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FROM BIODIVERSITY TO GEODIVERSITY AND SOIL DIVERSITY. A SPATIAL UNDERSTANDING OF SOIL IN ECOLOGICAL STUDIES OF THE FOREST LANDSCAPE

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THWAITES, R. N. 2000. From biodiversity to geodiversity and soil diversity. A spatial understanding of soil in ecological studies of the forest landscape. In field ecology we have to satisfy 'geographical' objectives because of the spatial nature of the landscape, rather than theoretical 'typological' objectives. To understand and maintain biodiversity we must have some understanding of geodiversity. We therefore have to adjust our attitude to the dynamism of the soil system accordingly through geoecology. This is best undertaken by using soil-landscape analysis within a geomorphological paradigm which treats soil as layers of material with spatial extent. The recommendation is for viewing a 3-dimensional micro-catchment, or 'catenary unit', rather than the soil profile, as the fundamental natural unit of study. The soil profile, or pedon, is best used for observation and generic classification only. Soil diversity is best expressed as variations in selected soil attributes that are ecologically relevant rather than preconceived soil types developed for agricultural or other puproses. Classifying soil attributes by 'fuzzy logic' (or by other mathematical clustering means) suits this form of spatial analysis for soil attribute prediction. A fuzzy classification gives a set of multiple possibilities of soil attributes at any one point, compared with an intuitive conjecture that is likely from a soil profile classification.

Key words: Forest soils – forest ecology – soil survey – fuzzy logic – terrain analysis – forest site - geoecology

THWAITES, R. N. 2000. Daripada biodiversiti kepada geodiversiti dan kepelbagaian tanah. Satu ruang pemahaman mengenai tanah dalam kajian ekologi mengenai landskap hutan. Dalam ekologi lapangan kita mestilah memenuhi objektif geografi kerana ruang semula jadi landskap, lebih daripada objektif tipologi secara teori. Untuk memahami dan mengekalkan biodiversiti kita mestilah memahami sedikit sebanyak mengenai geodiversiti. Oleh itu mestilah menyesuaikan sikap kita terhadap dinamis sistem tanah melalui geoekologi. Ini dapat dilakukan dengan menggunakan analisis landskap-tanah dalam satu paradigma geomorfologi yang menganggap tanah sebagai satu lapisan bahan dengan tambahan ruang. Cadangan tersebut adalah untuk melihat mikro-tadahan tiga dimensi, atau 'unit katenari', lebih daripada profil tanah, sebagai satu unit semula jadi asas dalam kajian tersebut. Profil tanah, atau pedon, hanya sesuai digunakan untuk cerapan dan pengkelasan umum sahaja. Diversiti tanah diungkapkan sebagai kepelbagaian dalam sifat-sifat tanah yang terpilih yang berkaitan secara ekologi berbanding dengan jenis tanah yang membenih yang dibangunkan untuk pertanian atau tujuan lain. Mengkelaskan sifat-sifat tanah secara 'logik kabur' (atau secara kelompok matematik yang lain) sesuai dengan bentuk analisis ruang untuk ramalan ciri-ciri tanah. Pengkelasan kabur memberikan satu set kemungkinan berganda dalam ciri-ciri tanah pada mana-mana tempat, berbanding dengan agakan gerak hati yang mungkin daripada pengkelasan profil tanah.

Introduction

As the focus on biodiversity conservation and restoration becomes ever more intense in the rain forests and rain forest ecology debate so should the whole rain forest landscape system come under scrutiny.

Investigation, analysis and interpretation of the tropical rain forest ecology cannot be deemed to be successful without the appropriate understanding of the soil and substrate environment. Many studies on tropical rain forests in the past have included detail about the soil characteristics at research plots or at single sites relating to a particular vegetation community. Nevertheless, rarely is a soil survey undertaken, or is referred to, nor are the spatial relationships of the soil characteristics expounded in the same way that species and vegetation associations patterns are. Soil (and the 'substrate') is often passively treated as an 'undynamic' and non-spatial entity that has a comparatively narrow relationship with the above-ground biota at a point in the landscape. A more integrated ecological research approach incorporating spatial soil components can depict the complexities and variability of the physical landscape more effectively, as the following discussion shows.

It is commonly known that soil characteristics can dictate the type, structure and health of vegetation that grows in it. We know that soil characteristics vary in space and over time as does vegetation type and structure. But how much do we know about biodiversity in relation to soil diversity? The variability of vegetation associations has been related to variation in soil type in countless investigations. But often it is vegetation *association* related to soil *type*. This sort of investigation is subject to the corruption of relating *a priori* classifications of soil and vegetation — sometimes coming up with new, statistical, classifications (e.g. Thwaites & Cowling 1988). Whilst these investigations are useful in their own right we must be cognisant as ecologists of the effects of variability of soil and soil materials in the landscape, particularly if we are to relate it to biodiversity. Hence the understanding of soil diversity [I hesitate to enter into the discussion on the confused concept of 'pedodiversity' (Ibáñez, *et al.* 1998, Camargo 1999) here. I will therefore avoid the term] is essential to the study of biodiversity. This is later related to the concept of geodiversity and geoecology.

