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Lithology and soil relationships for soil modelling and mapping

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ABSTRACT

Relationships between parent material and soil are not well understood and generally only reported in qualitative form. We present a classification of parent material for pedologic purposes, which includes twelve lithology classes based on mineralogical and chemical composition. The relationships of these lithology classes with six key soil properties (soil organic carbon, pH, cation exchange capacity, sum of bases, total P and clay %) were examined in a case study over New South Wales, Australia. We used multiple linear regression, Random Forest and Cubist tree models based on a soil dataset of over 3200 points. Semi-quantitative estimates are derived of change in these soil properties with a change in lithology class, and an associated *silica index*, for example, a 22% relative decrease in soil organic carbon with each 10% rise in silica, broadly equivalent to a change from shale to granite, assuming other factors remain constant.

Parent material covariates are essential for the effective modelling and mapping of soil properties. Widely available lithology data have the potential for greater use in digital soil modelling and mapping (DSMM) programs. We compared the performance of the classified lithology data with other continuous, geophysical parent material covariates such as gamma radiometrics in digital soil models and maps over NSW. The lithology covariate was demonstrated to exert the greatest influence on all six soil properties, coming well ahead of all geophysical parent material and other environmental covariates. Validation statistics demonstrated strong improvement in both model and map quality when the lithology covariate was included. For example, Lin's concordance for the Cubist sum of bases model rose from 0.46 with no parent material covariates to 0.58 with the continuous geophysical covariates to a high of 0.77 when lithology was also used. The improvement was typically slightly less marked in the final digital maps than for the calibration models, probably due to the lower reliability of the lithology grid derived from broad scale polygonal geological and soil data. A process is suggested for the application of lithology data into DSMM programs. Despite the potential drawbacks of using polygonal data, properly organised categorical lithology data can be a strong covariate to complement other continuous geophysical data sources in DSMM programs, particularly where reliable and fine scale geological and soil data are available.

1. Introduction

The importance of parent material in soil formation has long been recognised. Soil has been described as a "*kind of pathologic condition of the native rock*" (von Richthofen, 1882) and "*the residual product of the physical disintegration and chemical decomposition of rocks*" (Hilgard, 1906). Parent material was given prominence in the earliest theories of soil formation (Dokuchaev, 1899; Glinka, 1927; Hilgard, 1906; Joffe, 1936). It provides the raw starting material of the soil, be it bedrock or other unconsolidated material, upon which soil forming processes will act to create a particular soil. The essential chemical character of the parent material will be imparted into the derivative soil.

Parent material is recognised as a key component of most models of soil formation, and is an integral part of the fundamental soil equation (*clorpt*) of Jenny (1941). However, there appears to be little rigorous examination of broad universal relationships between parent material or lithology to soil formation and distribution, for example, how soil organic carbon (SOC) or pH systematically vary between soils derived from basalt to granite. Detailed investigation through literature search engines reveals a scarcity of studies on systematic lithology – soil relationships.

There are many studies that confirm the strong influence of lithology on soil distribution (Bui et al., 2006; Greve et al., 2012; Hengl et al., 2014; Xiong et al., 2014) but they rarely attempt to elucidate the actual relationships. Several studies have examined the differences in various soil properties under specific parent materials over particular regions (Cathcart et al., 2008; Chaplot et al., 2003; Cline, 1953; Graham and Franco-Vizcaino, 1992; Gruba and Socha, 2016; Jaiyeoba, 1995; Van de Wauw et al., 2008) but results are generally not synthesised to draw

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out clear universal trends. Existing relationships are at best qualitative; there appears an almost complete lack of any quantitative or semi quantitative relationships, a concern more broadly expressed by Heuvelink (2005). It has been suggested that this deficiency is due to difficulty in quantifying parent material in a meaningful way (Schaetzl and Anderson, 2005; Yaalon, 1975). This problem has been addressed to some extent through the use of geophysical indicators such as gamma radiometric or spectral imagery data in digital soil modelling and mapping (DSMM) programs, but the relationships so derived are difficult to interpret and translate more universally. The lead author has attempted to investigate parent material – soil relationships previously (Gray and Murphy, 1999, Gray et al., 2009, 2014, 2015a, 2015b), but further work is required.

1.1. Sources of parent material data for soil modelling and mapping

In addition to its essential use in conventional soil mapping programs, parent material data is widely used in digital soil mapping programs, being an element of the *scorpan* framework of McBratney et al. (2003). Parent material information is generally readily available in the form of lithology data in geological maps ranging from broad to fine scale, and now usually in digitised format. Lithology refers to the gross physical character of parent material, including its mineral composition, colour and grainsize. The data is often collected in soil survey programs, but a more systematic collection and recording of subsolum data in these programs is required, as recently called for by Juilleret et al. (2016).

