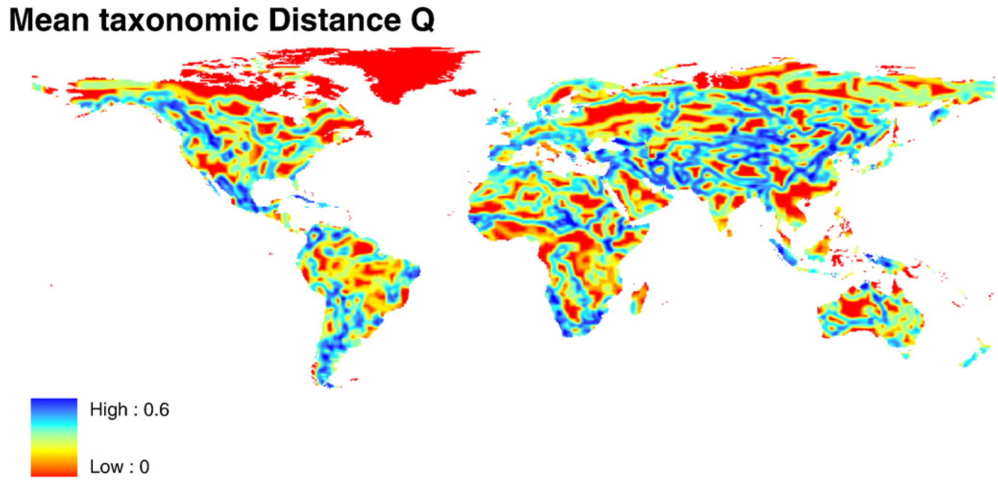

Fig. 8. The map of mean taxonomic distance across the world based on a 1.5° radius window.

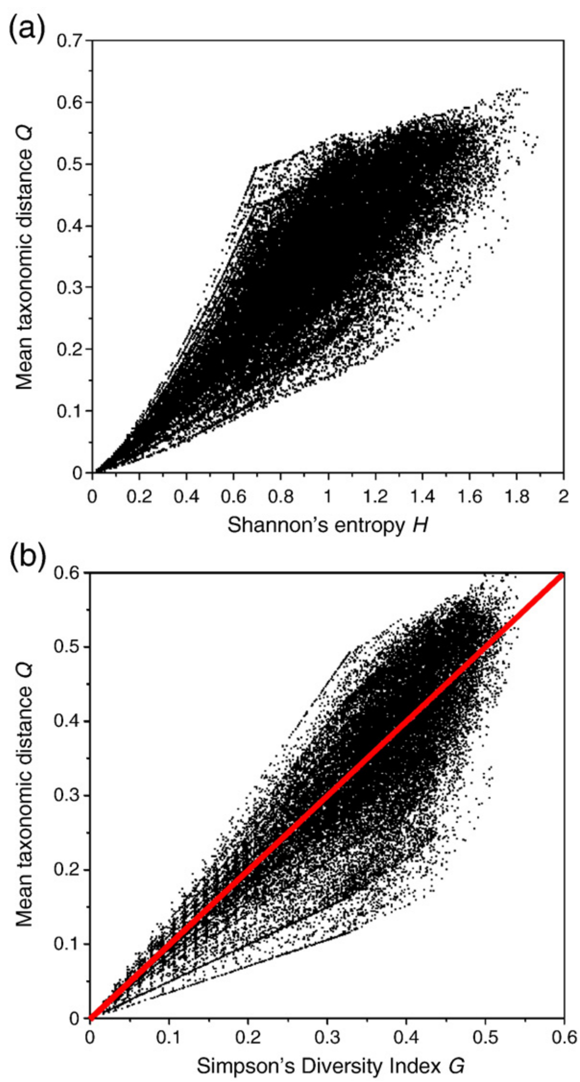

Fig. 9. Relationship between mean taxonomic distance Q and (a) Shannon's entropy H, and (b) Simpson's diversity index G. The line represents the value when $Q=G$.

detailed maps (Hartemink, 2008) and the calculations of pedodiversity might show that they are more diverse.

4. Conclusions

Taxonomic distances for the WRB soil groups have been established. Although they are based on the main key soil-environmental properties, it is the first attempt to visualise the relative position of the soil groups in character space. Much more work is needed to refine this approach. From this global study it can be concluded that:

1. The conventional pedodiversity measure is related to the abundance of the observed soil type, thus there is a relationship between land area and Shannon's entropy.
2. Mean taxonomic distance shows a good relationship between climate and soil classes. Areas with extreme temperatures and precipitation have the lowest pedodiversity. Mean taxonomic distance also appears to be a useful index of pedodiversity which combines the abundance and taxonomic relationship between soil groups.
3. Pedodiversity measures based on soil maps depend on the coverage and density of the soil map and in many cases the so-called pedodiversity is a reflection of the density of soil maps.