Current dominant themes in soil investigations in tropical forests are carbon cycling (and the soil as a carbon store or sink); nutrient cycling, particularly the effects on nitrogen; mycorrhizal relationships; physical degradation and rehabilitation; as well as indicators for sustainability — following some form of guidelines, such as the 'Montreal Process' (Montreal Process 1995). A recent development for native forestry in Australia has been towards Ecologically Sustainable Forest Management (ESFM) (Raison *et al.* 1997). All these investigations, including the complexities of the ESFM research, require a good understanding and expression of the spatial variability of the soil characteristics, as well as the dynamics of the processes, in relation to the plant ecology.

Practitioners in tropical rain forest reforestation and rehabilitation, as espoused in the majority of scientific articles in this area, clearly concentrate directly on the plants (phytecology) and the vertebrates/invertebrates (zooecology), as well as the fungal/micro-organism ecology. Some of these ecological issues, particularly those with strong spatial and holistic themes, may be better tackled with a viewpoint allied more with 'landscape ecology' (Vink 1983, Forman & Godron 1986, Rohdenburg 1989, Naveh & Lieberman 1993). Landscape ecology focuses on the spatial relationships between distinctive ecosystems, the interactions among the spatial elements of those ecosystems, and the alteration in structure and function of the ecological mosaic over time (Forman & Godron 1986). Thus landscape ecology can provide "... the functional ties of the objects and processes of the individual disciplines dealing with plants, animals, and man and their functional integration for present and future land uses." (Naveh & Lieberman 1993: 9). To tackle these landscape ecology issues successfully ecologists must include the appropriate involvement of what has been termed 'geoecology' (Rohdenburg 1989). This embraces the concept of the biogeocoenose (Sukachev & Dylis 1966) which emphasises the biotic community's place in the physical environment. Only with the integration of a true understanding of geoecology[1] can we be undertaking landscape ecological investigations with a spatial and temporal viewpoint, with appropriate and effective attention to the soil and substrate component of the forest ecosystem.

Recently the Australian Heritage Commission has outlined in its Australian Natural Heritage Charter (AHC 1997) the primary value of 'Natural Significance' which highlights "...the importance of ecosystems, biological diversity, and geodiversity[2] ..." for social, scientific, aesthetic and life-support values (AHC 1997: 6). This is the first time that a policy document on the environment has professed the importance of soil and geological materials in the environment to the conservation and ecosystem management ethos at such a high level.

Geodiversity should be considered equally alongside biodiversity and restoration issues as well as being *intimately related to them.*

Many natural and environmental scientists and land managers have shown themselves to be disinterested in, dismissive of, or dissociated from soils and soil science. This disorder results in a generalisation of soil character and cursory investigation or reporting of soil-related issues. An example is the common reference to soils by their assumed parent material such as 'basalt soil', 'metamorphics soil', 'alluvials', or their position in the landscape: 'upland soils', 'plateau soils', or their colour: 'red soil', 'black soil', 'pale soils'. This is acceptable in a broad sense, e.g. for 1:100,000 scale mapping, but is not so for detailed scientific study at finer scales. A more precise and relevant reference to soil aspects and soil dynamics in tropical forests is both necessary and possible.

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[1] Geoecology = The material composition and the structure of the physical landscape, the transfers of materials and energy within the landscape as a whole and, consequently, the relationships between rocks, relief, sediments, soil, and water. Interrelationships between vegetation and the soil and the biotic components of the soil are included as terrestrial ecosystem processes. (Adapted from Rohdenburg 1989).

[2] 'Geodiversity' is defined as 'the range of earth features, including geological, *geomorphological*, palaeontological, *soil*, hydrological ... *features, systems and earth processes*' (AHC, 1997:6). (Author's emphasis).

As an example of this from ecological studies, the genetic unity of the soil profile is often accepted, and the underlying bedrock is assumed to be the parent material. Many implicit assumptions are made regarding the perceived intransitory nature of attributes like the pH levels, organic CEC values, N levels. Anything below the soil (the rest of the regolith) is usually ignored. In agriculture this could be argued as being legitimate; for forested and other natural environments it cannot (see Thwaites & Slater 1999).

Soil as a landscape ecological component

Soil within the landscape and its interaction with both the biological and physical systems has been treated, and mistreated, in many ways. The perceptions of soil in the landscape and its 'role' sometimes have been, unwittingly, misleading. For example, there is a common perception that the current climatic regimes dominate the observed soil morphology at any scale (past climates have had major influences), that the soil profile (or pedon) is a universal soil entity (it is only a convenience for classification), and that soil maps represent discrete soil types (polygons and crisp boundaries poorly represent the variation in soil continua). This situation is probably due as much to the failure of soil scientists themselves in the appropriate expression and communication of soil-landscape problems as it is to any non-specialists' misconceptions. Soil scientists have rarely provided a satisfactory spatial and ecological framework in which to conduct true ecological studies, although soil-landscape analysis (e.g. Huggett 1975) has been conducted for many years. The training and education given in soil science to botanists, zoologists, ecologists and foresters have been, more often than not, a conventional cocktail of soil chemistry, hydrology and physics (but largely chemistry) within an edaphological[3] paradigm. This is presented in terms of interaction in a vertical soil profile with no real relation to spatial references and landscape processes. Training in pedology, the study of soil development and interpretation *in the field* as soil-landscape analysis, has been increasingly marginalised in favour of investigating soil *in situ*, relating to its immediate environment. The result has been a strongly reductionist direction in the soil science discipline (which is more important for very localised edaphic studies) to the detriment of a more holistic, systems-based understanding of how soil behaves, and can be interpreted, in a spatial manner within the ecological landscape.