Despite its availability, lithology data is frequently omitted altogether as a data source in DSMM programs. Where it is used it may be in a simplistic manner where different stratigraphic units (for example, Rylstone Volcanics or Winton Formation) are used as separate classes and not re-classified in any meaningful way. This can be cumbersome when large areas with a large number of different units are involved. In other cases, geological materials are broadly grouped together into very general classes such as coarse igneous, sedimentary or alluvial material that do not sufficiently distinguish key soil forming attributes, for example, grouping diorites with granites or feldspathic sandstones with quartz sandstones. Other approaches to classifying geological data for DSMM purposes have also been trialled (Vaysse and Lagacherie, 2015).

Remotely or proximally sensed geophysical and other modelled sources of parent material data are frequently used in digital soil mapping programs, having the benefit of providing continuous datasets down to fine pixel resolutions, such as 30 m or finer (McBratney et al., 2003; Mulder et al., 2011). Foremost amongst these are gamma radiometric data (Taylor et al., 2002; Wilford, 2012; Wilford and Minty, 2007); multi- and hyper-spectral data such as visible and near infrared (VNIR) (Lagacherie and Gomez, 2014; Viscarra Rossel and Webster, 2012) and Landsat Thematic Mapper (Boettinger et al., 2008); and electromagnetic induction/electrical conductivity (Triantafilis et al., 2009, Zhu et al., 2010). Other geophysical data sources such as magnetometry (Jordanova et al., 2008; Ryan et al., 2000) and gravity anomalies (Viscarra Rossel et al., 2015) are occasionally used. However the geophysical signals can be distorted in various ways and their relationships to lithology or direct soil properties are not always strong and well defined. It can be difficult to clearly understand and interpret the role that the data are having in the soil model meaning there can be a lack of transparency and less opportunity for the gaining of pedological knowledge.

An examination of 265 recent DSMM papers from around the globe as presented in the conference proceedings of Minasny (2012) and Arrouays et al. (2014b); and the meta-studies of McBratney et al. (2003); Grunwald (2009) and Minasny et al. (2013) provide an indication of the extent and variety of auxiliary data sources used to represent parent material or direct soil conditions. The application rates for the different sources was as follows: soil maps/data - 40% of studies; geology and lithology maps - 22%; spectral sensing techniques (Landsat, hyper-spectral VNIR, etc.) - 21%; gamma radiometrics - 9%, other geophysical sources (electromagnetic induction, electrical conductivity, etc.) - 7%; and nil parent material/soil data - 25%. It would appear there is potential for primary geological/lithologic data to be more widely utilised as an auxiliary data source in DSMM projects being carried out around the globe.

There is a need to elucidate relationships between parent material and key soil properties, so as to improve our knowledge of factors controlling soil formation and distribution. Quantitative or semi-quantitative relationships with lithology would be a useful addition to the generally poorly defined and qualitative relationships that exist at present. Widely available lithology data could provide a strong and easily applied predictor in both conventional and digital soil modelling and mapping programs, to complement other geophysical continuous parent material data sources. This paper builds on previous work of the lead author and others to develop lithology – soil relationships and to assess the potential effectiveness of incorporating lithology into DSMM programs. More specifically, the paper aims to:

- present a possible classification scheme of parent material for pedologic purposes based on broad chemical composition with 12 lithology classes
- derive semi-quantitative relationships between lithology and six key soil properties in a case study over New South Wales (NSW), Australia
- demonstrate the effectiveness of lithology as a covariate in DSMM, including comparing its effectiveness relative to other potentially available geophysical parent material covariates
- suggest a strategy for the inclusion of lithology as a predictor in DSMM programs.

2. Classification of parent material for pedological purposes

For pedological purposes, the most important feature of parent material is its lithology, and more specifically its mineralogy and chemical composition. These greatly influence both the chemical and physical properties of derivative regolith material and soils. Key chemical characteristics are the silica (SiO_2) content and selected base cation content (Ca, Mg and K), which usually have an inverse relationship with each other. The higher the silica content of a parent material, the generally higher the quartz content and lower the clay and base cation content of derivative soils. Ultimately all key soil properties are greatly influenced by the original parent material.

Other physical characteristics of the parent material such as grain size and macro-structure (layering, fracturing, etc.) are generally of lesser significance, although they can be important in some situations. Most major minerals apart from quartz will weather to clay irrespective of whether they were originally coarse or fine grained, thus for example, basalt and its coarse grained equivalent gabbro will normally give rise to similar soils. When quartz is a major component of the parent material, such as in siliceous sedimentary or igneous rocks, its grainsize becomes a more important factor and will determine whether the material classifies as coarse sand, fine sand or silt. In younger soils, such as derived from alluvial deposits, the grainsize of all minerals can be important. Bedrock structure such as the degree and orientation of fracturing can influence soil hydrology and depth of weathering properties.

The origin of the material, be it igneous plutonic or volcanic, sedimentary, metamorphic, alluvial, aeolian, etc., should not in itself directly influence soil formation. It is only the inherent chemical and to a lesser extent physical properties of the material that are important.

We propose a possible parent material classification with 12 lithological classes based on their chemical composition, as presented in Table 1. The first eight categories are based on silica and base cation levels, ranging from extremely siliceous (>85% silica) to ultra-mafic (<45% silica). Each of these first eight classes may be allocated a single "*silica index*", being its median silica percentage, which can be useful