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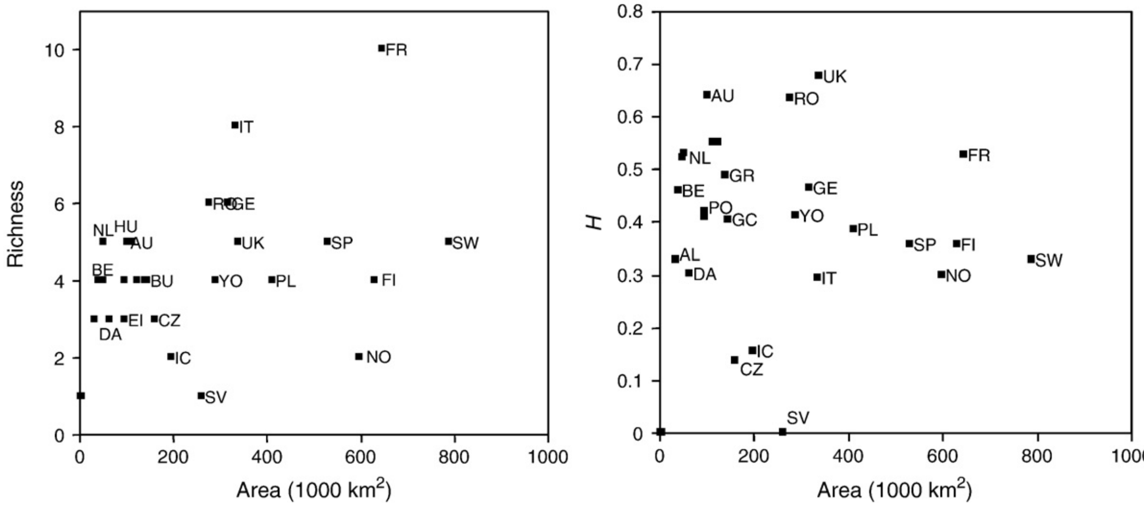

Fig. 10. The relationship between land area and richness and Shannon's entropy (H) for western European countries.

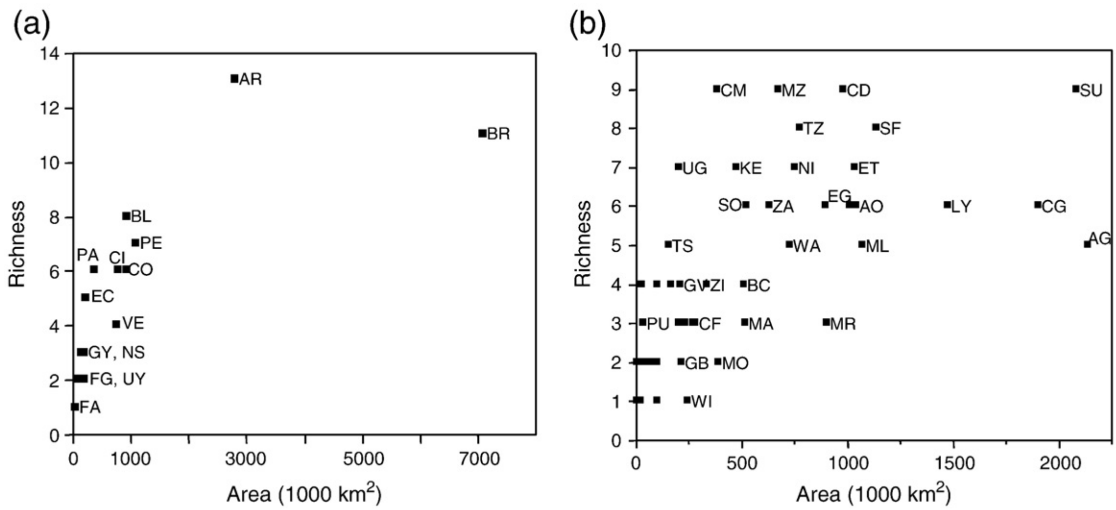

Fig. 11. The relationship between land area and richness for countries in (a) South America, (b) Africa.

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