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Automatic landform stratification and environmental correlation for modelling loess landscapes in North Otago, South Island, New Zealand

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ABSTRACT

The advent of quantitative soil-landscape modelling techniques has seen the mapping of pedological phenomena placed on a more scientific footing. In New Zealand, the spatial distribution of loess has a significant influence on soil properties, and recent regional-scale quantitative models have attempted to model the thickness and pattern of this important soil parent material. Here we apply two quantitative modelling techniques, automatic landform stratification and environmental correlation, to test and refine loess-landscape models for a higher-resolution study window in North Otago, South Island. Field validation demonstrated that previously developed coarse-scale models were moderately successful in predicting loess thickness, but these models required refinement. Automatic landform stratification based on conceptual models of loess distribution was a good predictor of primary loess in the field (85% success), but predicted poorly occurrence of colluvial and thin loess. Environmental correlation using nominal logistic regression with equal prior probabilities was a good predictor of primary loess in the field (70% success), but predicted poorly occurrence of colluvial and thin loess. Quantitative loess-landscape models need to be further refined using higher-resolution terrain data derived from LIDAR and photogrammetric surveys. In addition, morphometric similarities between different loess landscapes needs to be addressed and the historical and spatial contingency inherent in loess-landscape evolution incorporated in models for improved spatial prediction of loess parent materials.

1. Introduction

The last few decades have seen a proliferation of quantitative techniques utilising Geo-Information Systems (GIS), Digital Terrain Models (DTMs) and Global Positioning Systems (GPS) for modelling soil-landscapes (McKenzie et al., 2000; McBratney et al., 2003; Scull et al., 2003). These technologies, in combination with sound field data and pedological expertise, will continue to be essential for mapping and modelling the spatial variability and temporal dynamics (e.g. Tugel et al., 2005) of the pedosphere relevant to global change and human civilisation (e.g. sustainable land use, desertification, salinity, the carbon cycle). The reviews of McBratney et al. (2003) and Scull et al. (2003) highlighted the plethora of quantitative soil-landscape modelling techniques that have emerged paralleling the development of GIS and DTMs. Most of these techniques fall into one of two general classes: environmental correlation or landform stratification. Both methods involve digital terrain analysis, but are different in their approach. Environmental correlation establishes quantitative relationships between soil classes and properties, DTMs and remotely sensed data, using both linear and generalised linear models, classification and regression trees, neural networks, fuzzy systems or geostatistics, and the subsequent models are used to predict these soil properties and classes at other locations (McBratney et al., 2003). Empirical functional soil-landscape models (Hoosbeek and Bryant, 1992) derived from environmental correlation include those of McKenzie and Austin (1993), Gessler et al. (1995), McKenzie and Ryan (1999), Bell et al. (2000) and Ryan et al. (2000), and all are based on correlations between soil point data and raster grid cell data describing terrain and other environmental variables. Landform stratification is an alternative approach that uses digital terrain analysis to identify soil-landscape units, and encompasses landform mapping utilising semantic models of landform classification as well as the quantitative spatial expression of conceptual soil-landscape models (Dymond et al., 1995; Fels and Matson, 1996; Bui et al., 1999; MacMillan et al., 2000; Bui, 2004; MacMillan et al., 2005). Soil classes and/or properties are then ascribed to the quantitatively defined soil-landscape units.

Soil-landscape modelling has played a key role in mapping New Zealand's soil resources (Webb, 1994) and since the mid 1990s quantitative techniques have been applied in a variety of landscapes. In the North Island, DeRose (1994) produced a DTM-derived predictive

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map of regolith depth in steep, dissected hill country underlain by landslide-prone sediments, and Dymond et al. (1995) and Bakker et al. (1996) showed that DTMs can be used for automated landform classification on dissected volcanic terrain. In the South Island, Dymond and Luckman (1994) investigated the relationships between DTMs and soil classes on loess-mantled basaltic hill country, and Jones (1998) utilised terrain analysis for mapping forest soil properties on marine sediments. For South Island mountain areas, Schmidt and Hewitt (2004) showed that DTM-derived landscape elements based on fuzzy geometry and landscape context could be derived and related to soil properties, and Schmidt et al. (2005b) presented a method for deriving soil maps from a qualitative soil-landscape model using quantitative spatial modelling techniques. The continued development of quantitative soil-landscape models will contribute to the ongoing modelling and mapping of New Zealand's terrestrial ecosystems (e.g. Leathwick et al., 2003; Lilburne et al., 2004).

The spatial distribution and thickness of Quaternary loess deposits strongly influences soil properties and other environmental subsystems on the plains and lowlands of New Zealand's South Island, and therefore modelling loess distribution is a prerequisite for soil and land resource management (Schmidt et al., 2005a). Local and regional models of loess generation and distribution have been developed (see Eden and Hammond, 2003), and spatial information on loess distribution has been captured in detailed regolith studies, as part of soil-landscape studies and as part of investigations into large-scale patterns (Raeside, 1964; Ives, 1972; Bruce, 1973; McCraw, 1975). However, due to variability in loess sources, transport paths and local potentials for deposition and erosion, the spatial distribution of loess is highly complex (Ives, 1972) and models of the spatial distribution of loess tend to be conceptual (Ives, 1972; Mason et al., 1999). Schmidt et al. (2005a) recently attempted to map South Island loess by defining quantitatively coarse-scale loess-landscape models, the internal loess pattern of which was explained by a conceptual loess-landscape model developed from expert knowledge. Loess maps derived from these models were more accurate and had greater resolution than earlier maps, and they provided a more detailed description, including uncertainties, of extent, depth, and pattern of loess distribution within loess-landscapes. Schmidt et al. (2005a) concluded, however, that these models needed to be refined and tested by higher-resolution studies in selected areas, with quantitative models complemented by intensive field data.

