Digital terrain modelling for site productivity assessment and stand management in plantation forestry

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Abstract

Digital terrain modelling and sampled plot productivity data is used to generate a predictive surface of site productivity across a heterogeneous landscape of 35,000 ha of plantation forestry. The productivity surface is generated from terrain and topographic attributes, specifically slope, elevation and a solar radiation index, using map algebra functions in a Geographic Information System. The quantitative surface is able to explain 41% of the variation in site productivity across the landscape. The within-compartment variation in site productivity was related to the variation predicted by the model surface. This technique makes it possible to model site productivity from terrain characteristics, reducing the need to collect detailed soil or other environmental data. This approach is relatively low cost, directly links the terrain to forest productivity and provides a useful tool for planning and optimising stand management units in the forestry enterprise with respect to the environmental variability of sites across the landscape.

Introduction

Plantation forestry in New Zealand, of which 89.2% is *Pinus radiata D.Don*, provided 11% of New Zealand's export income, 3.1% of New Zealand's GDP and covered approximately 7% of New Zealand's land area in the year ended March 21, 2006 (New Zealand Forest Owners Association *et al*. 2006). Environmental and financial pressures both increase the requirement to model and predict forest productivity. Environmental sustainability requires land and forest resource assessments, while financial sustainability requires the ability to evaluate, manage and optimise forestry operations.

Land resource information may be collected through the traditional procedures of geomorphological mapping and soil surveys. However, much of New Zealand's forestry environment is rugged and relatively remote hence there are significant costs and access problems associated with these methods.

Foresters require information to improve management for individual stands or some similarly named unit of land management, such as "pods". A pod, literally "piece of dirt", is a term used by Carter Holt Harvey forest managers for their management units in the forest. Detailed land resource information at the individual stand or pod scale is often limited; however, this information may be provided to a sufficient level of accuracy through predictive terrain modelling in a Geographical Information System (GIS) environment (Thwaites, 1995).

Since the 1920s growth data from permanent sample plots (PSPs) have been collected in New Zealand to provide a measure of site productivity. The growth measurements from these PSPs cover a wide range of locations and terrain and provide a valuable source of data that may be used with digital terrain analysis to model the relative suitability of a landscape as a habitat for tree growth.

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The objective of this paper is to test the hypothesis that digital terrain modelling and tree growth data from plots can be used to adequately model a predictive site productivity surface for plantation forestry in heterogeneous terrain. Secondly, we demonstrate that the predictive model can be used to optimise the location of the spatial management units of forestry operations in terms of environmentally homogenous units.

Methods and Techniques

Study site

The study area is 35,353 ha of the northern Kinleith Forest near Tokoroa, in the central North Island of New Zealand. The forest is predominantly a *Pinus radiata* plantation (Figure 1). The studied forest is situated on the southern Mamaku Plateau, on the edge of the Taupo Volcanic Zone, with elevations ranging from 160m asl on the western margins to nearly 700m asl in the south east. Rainfall generally increases with altitude from 1400mm per year at lower elevations to 2400mm per year at higher elevations[2]. Mean annual temperatures are moderate and average 10°C, though they may differ around the mean as a result of the altitudinal range.

The landscape of this area has evolved as a result of deposition events of ignimbrites, tephras and loess and by subsequent weathering and erosion. The landscape can be subdivided into three regions[2]: 1. An upper plateau area of higher elevation, dominated by small conical shaped hills or hummocks; 2. Broad interfluves separated by steep-sided gullies; and 3. Rolling hills, wide valleys and rounded ridges. The predominant soils are referred to as pumice soils, which are developed on rhyolitic tephra parent material (Hill, 1999).

[2] *Rijkse, W.C (1994): Soils of Kinleith Forest. Unpublished contract report to Carter Holt Harvey Forests Limited, Landcare Research, Hamilton.*