This contemporary direction in soil science can be attributed to three underlying reasons:

- the persistence of the discipline being conducted largely within the confines of agriculture and crop sciences, with some exceptions, in contrast to being within earth or geographical sciences—both in teaching and research as well as in the literature. The motivation behind the development of soil science has come from the agricultural land management sector.

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[3] Edaphology: the study of soil and soil processes in relation to plant growth and production.

- the remarkable adherence to a 'zonality' and 'maturity' paradigm of soil and soil development which were untested, and even unquestioned, assumptions made by the Russian and German pioneers of the discipline in the last century[4]. This has led to a general pedological paradigm that still implicitly allows the current climatic and botanical factors of soil formation to dominate over the geomorphic ones. Depending upon the scale of investigation and environmental conditions, this can be shown not to be the case in many circumstances (see Paton *et al.* 1995).
- the apparent ineffectuality of pedologists and other soil scientists to convey to practitioners in allied disciplines that soil materials are spatial and temporal continua, and should be portrayed as such. Many soil scientists appear not to be aware of this themselves (Hewitt 1993).

Pedology is an earth science that has strong relevance to the agricultural and silvicultural disciplines. It requires a predominantly geomorphological understanding to the basis of pedogenesis (soil formation and development), interpretation and classification. Edaphic interpretation of the soil is an *application* of pedology, not its raison d'etre.

Pedology and the other soil sciences can provide an essential component to ecological study if it is considered in a more landscape ecological context as a natural resource science. This must be alongside the more traditional agricultural productivity and crop interaction (edaphic) viewpoint — for which, of course, there is still a vital need.

The scale of investigation and the conceptual environment in which studies are being carried out are of central importance to how soil and soil material are perceived, observed, and interpreted. A hierarchy of scales may apply for any one particular study, or only one scale 'level' is of relevance. The unit of study, the soil entity, or the importance of soil material in the ecosystem may vary according to the scale of enquiry but the fundamental perception of what is 'soil', and how it functions as part of geoecological processes, must remain the same. Because of this it is suggested that soil and soil materials be investigated at more than one scale for any one study to put it into appropriate geoecological context and be dependant upon the relative quantitativeness and complexity of the data being sought. Hoosbeek and Bryant (1992) encapsulate this process in a quantitative way by levels of organisational hierarchy acting as distinct systems, expressed 3-dimensionally. An example stated being the level of the soil profile, or pedon, considered as 'i', with a soil unit being i+1, the catena as i+2, and the soil horizon as i-1, etc. For each level the 3-dimensionality is expressed with a 2-dimensional plane comprising the relative intensity of quantitativeness (from 'qualitative' to 'quantitative' on one axis and grade of functionality (from 'mechanistic' to 'functional') of the model on the

[4] This was then entrenched by the seminal work of Hans Jenny (1941) reducing the process of soil formation to being the result of five 'independent' factors. The 'zonal' ones of which (organisms—as expressed by vegetation, and climate) being the termed 'active' and therefore dominant. Hence the definition of 'zonal soils'. A comprehensive discussion and ultimate rejection of the zonality/maturity paradigm is given by Paton *et al.* (1995).

other. Models of soil landscape interpretation can thus be defined in terms of scale of investigation (related to appropriate data availability and/or capture), quantitativeness and functionality. This definition of model parameters is crucial to geoecological study. Thwaites and Slater (1999) have modified this concept to accommodate the 'catenary unit' (a 3-dimensional catena) as the fundamental level of investigation (*i*) as use it to express a multi-scale approach to soil-landscape modelling.

Soil scientists have, for too long, concentrated on the study of soil through the 'soil profile'. This soil profile (or the 'pedon' of the USDA—Soil Survey Staff 1975) is taken as the basic unit of study, whereas geomorphologists profess the hillslope to be the fundamental natural unit. Soil as a geomorphic concept and as a geomorphic material should then perhaps be considered by relating more to the 'hillslope' than the soil profile. The soil profile remains as the basis for observations only, particularly in pits and auger holes.

The geomorphological paradigm

Soil is largely a continuum, in both space and time. The concept of soil in the landscape as a set of discrete soil types is a purely human construct. Viewing soil at a point, describing it by the vertical soil profile and relating it to the above-ground characteristics at that point (in a research plot, say: see Appendix 1) has resulted in a predominant verticality of thought. Perception of soil types in an areal arrangement expressed by choropleth ('patchwork') maps is still an extension of vertical thinking. The requirement for all ecological interpretation of soil is for a truly spatial understanding of the dynamics of soil processes. We need to know how the soil 'behaves' between the points of observation or even within the plots and understand its variability in this space. Unlike the flora and, to some extent, the fauna on the surface, we cannot view it practicably – a feature it shares with the underlying geological material. That does not make the soil any less important. In fact, it makes it a more important focus for study because of our restricted ability to observe it. We need a conceptual model of soil as an ecological component. This ecological model of soil diversity is best viewed as a set of continuing variables related to landscape processes in a spatial framework.

