Patterns of global soil distribution as revealed by two major soil databases

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Abstract
The ISRIC WISE Global Soil and CSIRO National Soils databases are used to demonstrate the important role that large, properly established soil databases can play in understanding and modelling of the global distribution of soils and their properties. These databases were systematically examined to yield soil types and a suite of key soil properties in 112 environmental regimes, being combinations of different parent material, climate and topography. The results were plotted in a series of charts to facilitate examination of key patterns of soil distribution.

There was generally good correlation of soil types and soil properties with these soil environmental parameters. While most results and trends in the data are in accord with standard theories of soil formation, there are several unexpected results and subtle complexities that are not easily explained and deserve further examination. The results provide a useful base for the development of global soil predictive models.

Keywords
soil, modelling, distribution, lithology, climate, topography

1. Introduction
An understanding of the relationship of soil properties to their environment is essential for the effective modelling and mapping of soil distribution. Jenny’s (1941) original formulation that soil is a function of climate, organisms, relief, parent material and time ($s = f(cl, o, r, p, t)$) is still considered universally valid today. These relationships have been supported by numerous authors in recent years including Paton et al. (1995), Birkeland (1997), Bridges (1997) and Gray & Murphy (2002), however the relative importance of the different factors is still debated.

This study examines whether large world soil databases can assist in understanding these relationships. Can they help in modelling of patterns of global soil distribution and in predicting likely soil types that may occur in various environmental regimes? Do the patterns revealed match with expectations based on current thinking of soil distribution and formation?

This study uses the CSIRO National Soil and ISRIC WISE Global Soil databases to examine these questions. As far as the authors are aware, this is the first time that major world soil databases have been systematically examined in this way.

2. Methods
The CSIRO National Soils database contains 9291 geo-referenced soil profiles from all states and major territories of Australia. The International Soil Reference and Information Centre (ISRIC) WISE Global Database contains 4382 geo-referenced soil profiles from 123 countries and is described in Batjes (2002). Both databases are in Microsoft Access format and include, for the majority of soil profiles, a comprehensive listing of site conditions (including parent material, topography and climate (ISRIC only) soil type and soil physical and chemical data. The CSIRO database had to be supplemented with a climatic grid (annual rainfall) provided by the Australian Bureau of Meteorology.

Queries were created to extract soil type and key soil properties in different combinations of parent material, climate and topography. This yielded 112 such combinations or “environmental regimes” composed of:

- 8 parent material categories – arranged in order of decreasing silica content, then other non-siliceous materials: 1. Extremely Siliceous (eg quartz sands, quartzite); 2. Highly Siliceous (eg, granite, rhyolite, quartz sandstone); 3. Intermediate (eg, andesite, diorite, shale, mudstone, loess); 4. Mafic
(eg, basalt, gabbro, dolerite); 5. Ultramafic (peridotite, serpentineite); 6. Calcareous (carbonates, limestone); 7. Organic (eg, peats) and 8. Sesqui-oxidic (eg, laterites, bauxites).

- 7 climatic categories – arranged in order of increasing moisture availability with the following definitions for the two databases:
  - ISRIC – based on Koppen system: 1. Arid (BW); 2. Semi-arid (BS) 3. Temperate Sub-humid (Cs); Cool Humid (D); 4. Temperate Humid (Cf/w); 5. Tropical Dry (Aw); 6. Tropical Wet (Koppen Af/m)

- 2 topographic categories, with the following definitions for the two databases:
  - CSIRO – 1. Sloping sites: slope classes - gently inclined, moderately inclined, steep or very steep; and/or morphology type: mid slope, simple slope, upper slope, crest, hillock or ridge. 2. Level sites: slope class – very gently sloped or level
  - ISRIC – 1. Sloping Sites: “Sloping or Steep” landform and/or slope > 5%. 2. Level “Level” landform and/or slope ≤ 5%.

Only 2356 profiles within the CSIRO database and 1670 profiles within the ISRIC database matched the query requirements. The main reasons for the relatively low return rate were incomplete site data for many profiles (eg, no parent material or topographic data) or inadequately defined parent material (eg, “fluvial” or “aeolian”, terms which give little indication of lithological composition). Because of this, and the non-uniform spatial distribution of samples, some environmental regimes were represented only poorly or not at all.

The CSIRO database was used to examine the distribution of soil types within different environmental regimes while the ISRIC database was used to examine the behaviour of various key soil properties. Among the soil properties extracted or derived were the B horizon properties of pH, sum of bases, cation exchange capacity (CEC), base saturation, exchangeable sodium percent (ESP), electrical conductivity (ECe), P, N & C content, carbonate content, clay content and sand content.

The query results were then further sorted and analysed to give mean values for each of the properties using Excel. Finally, the results were formatted into summary plots and charts to provide a broad overview of results and allow a preliminary identification of trends. Formal statistical analysis was not undertaken for this preliminary study.