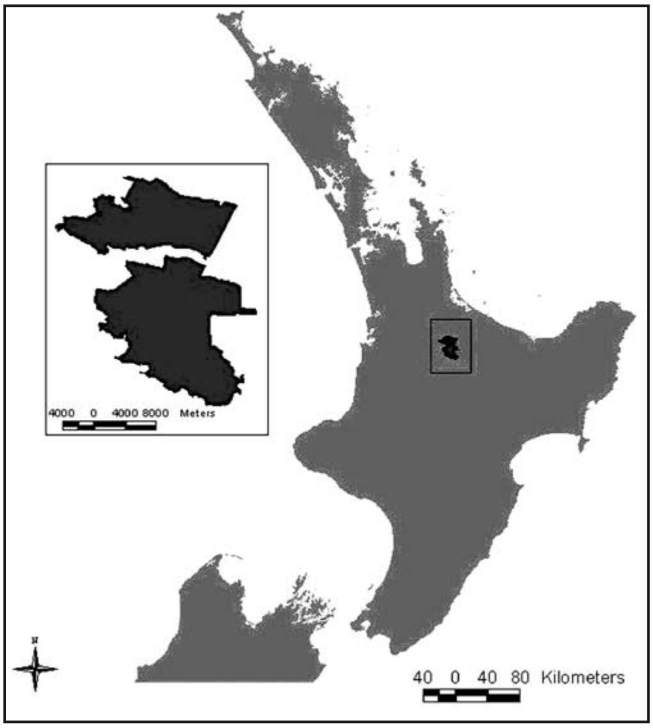


Figure 1. Location of study area.

Digital Terrain Modelling

Rather than attempt to represent or describe a land surface in terms of discrete units, e.g. a soil polygon map, or landscape entities, the use of a digital terrain model enables landscapes to be treated as continuous surfaces of quantitative variables. This explicit quantitative model is a departure from the more intuitive, qualitative and subjective approach of land resource evaluation (Pike, 1995). Rather than imprecise terms such as hilly and plateau (Frank *et al*. 1986) the use of digital terrain models (DTMs) has made it possible to quantify the topographic attributes in a repeatable, explicit and objective manner (Moore *et al*. 1993b).

The shape of the terrain influences the flow of surface water; the transfer and translocation of sediments, solutes and nutrients; the microclimate with respect to exposure to solar radiation; and the nature, quality and distribution of habitats for plants (Blaszczynski, 1997). These topographic controls form the basis of disciplines such as landscape ecology and phytogeomorphology (Howard and Mitchell, 1985; Moore *et al*. 1993c), geomorphometry (Thorn, 1988; Morisawa, 1988; Clarke, 1990,) and soil landscape modelling (Hall, 1983; Pennock *et al*. 1987; Moore *et al*. 1993a; Odeh *et al*. 1994; Boer *et al*. 1996; McKenzie and Ryan 1999; Minasney and McBratney 2001). Soil properties are necessary inputs for most plant growth models, such as the widely used tree growth model JABOWA (Botkin and Nisbet, 1997). However, in this study the topographic attributes of the terrain form the predictive components of the forest growth model, with the soil and hydrological elements being implicit in the landscape model.

As with any study of landscape the scale of the investigation is important. Whatever the scale used the methods and assumptions must be appropriate to the resolution of the data. According to the broad classification of scale outlined by Hutchinson and Gallant (2000) a digital elevation model (DEM) with a resolution of 5 - 50m, known as the fine scale, is appropriate for analysis of soil properties, hydrological modelling, solar radiation and vegetation patterns. A DEM[3] with a resolution of 20m was used for this study based on the available contour data and computing power.

The fine toposcale of modelling captures the exogenous vectors of pedogenesis, as described by Johnson *et al*. (1990), which are the external environmental factors such as temperature, wetness and topography. Endogenous factors, which evolve in the soil system itself, cannot explicitly be modelled at a fine toposcale or landscape scale as proposed here.

From the DEM, primary and secondary topographic attributes can be derived (Gessler *et al*. 1995). Primary attributes are calculated directly from the DEM and include derivatives such as slope angle, aspect, plan curvature and profile curvatures. Secondary, or compound, attributes involve combinations of the primary attributes that quantify or characterise the spatial variability of specific processes occurring in the landscape; for example flow accumulation surfaces, specific contributing areas, solar radiation exposure, and various compound terrain indices (Moore and Hutchinson, 1991; Moore *et al*. 1991, 1993b).

Using the spline fitting algorithms in ANUDEM (Hutchinson, 1989) a raster DEM was interpolated from 20m contours, spot heights, and drainage lines to produce a hydrologically accurate landscape surface without spurious pits or spikes. From this DEM the following topographic attributes were generated for each of the 20m grid cells: slope angle (degrees); slope position (based on the geomorphological model of Ruhe, 1960); aspect (degree clockwise from N); plan and profile curvature; topographic wetness index using the formula

$$W = \ln\left(\frac{A_s}{\tan b}\right)$$

where A^s is the specific catchment area, and β is the slope angle (in degrees); and a solar radiation index. The solar radiation index was computed by calculating the sun's azimuth and altitude for the study site for each hour. This data was then used to create an index of relative shading, as controlled by topography, for the course of the year. This gives a shading index to represent the most to the least shaded pixels on a per grid cell basis (20m by 20m on the ground), not the actual solar radiation input expressed as units of energy (Duffie and Beckman, 1980).