Soil within the geomorphological paradigm is viewed as part of the geoecological system and expressed as soil landscapes. This means that geomorphological and geological concepts and means of investigation dominate, such as:

- investigating soil as a complex of soil materials (as earth materials) and classifying soil as such. Not to perceive soil a set of *a priori*, generic taxonomic groups but as a combination of geomorphic soil-landscape components, or attributes,
- employ the principles of stratigraphy, where possible, in describing soil materials and soil layers rather than vertical soil profiles. Therefore using soil profiles applied in the same manner as bore-logs are used to interpolate geological strata,

- introduce spatial concepts into the understanding of soil by perceiving 'soil layers' (through stratigraphy) and 3-dimensional soil-landscape systems as 'soil units',
- perceiving soil as part of hillslope (geomorphic) surface processes with energy and matter fluxes as part of an open system–revitalising the true concept of the 'catena' (see below),
- making drainage pattern and water movement processes central to soil-landscape interpretation.

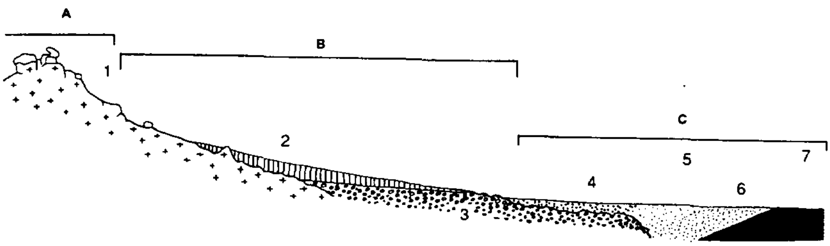
(Thwaites 1995).

The importance of this to the relationships with plants in a natural environment is extensively explored by Howard and Mitchell (1985) in the establishment of the concept, and coining of the term, of 'phytogeomorphology'. This has led to an effective but poorly appreciated discipline of phytogeomorphic mapping at many scales.

A geomorphic model of the soil-landscape can be enhanced if airborne gamma-ray spectrometry (AGS) data are available. AGS is a low-level airborne remote sensing technique that provides an opportunity to measure directly from the soil material. It captures gamma-ray emissions from uranium, thorium and potassium in the minerals within the top 30 cm of the soil. This type of survey is usually carried out for geological and mineralogical prospecting purposes but it can provide an indication of soil mineralogy, its weathering status, and its geological provenance. It is now being successfully introduced into advanced soil survey procedures in Australia (Cook *et al.* 1996, Ryan *et al.* 1999, Slater & Grundy 1999).

The spatial context

The understanding of soil and soil characteristics and functions in the spatial sense of soil-landscape analysis can be an extremely complex issue. However, viewing soil in a geomorphological context and away from the soil profile-based point observation can provide a strong spatial framework to perceiving the continuum characteristics. The mode of investigation and interpretation must be flexible in scale. We may still have to record soil attribute data at a set of points through limited observations but we must do so with a vision of how those attributes vary over space and through time on a scale appropriate to the investigation (Thwaites & Slater in press). This scale is *invariably* beyond that covering the local ecological 'site'. This 'scale of interpretation' (compared to the perceived 'scale of investigation') has been expressed in many terms but is referred to here as the 'catenary scale'. The catena, as first espoused by Milne (1935) as a hillslope unit of soil study, is discussed by Birkeland (1984), Gerrard (1995) and others as a conception of a suite of interrelated soil attributes over a topographical and hydrological (hence geomorphological) gradient which usually involves changes of parent material. This results in a pattern of soils (however defined) linked by the geomorphological and pedological processes acting upon them (Figure 1). It is also an ecological concept.



Legend:
Materials
1. Shallow, skeletal, dark grey loam, **2**. Red earth, **3**. Groundwater ferricrete, **4**. Washed sand, **5**. Silty sand, **6**. Clayey sand, **7**. Clay floor

Weathering/erosion dynamics
A. Residual zone, **B**. Transitional zone, **C**. Depositional zone

Figure 1. A stylised 2-dimensional catena on a single parent material based on the original catena sequence of Milne (1935) in Tanzania. The catena is the *sequence of changing soil characteristics* owing to the effects of topography, hydrology, parent material and surface wash (non-catastrophic erosion and aggradation) through time: a lateral fining sequence.

Viewing soil as part of the geomorphological landscape provides a closer relationship to the understanding of the biological (both phytological and zoological) landscape. At the 'catenary scale' we are dealing with soil as a 4-dimensional phenomenon. The catena concept was expressed, perhaps unintentionally, by Milne and everyone after him as a 2-dimensional model acting over time (refer Figure 1). In order to fully appreciate the soil-landscape[5] we need to apply this model in a truly 3-dimensional sense. This does not mean simply portraying the catena hillslope as a series of cross-sections of the landscape in different hillslope conditions orthogonal to the hillslope on any one compass-bearing. The model must be re-conceptualised as a 3-dimensional whole. To this end the hillslope as the fundamental unit of expression for the catena becomes the geomorphological form of the 'sub-catchment' in the 3-dimensional expression (Figure 2). This has been termed the 'valley basin' by Huggett (1975) or the 'soil-landscape unit' (Thwaites 1995). Owing to the potential confusion of the latter term with soil mapping units of soil-landscapes used widely throughout the world and the perceived inadequacy of Huggett's term, the concept is hereafter called the 'catenary unit'.