The objectives of this study are to 1) test the validity of the model of Schmidt et al. (2005a) to identify those parts of the North Otago, South Island, landscape where the model performs well and where it performs poorly, 2) develop loess distribution models using environmental correlation based on field data, and using a landform stratification approach based on a 1:50,000 soil map and associated conceptual models, 3) validate and test the performance of the models against at dataset of field observations of loess distribution.

2. The study area

The study area is located in coastal North Otago in the South Island of New Zealand, and covers approximately 20,000 ha of lithologically and geomorphologically diverse loess-mantled terrain (Fig. 1). The lithology consists largely of an uplifted, unconformable Paleocene to Pliocene marine transgressive/regressive sequence punctuated by submarine and sub-aerial volcanism. This sequence is underlain unconformably by Mesozoic metamorphics that outcrop where the Cenozoic cover sequence has been removed. Late Pleistocene gravels occur as caps forming terrace remnants, and Holocene valley fills are associated with major streams (Gage, 1957; Forsyth, 2001). Lithology largely controls landform, with Oligocene limestone cap rocks forming mesas, uplifted Quaternary alluvial terraces forming broad flat surfaces adjacent to the present Waitaki River, and widespread Paleocene conglomerates and sands comprising a highly dissected ridge and valley terrain. The area was covered with podocarp-hardwood forest throughout the Holocene, which was cleared after human arrival c. 1000 B.P. (McGlone et al., 1993). Since European colonisation (from 1840) land use has consisted largely of sheep, beef and deer farming with minor cropping. Dairy farming has increased with the availability of irrigation.

Quaternary quartzofeldspathic loess of varying thickness derived from the Waitaki River floodplain covers much of the area (Young, 1964; Forsyth, 2001). Although direction/distance from loess source (the Waitaki River floodplain) has been shown to influence loess particle size and soil morphology (Young, 1964; Wilson, 1970; Hughes, 2003), no significant relationship between loess thickness and distance from the loess source has been shown. The presence or absence of loess is a major controlling factor on the North Otago soil pattern. Where loess is greater than approximately one metre thick, loess is considered the parent material and the soil inherits the physico–chemical properties of the loess. Where loess is less than one metre thick the underlying lithology influences soil physico–chemical properties and morphology, and soils range from relatively nutrient poor Pallic Soils (Hewitt, 1998) on silicic sandstones and mudstones (Hapludalfs) to nutrient rich Vertic and Rendzic Melanic Soils on basalts and calcareous sediments (Vertisols and Rendolls). Loess textural variation is consistent with downwind fining from the source area (Young, 1964; Ruhe, 1969; Mason et al., 1999), with resultant influences on soil morphology: well-drained fine sandy Laminar Pallic Soils (Haplustalfs) are found adjacent to the Waitaki River while Perch-Gley Pallic Soils (Inceptisols) further south are comprised mainly of silts with fragic and reductimorphic features. Soil maps and conceptual soil-landscape models have been used to infer loess distribution (Mason et al., 1999; Schmidt et al., 2005a), and the 1:50,000-scale soil map of the study area and associated soil-landscape models of Wilson (1970) may be used in this way. Wilson (1970) divided North Otago into distinct physiographic regions defined according to their lithology and pattern of landform components (e.g. dissected uplifted terraces, dissected hill lands, dissected limestone tablelands; Lynn and Basher, 1994) and provided conceptual diagrammatic models of loess parent material occurrence (Fig. 1). According to these models primary depositional loess (greater than approximately 1 m depth) occurs on uplifted terrace surfaces, moderately sloping terrace edges, broad interfluves, upper hillslopes and gully head slopes. Redeposited colluvial loess occurs on moderately steep hill slopes, moderately steep to steep gully slopes and both footslope and midslope positions. As with primary loess, redeposited loess occurs on gully head slopes. The models of Wilson (1970) suffer from the inadequacies attributed to most traditional soil survey and soil-landscape modelling techniques: complex qualitative conceptual models based on a single pedologist's field experience with little scope for testing and verifying through the scientific method (Hewitt, 1993; Cook et al., 1996; McKenzie and Ryan, 1999). For example no locations are given for most of the pedon observations of Wilson (1970), there are no quantitative definitions of “moderately sloping,” “moderately steep” and “steep” descriptors of landform elements, and there are no quantitative descriptions of loess thickness or patchiness within physiographic regions. Nevertheless, the soil-landscape models and maps of Wilson (1970) provide field-based experiential knowledge of loess pattern in the North Otago landscape that needs to be incorporated into quantitative models. The North Otago landscape therefore provides an ideal study window in which the loess landscape models of Schmidt et al. (2005a) can be validated, and further higher-resolution quantitative models can be developed based on the map and conceptual models of Wilson (1970) as well as more recent field observations of loess distribution.

3. Data and methods

Spatially referenced observations of loess occurrence in the study area (n=148) were made during the course of investigating the purity