3. Results and analysis

3.1 Soil types

Figures 1 and 2 present plots of the frequency of occurrence of ASC soil orders, sub-orders and great groups, plus Great Soil Group soils in each of the environmental regimes, based on the CSIRO database. Figure 1 deals with Sloping sites and Figure 2 with Level sites. Within each regime (or box on the figure) the five most common occurrences of these soil types and descriptors with relative percentages are recorded, together with the total number of profiles upon which the calculations were based.

These plots can be used as a predictive guide to the types of soils that may be expected under different parent material-climate-topographic regimes. Important trends in distribution observed in the plots, include:

- **Extremely Siliceous Parent Materials** – in both topographic regimes, Tenosols, Rudosols (siliceous sands & earthy sands) and lesser Kandosols (yellow earths) are widespread in all climates; Chromosols (yellow podzolics) are surprisingly common in dry to humid climates; Podosols (podzols) are common in humid to wet climates

- **Highly Siliceous Parent Materials** – in both topographic regimes, Kandosols (red & yellow earths) are abundant in all climates; Chromosols (red & yellow podzolics) are abundant in semi-arid to humid climates, Tenosols are common (but note only rare recordings of siliceous sands or earthy sands);
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Figure 1. Soil Types in Sloping Sites by Parent Material and Climate

Figure 2: Soil Types in Level Sites by Parent Material and Climate. Legend: refer to Figure 1
Sodosols (solodic soils & soloths) are common in dry to lower-humid climates. In sloping regimes, Kurosols (red and yellow podzolics) are common in lower-humid to wet climates

- **Intermediate Parent Materials** – in both topographic regimes, in arid to humid climates
  Chromosols (non-calcic browns, red-brown earths & red podzolics) are abundant; Vertosols (brown & grey clays) are common and Sodosols (solodic soils; soloths & solodized solonetz) are common. In humid to very wet climates, both topographies, Kandosols (red earths) are abundant, they are also common in sloping sites in the drier climates. In sub-humid to very wet climates, both topographies, Dermosols are common. In wet to very wet climates, sloping sites, Ferrosols (xanthozems & krasnozems) are common.

- **Mafic Parent Materials** – in both topographic regimes, from sub-humid to very wet climates
  Ferrosols (krasnozems & euchrozems) are abundant; from semi-arid to very wet climates Dermosols (euchrozems, prairie soils and chocolate soils) are common. In arid to lower-humid climates Vertosols (black earths & brown clays) are abundant in level sites but also common in sloping sites. In semi-arid to lower-humid climates, both topographies, Chromosols (non-calcic browns & grey-brown podzolics) are occasional.

- **Ultramafic Parent Materials** – insufficient profiles for analysis, but Chromosols are suggested for level sites in arid to humid climates

- **Calcic Parent Materials** – in both topographies in semi-arid to lower-humid Calcarosols (calcic sands, solonized brown soils, terra rossa soils & rendzinas) are abundant. In level sites from semi-arid to sub-humid climates Vertosols (black earths & grey clays) are abundant. A wide range of other soils is represented including Dermosols, Kandosols, Tenosols, Podosols and others

- **Sesqui-oxide Parent Materials** – in both topographies over all climates represented, Chromosols (lateritic & yellow podzolics & non-calcic browns) and Kandosols (red & yellow earths) are abundant and Tenosols (siliceous & earthy sands) are common

- **Colours** – in sloping sites, red is clearly the dominant colour in all climates (as shown in ASC sub-order), except in extremely siliceous and sesqui-oxide parent materials where brown and yellow are nearly as common. In level sites, red is also the major colour in all climates, but brown, yellow and grey are relatively more common, often approaching or exceeding red listings. In semi-arid to lower-humid climates, both topographies, mafic, calcareous and to a lesser extent intermediate parent materials, black is a common colour (as is self-mulching character)

- **Base status of clays** – predominantly controlled by climate; arid to lower humid conditions – dominant eutrophic; upper humid – dominant mesotrophic; wet to very wet – dystrophic. Parent material has secondary influence with dystrophic clays being more widespread in extremely and highly siliceous materials and mesotrophic & eutrophic being more widespread in mafic materials. Base status is generally slightly higher in the level sites.

Most of the observations made for the soil types and qualifiers from Figures 1 and 2 are as would be expected from their descriptions in the literature, eg, McKenzie et al. (2004), Isbell et al. (1997) and Stace et al. (1968). There are, however, some unexpected results and anomalies that deserve further consideration. The small sample size for many of the environmental regimes needs to be borne in mind when trends are examined.

3.2 **Key soil properties**

A number of charts were prepared to plot the behaviour of mean values of key soil properties under different environmental regimes, ie, different combinations of parent material, climate and topography. These were based on the ISRIC database. The properties examined include pH, sum of bases, CEC, base saturation and others from the B horizon. The patterns and trends observed in these charts are outlined and discussed below.