[3] *Barringer, J.R.F.; Pairman, D.; McNeill, S.J. 2002, Development of a high-resolution digital elevation model for New Zealand. Landcare Research Contract Report LC0102/170 (unpublished).*

Site Productivity Data

Site productivity data are typically derived by making repeated standardised measurements that are combined into a defined index. The index acts as a surrogate measure of all the properties of a site that together contribute towards tree growth. These include soil and hydrological properties, as well as topographical aspects such as elevation, aspect and solar radiation input, and shelter from prevailing weather. Two indicators of site productivity are used in this study: the site index and the mean annual increment.

Site index (SI), a universal and standard measuring procedure in forestry operations for measuring tree growth performance (Tesch, 1981; Hunter and Gibson, 1984; Eyles, 1986), is defined as the mean height at age 20 years of the 100 largest diameter trees per hectare (Hagglund, 1981). While there are some drawbacks with site index, its relative insensitivity to management practices, compared with basal area or volume, make it a good measure of site quality (Richardson *et al.* 1999).

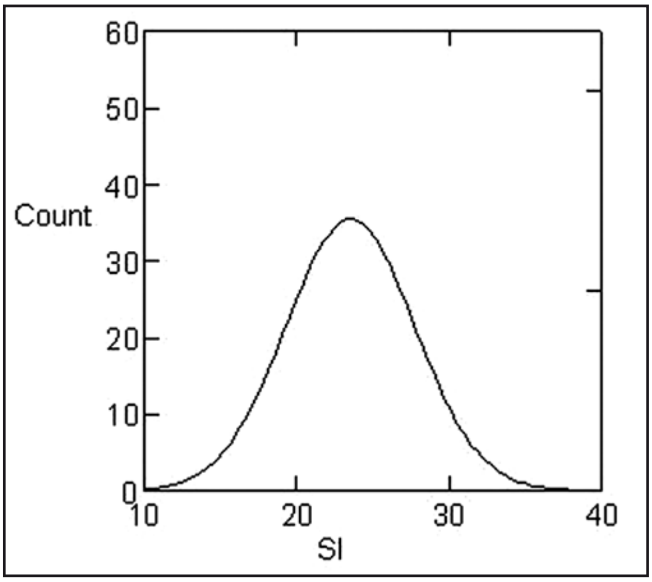
As different silvicultural practices such as stocking, thinning and pruning do, however, have some influence on an index such as the site index, Scion (then known as Forest Research) in conjunction with the Forest and Farm Plantation Research Cooperative developed an indicator that removes the influences of silvicultural effects. This indicator, the mean annual increment for 300 stems per hectare (MAI-300) or as the 300 index (Kimberley *et al.* 2005), corrects for the effects of age, stocking, thinning and pruning, and was developed based on the analysis of data from over 600 growth plots. The calculation of MAI-300 requires at least one measurement and the full silvicultural history of the plot to be known.

The MAI-300 data were used as input to the DEM-based productivity model. In addition, where SI data were available without any silvicultural history, these were also used during the modeling process but only in a limited manner, as described below.

Study Site Growth Data

For the study area, tree growth data and stand history for 302 PSP sites were obtained and their MAI-300 index calculated. Of these, 262 plots were used to develop the productivity model, while 40 were reserved to verify the model (representing slightly more than 10% of the sample). These 40 data points were randomly selected from the set using a prime modulus linear congruential generator (Marse and Roberts 1983). The MAI-300 values for the study area have a normal distribution (Figure 2). The MAI-300 for the 40 reserved points are also normally distributed.

The distribution of the plot sites shows a reasonable spatial spread across the entire study area (Figure 3).



N of cases	262
Minimum	13.6
Maximum	39.2
Range	25.6
Mean	23.5
Standard Dev	4.2

Figure 2. The fitted Normal distribution for the 262 MAI-300 values.