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[5] Soil-landscape = The perceived interrelationship between soil material, bedrock structure and lithology, topography, landform, and drainage pattern that occurs as a characteristic, maybe repetitive, pattern in the terrestrial ecosystem. As a class of land soil-landscapes have a limited range of topography and geological variability but with a similar drainage pattern, and often similar native plant distribution, throughout. (Author's definition).

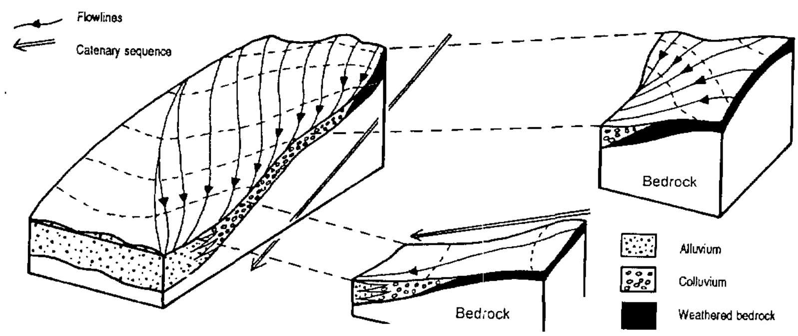

Figure 2. A stylised visualisation of a 'catenary unit' showing water and surface material transport flowlines. Catenary sequences can be observed in two or more directions. This 3-dimensional catena is adapted from the concept of Hugget's (1975) 'valley basin'.

Spatial analysis and prediction

Within landscape ecology, and particularly in forest ecology, we are often asking spatial questions. We are therefore needing spatial answers to spatial questions, a condition that is often not satisfied. Moreover, the spatial answers attained have usually been highly mathematical and may not be appropriate to the required outcomes of the investigation. However, the development of analytical spatial analysis and presentation systems, known conveniently as a geographical information system, or GIS, has allowed the effective investigation of spatial questions at the required scale. The more recently developed analytical and modelling functions of GIS now play a central role in providing spatial answers to soil-landscape questions, whether couched in individual terms or as part of an ecological problem.

The compatibility of GIS data structures with those of remotely sensed data and survey-based data (of vegetation, soil, topography etc.) has now provided the basis for a remarkably powerful spatial analytical tool. It is precisely the type of tool necessary to be employed in characterising and expressing spatial inter-relationships between the plants, animals, soil characteristics and the physical form of the landscape. We can make it a truly landscape-ecological tool.

The role of digital elevation models (DEMs) through GIS is clearly becoming central to soil-landscape modelling and is therefore directly relevant to landscape ecological investigations. DEMs are statistical surfaces of elevation data (z-axis) over horizontal planar space (x/y-axes). They can be refined by sophisticated procedures to emulate the topographical surface which they are constructed to represent. Hence they can be assumed to be spatially correct and 'hydrologically' correct so that they can be treated mathematically as if they are the land surface. In this respect they are more than a altitude matrix (a DEM) and can be conceived as digital terrain models (DTMs) (Figure 3). Their usefulness extends from emulating surface hydrological processes to aiding also the modelling of macro- to meso-climatic variability (e.g. through air mass disturbance, aspect to prevailing moisture-laden winds, insolation, temperature-altitude flux) (Moore *et al.* 1991).

(a)

(b)