(a) **pH**

The charts for pH of B horizon are presented in Figures 3a & b. They reveal:

- a slight increase in pH, ie, increasing alkalinity, as parent material becomes more mafic in character. This is expected due to the higher base content of mafic materials.
- a clear increase in pH as climate becomes drier. This reflects lesser leaching of bases in drier climates
- the increase in pH that occurs as parent material becomes more mafic generally becomes more pronounced as climate becomes drier, with the exception of the arid climate results. For example, for
level sites, in wet tropical climates the increase in pH from extremely siliceous to mafic parent material is only 0.05 units (5.03 to 5.08), whilst for semi-arid climates, the increase is 1.77 units (5.60 to 7.37). This reflects a greater relative loss of bases in mafic materials under strong leaching conditions. The lack of increase in arid climates is anomalous, and may be due to the addition of externally derived carbonates and other salts.

- the pH values between the equivalent sloping and level sites are generally constant or slightly higher for the level sites. One would have expected a more marked increase in pH in level sites due to the leaching of bases from higher to lower points in the landscape.

(b) Cation exchange capacity, base saturation and sum of bases
The charts for these properties in the B horizon are presented in Figures 4a & b, 5a & b and 6a & b. The trends they reveal include:

- a clear increase in the CEC with increasingly mafic parent material, explained by the higher activity clays in these materials
- a general increase in CEC with drier climate but there are several anomalies, particularly in semi-arid and cool humid climates with extremely siliceous and highly siliceous parent materials. This trend may be explained by less weathering of high activity to low activity clays in drier climates. There is no obvious explanation for the anomalies.
- base saturation shows a clear increase with drier climates apart from some minor anomalies. This reflects decreased weathering and loss of bases from the soil exchange sites in drier climates
- a slight but poorly defined increase in base saturation with increasingly mafic parent material. The reason for this ill-defined relationship has not been determined as yet
- a clear increase in the sum of bases with increasingly mafic parent material, explained by higher content of bases and high activity clays in these materials
- a clear increase in sum of bases with drier climate, explained by the lower leaching of bases
- the increase in sum of bases that occurs with increasing mafic character becomes more pronounced as the climate becomes drier. For example, for level sites, in wet tropical climates the increase from extremely siliceous to mafic parent material is only 3.60 cmolc/kg (0.14 to 3.74), whilst for arid climates, the increase is 73.42 cmolc/kg (14.055 to 87.47). This is the same trend as observed for pH and reflects the greater relative loss of bases from mafic materials under leaching conditions. One might have expected a similar trend from CEC but this is not observed.
- no clearly defined change in sum of bases, CEC or base saturation between sloping and level sites. One might have expected higher values of base content and CEC in level sites due to the leaching of bases and clays from the upslope positions and accumulation lower in the landscape.
Figure 3b: pH of B Horizon by Parent Material and Climate for Level Sites

Figure 4a: CEC of B Horizon by Parent Material and Climate for Sloping Sites

Figure 4b: CEC of B Horizon by Parent Material and Climate for Level Sites

Figure 5a: Base Saturation of B Horizon by Parent Material and Climate for Sloping Sites

Figure 5b: Base Saturation of B Horizon by Parent Material and Climate for Level Sites

Figure 6a: Sum of Bases of B Horizon by Parent Material and Climate for Sloping Sites
4. Conclusion

The CSIRO National Soils and ISRIC WISE Global soil databases have been used to systematically examine patterns of distribution of soil types and key soil properties under 112 different global environmental regimes, being combinations of different parent material, climate and topography.

The plots and charts derived from the study reveal generally clear trends in the occurrence of soils types and properties in the different regimes. There are, however, a number of unexpected observations and subtle complexities that are not easily explained by standard theories of soil formation and deserve further consideration. The systematic poor correlation of topography with many soil properties is particularly curious. The relatively small effective population sizes suggest the results need to be treated with some caution.

The results provide a useful base for the development of predictive global soil distribution models. For example, if one was attempting to predict the character of soils in wet climates (tropical dry) – highly siliceous parent materials – level sites, one could refer to the plots and charts presented here to gain a first estimation. They suggest that the soil types may be red, yellow or brown Kandosols or possibly Kurosols (red, yellow or brown earths or possibly yellow podzolic), with dystrophic or lesser mesotrophic properties. Typical B horizons properties might be pH - 5.4, CEC - 6.4 cmolc/kg, base saturation - 42%, ESP - 2.5%, ECe - 3.1 dS/m, carbonates - 1.1%, clay - 37% and sand – 44%. In summary, they would be expected to be acid, low fertility soils with sandy clay subsols.

The results of this study demonstrate the important role that large, properly established soil databases can play in assisting in the understanding of soils in relation to their environment. Further examination of these and other world soil databases is proposed by the authors to continue the development of this predictive modelling.

5. References