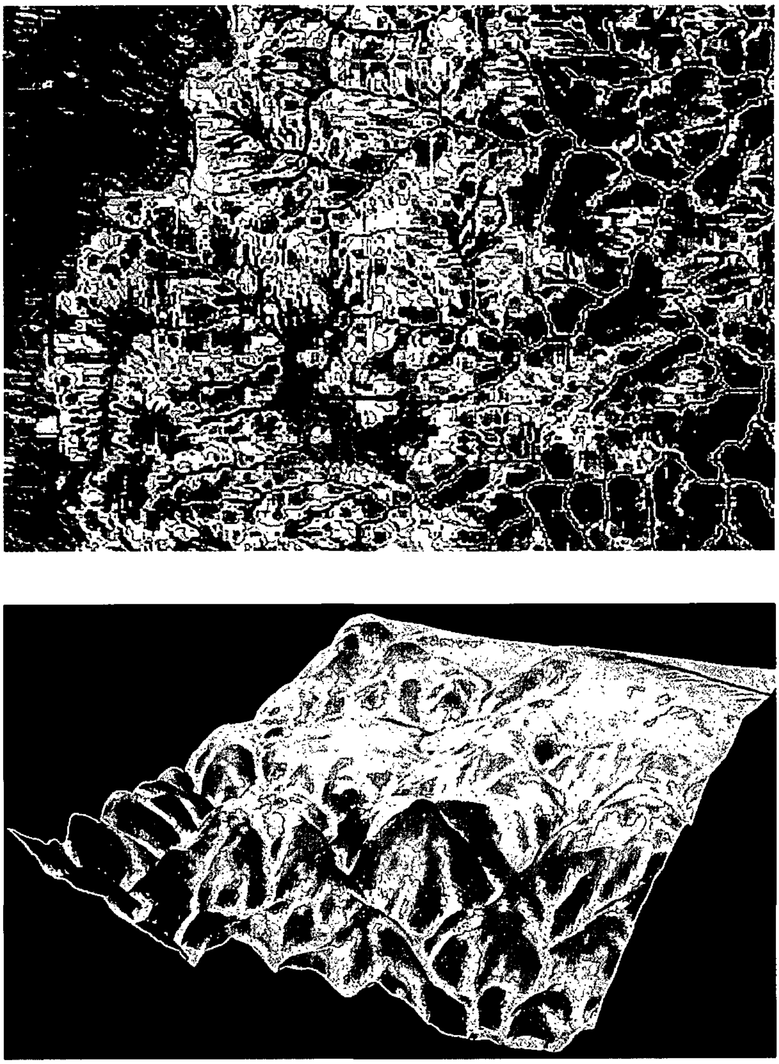

Figure 3. A hydrologically corrected digital terrain model derived from an altitude matrix of part of Benarkin State Forest, Southeast Queensland. This model shows a hydrological terrain derivative called 'topographic wetness index' which relates directly to catenary unit surface processes. The denser shading (blue colours) represents higher TWI values, i.e. greater concentration of water and materials (residual and depositional zones) the lighter shades (brown and lighter colours) are lower TWI (transitional zones, esp. erosion-prone). Cell size is 20 x 20 m. (a) Plan view, (b) Perspective view.

Through our knowledge and understanding of dynamic geomorphological and pedological processes we can attempt to predict the spatial pattern and temporal development of selected soil-landscape attributes, such as soil wetness, soil depth, soil texture, soil fabric, and leaching status and processes such as erosion, sedimentation, decomposition. Much of this DTM work has been related to surface hydrology of the hillslope which can be expressed by comparatively simple algorithms but which require a great amount of processing time and resources (Moore *et al.* 1991). The processing power to do this is now readily available using a desktop computer. The basis to this analysis are the primary derivatives of digital altitude data (slope gradient, length and aspect), and their secondary derivatives (the rate-of-change of primary derivatives: slope convexity/ concavity in both section and plan form) (Thwaites 1988). These are employed to represent surface hydrological flow and material movement on a hillslope. This 'flow' can also represent soil water and material movement, dissipation and accumulation, and the pedological processes associated with such movement. Within a soil-geomorphological paradigm this opens up new possibilities for spatial modelling that relate directly to the soil-landscape. Using such an algorithm to create a topographic wetness index (TWI) or compound topographic index (CTI, Moore *et al.* 1993) can lead to the first approximation of the character and dynamics of the surface soil continuum over a catenary unit. This approximation is based on the expression of dynamic processes operating over a topographical surface rather than interpolating values between point observations.

Moore *et al.* (1991) indicated that significant correlation occurred between quantified terrain (DTM) attributes and measured soil attributes, including A horizon thickness, organic matter content, pH, extractable P, and silt and sand contents. They also state that to apply linear relationships between terrain (DTM) attributes and soil attributes *a priori* knowledge of the catenary sequences is needed.

This approach has had significant implications for the *modus operandi* of soil surveys and assessment (e.g. Hammer *et al.* 1991, McKenzie & Austin 1993, Thwaites 1996, Slater & Grundy 1999, Thwaites & Slater in press) as well as for spatial soil research methodologies.

Soil variability and spatial relationships within forested landscapes

Soil variability is an intrinsic property of the landscape ecosystem. Biodiversity, too, is an intrinsic property that is being degraded in many areas and is the focus for redress within the landscape ecosystem. Is there a link between soil diversity and biodiversity, in the sense that there is a pattern to their relationship? There have been many studies that have attempted to show the links and many that take this interrelationship as a premise to their argument. The methodology behind soil and land resource survey (e.g. Dent & Young 1981, Gunn *et al.* 1988), even geological survey, relies on the existence of 'phytoindicators': vegetation patterns, or individual species, reflecting certain soil (or substrate) characteristics. This model for interpretation has also been deceptive. It has relied too much on a broad 'indication' relationship concept (e.g. major vegetation associations, presence of dominant species, simple vegetation structure). There are other characteristics of vegetation (particularly forests) that can be related to soil diversity. More particularly, there are aspects of soil diversity relating to certain characteristics of forests that may aid biodiversity and rehabilitation investigations.

As an example of the soil spatial relationships to rain forest characteristics, Mackey (1993) showed that plot observations of vegetation dynamics could be extended spatially to larger areas. The basis being to determine the extent to which spatial variability in vegetation attributes relates to variation in physical environmental variables. Whilst climatic relationships had been satisfactorily investigated, questions remained as to the dependence of rain forest structure on topography, soil, and hydrology. He concluded that soil and topographic variables (particularly a topographic dynamic wetness index) need to be considered when predicting the potential distribution of rain forest structure. Spatial analysis of soil-terrain factors was undertaken through digital elevation modelling within a GIS framework. This brings in the essential 3-dimensionality to solving the problem. The spatial relationships between soil-terrain factors (and climate) and the vegetation structural attributes were deemed to be the basis of the models predicting distribution of rain forest structure (Mackey 1993).

This kind of investigation is scale-sensitive, being dependant upon data resolution and scale of ecosystem investigation, but it is the 'landscape' scale (between the plot/hill slope and the regional, or catchment scale) that these relationships need to be investigated, and apply most effectively (Thwaites & Slater in press).

Classifying the soil material, not the soil profile

Comment must be made about pedological soil classification. Often it has been a major purpose to classify the soil(s) under investigation, and soil sample data have been collected solely for that purpose. For soil-landscape investigations within an ecological context classifying the soil is not usually a primary task. In fact, in using spatial analytical techniques it is expedient to classify last. For the purposes of a forest ecology study, naming the soil (i.e. the soil *profile*) is of little consequence. It is only convenient in a conventional soil-survey sense (in which groups of soil profiles are named). For the purposes of communicating results to the scientific or other communities a classification to a generic Order or Sub-order level (e.g. for Soil Taxonomy, USDA 1995) is usually sufficient. *It is the spatial arrangement of the soil characteristics in the landscape that is important to us, not the names of the soil profiles.*

Baize *et al.* (1990) distinguish between what they term 'typological' objectives and 'geographical' objectives in soil relationships. It is this duality which Hewitt (1993) believes is fundamental to the concepts of soil classification and survey. This 'typological' and 'geographical' dichotomy leads us to the basic differences in understanding soil as a profile of properties for taxonomic classification (typological) as contrasted to viewing soil from its spatial interrelationships of properties (geographical). Typological objectives lead to 'taxonomic' expression of the profile – geographical objectives lead to 'spatial' expression of soil-landscapes. *We need to be investigating this 'geographical' spatial expression in forest ecological studies.*

Generic, taxonomic classification of soil types inevitably leads us to the areal expression of 'like' soil types within the familiar soil map. This, of course, is a presentation of not only an *a priori* condition on the soils but a conceptual one also. Generic soil classifications imply that any soil described will fit into a pre-conceived nook within a conceptualised framework. Some classifications are better at doing this than others. Soil, as a spatial continuum in the landscape, cannot be satisfactorily described in this manner (unlike plants or animal individuals). It is more logical, and of more use, to describe the variability of the relevant properties of the soil in a spatial context. Classifying a soil profile only identifies the vertical arrangement of that soil at a point in the landscape, with reference to a pre-conceived classification structure. A structure which will have been necessarily generalised to suit a plethora of uses (and users) and be biased towards a morphological and/or pedogenetic model which may or may not be edaphically sound for any singular purpose. These inherent characteristics are of little value to the scientific research of forest ecological interrelationships with soil.

A solution is to classify last, particularly if soil survey is not the primary task. For research purposes it is a suite of soil properties (or 'attributes') that are more important. Soil attributes that have been predicted through DTM analysis, or other spatial statistical means, can eventually be subjected to a classification after all the necessary analysis has been completed. Forms of clustering analysis of varying complexity can do this, but fuzzy logic theory can also provide a powerful means of describing and classifying soil attributes from any form of spatial prediction.

Fuzzy soils

Spatial prediction is the basis to conventional soil survey which is a complex conceptual and heuristic process. The process, however is largely intuitive and implicit, and is *post hoc*, i.e. variation is predicted through interpolation by sampling of patterns of unknown distribution. It inevitably results in a soil map of some form showing outwardly homogenous units of soil (however classified and defined) in 'crisp' sets of binary status (membership or non-membership of a class or unit). This is a model of discontinuous variation whereas we know, in the vast majority of instances soil variation is continuous. The soil unit boundary is not real in nature but is so on the map. It encapsulates soil-types in crisp sets (discrete classes) and is purely a construct of classification. Spatial analysis through GIS, with spatial statistics, provides opportunities to enhance our interpretation of spatial (and temporal) soil variability in a more continuous manner, particularly by realising *gradients* of parametric attributes through space and obviating the need for boundaries. It can also aid the true need to predict soil variability by recognising the pattern of variation in soil attributes through soil-forming and soil-changing (pedogenetic) processes.

The variability in soil attributes, both individually and conceptually, within the landscape is naturally 'fuzzy', not discrete. We can attempt to portray these soil attributes (not 'soil-types' or 'classes') in a form relating to fuzzy set theory (Zadeh 1965). Fuzzy classification (a development of clustering analysis with abstract sets) handles well the inexactness and uncertainty of natural phenomena in a quantitative way (Odeh *et al.* 1992). All that a fuzzy approach does to our soil data is present it in form of proportional participation (e.g. a percentage) of any attribute set determined by the user – not a categorical membership/non-membership of a soil class. These attribute sets (e.g. topsoil sand, topsoil clay, organic matter, subsoil pedality, A-horizon depth) can be further categorically expressed (e.g. high to low; weak to strong; poor to excellent), if desired, using empirically-derived or heuristic rules. Thus, for any one point (grid cell) on the digital landscape there will be a proportional representation of some or all sets of attributes predicted, providing an expression of multiple values for each point. This classification approach lends itself directly to spatial analysis through DTM. This is not only because of its quantitative and statistical form but also because, as Odeh *et al.* (1991: 515) point out from an application of fuzzy classification to soil attribute data "...slope appears to be the most significant feature influencing the soil pattern...", which is as a consequence of slope/landform processes. Computation is still complex but work is continuing on this and the operational application to soil survey (Slater & Grundy 1999).

Prediction of soil diversity related to terrain in a continuous form, as a raster format, is compatible with ecological understanding of climatic and ecosystem processes. At the 'catenary' scale this conceptual approach is not only valid but also desirable to integrate with other ecological data.

Such a methodology is currently being applied to rain forest species–site for reforestation on private land over parts of the Atherton Tableland of north Queensland, Australia (Thwaites in press). This is to establish the best sites for planting individual species based not only on computer-derived climatic surfaces, but also soil-landscape data generated through digital terrain modelling, and specialist knowledge of the soil-landscape environment.

Results from this study will be published upon its completion.

Summary

Geoecology is vital to the understanding of plant ecological relationships. The integration of pedological, geomorphological and geological influences on the biotic landscape complements the inclusion of climatic and atmospheric aspects. What is more, these influences are both spatial and temporal. Therefore, we have to be particularly careful when conducting studies that substitute space for time, as is often done in forest ecological chronosequences: for every point in space there is a temporal aspect to consider. Likewise, for any point in time there is clearly a spatial aspect to consider.

Soil is a spatial entity, as are its constituent materials. It is also a geomorphological entity. Forest ecology, along with all plant ecology investigations, must include the soil as a geomorphic component of the ecological system, rather than just an edaphic medium for plants.

In field ecology we have to satisfy 'geographical' objectives because of the spatial nature of the landscape, rather than theoretical 'typological' objectives. We must adjust our attitude to the dynamism of the soil system accordingly. This is best undertaken through soil-landscape analysis which treats soil as a spatial entity with the 3-dimensional micro-catchment, or 'catenary unit', rather than the soil profile, as the fundamental natural unit of study. The soil profile is best used for observation and generic classification only.

If soil classification is not the primary aim, then classify last. Mathematical means (such as clustering) can do this, though classifying by 'fuzzy' means may be of advantage. A fuzzy classification gives a set of multiple possibilities of soil attributes at any one point, compared with an intuitive conjecture that is likely from a soil profile classification.

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Appendix 1

A hypothetical scenario

Given an R&D programme in rehabilitating degraded tropical forest the most common method to investigate soil interaction would be to analyse the soil profile within growth plots, control plots, or within various biogeographical sites. Soil sample sites are selected specifically to relate to the trial plants or stand being investigated. Little *physical* site information, including surface condition, is collected relating the soil sample to the geomorphic environment. Soil samples are taken from the surface and bulked. Sub-surface samples are taken at *regular* intervals down the profile (of the A and B horizons only) and, depending on the number of samples and purposes of the investigation, are *also* bulked. This process is often done through augering or coring if the number of samples required is high, or it is not part of a scientific research project. Otherwise pits are dug to take samples *in situ* and the profile (A and B horizons only) is described to a level required to provide a satisfactory classification. For Soil Taxonomy classification (USDA, 1975 *et seq.*) this will need extensive description and laboratory analysis. Soil samples are taken for laboratory analysis purposes—usually for fertility assessment. Fertility is then described following an accepted procedure. Soil analytical results are then related to growth parameters of the plot or stand site, sometimes involving a comparison of foliar nutrient data from the flush of new growth. Conclusions are then drawn on these comparisons as to the performance of this 'site' to sustain the growth of the trees investigated based on this 'snapshot' instant within the temporal continuum. These conclusions are in turn transferred to the rest of the landscape through reliance upon analogues (a technical term for act-of-faith). Even using expert knowledge in the transfer of results by analogy to 'similar' sites can still be questionable unless the area to which the results are being applied is known intimately or recourse to a reliable, detailed, and comprehensive soil survey is possible.

The tree planter/manager or ecologist requires more detailed expression of soil material spatial variation than this provides. Even the output from a detailed conventional soil survey can be restrictive. As a possible alternative for the catenary and landscape scale investigations the users need to select those aspects of the soil that are or greatest relevance to their requirements and then aim to maximise their expression. More often than not these will be related to soil water movement and storage ability, as well as nutrient availability. This latter property is problematic to predict as it is temporally very variable, and is dependent upon many other environmental variables.

Soil sampling should be undertaken systematically within catenary units (previously delineated from air photos, maps or a DEM) and observations should be recorded with reference to defined regolith layers and soil horizons. Accurate location of sampling sites, preferably with a differential GPS (global positioning system) is necessary. Road and stream cuttings and any other types of exposures should be used to observe the regolith in concert with pit and auger observations.

Physical landscape information is necessary to develop a geomorphological model of the study area. This, along with geological information and any available AGS data, aids the subsequent terrain modelling.

A DTM can be generated from contour data, stereo aerial photography, or land survey data in raster (grid) format. Processing of the model provides slope derivatives (including a topographic wetness index) that can be combined with the spatial physical landform, geological, and remote sensing data to provide a basic landscape model. Soil data from the geo-referenced sample sites in catenary basins are then incorporated. Rules are then devised to characterise the terrain parameters that correlate with the soil attribute data. These rules are then defined in terms of 'fuzzy sets', which then can be used to portray the soil attributes as proportional membership in the relevant groups (e.g. low, medium, and high pH) on a grid cell basis. This process can be replicated and refined at will with further data, when available.