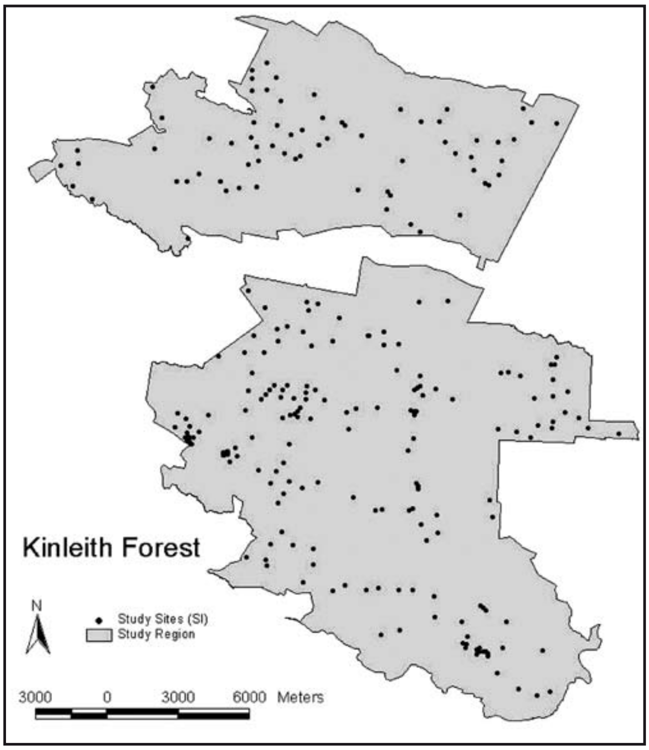


Figure 3. The 262 PSP locations used for the modelling of the productivity surface.

Pod Validation Data

In addition to the permanent sample plot data, additional site index data was available for 450 pods. These additional measurements were from inventory plots that are laid out as a matrix of sample sites across the extent of a pod, and are measured once near to harvest time. These inventory plots were at different spatial locations than the permanent sample plot sites used for the MAI-300 surface derivation, and had a much finer spatial resolution. As stand history was not available for these inventory plots, the data could not be standardised to MAI-300. However, it was still possible to use this data to compare the curvature (rate of change) of the predicted surface, in order to determine if the predictions followed similar trends to the measured indices.

Productivity Surface

MAI-300 was used as the dependant variable for site productivity modeling. This data was analysed statistically with the following landscape variables: slope, curvature, solar radiation index, and topographic wetness index by using regression analysis; including linear regression, step-wise multiple regression and regression trees to ensure the determination of the optimum model. The objective was to find the best fit model to be used to build a predictive surface of site productivity, not by spatial interpolation between existing data points but by calculating the model for each cell in the raster model. With this approach there is no error component associated with spatial interpolation, just the error component in the underlying model used to populate the spatial surface with data.

The 40 data points not used in the model building were used to verify the surface generated.

Pod variability assessment

The productivity surface was used to examine the possibility of rearranging pod boundaries so as to minimise within-pod variance, in effect, designing the management units to homogenise terrain and micro-climate conditions. Also the degree of variation in elevation within the pods could be compared to the variation in the site index surface over the same areas.

Results

Correlation testing of the MAI-300 data with categorical data such as soil units, landforms and slope classes indicated that this was not a fruitful avenue of investigation because the variation of the index within these classes was of the same magnitude as the between-class variation.

The best model, determined by regression analysis with a method of least squares fit, used three variables: slope angle, elevation and shade index (Table 1); i.e.

Predicted MAI-300 = 28.947 + (-0.025 x elevation) + (-0.219 x slope) + (0.062 x shade index)

This model was used to produce a productivity surface for the study area (Figure 4), within a raster GIS environment. Map algebra functions were used with slope, elevation and solar radiation index layers as inputs, the regression equation as the operator, and with the output layer being the predicted MAI-300 surface.

The mean and standard deviations of the predicted MAI-300 and the 40 verification points were not significantly different. The points cluster along the 1:1 line (Figure 5), with the coefficient of determination indicating that

Table 1. Multiple regression model for site productivity.

Productivity Prediction Model:				
Number of data points:	262			
Squared multiple R:	0.411			
Standard error of estimate	3.687			
Overall p-value (F-test)	0.000			
Effect	Coefficient	Std Error	Std Coefficient	P-value (2 Tail)
CONSTANT	28.947	3.306	8.755	0.000
SLOPE	-0.219	0.044	-0.398	0.000
ELEVATION	-0.025	0.003	-0.586	0.000
SOLAR RADIATION INDEX	0.062	0.020	0.238	0.002

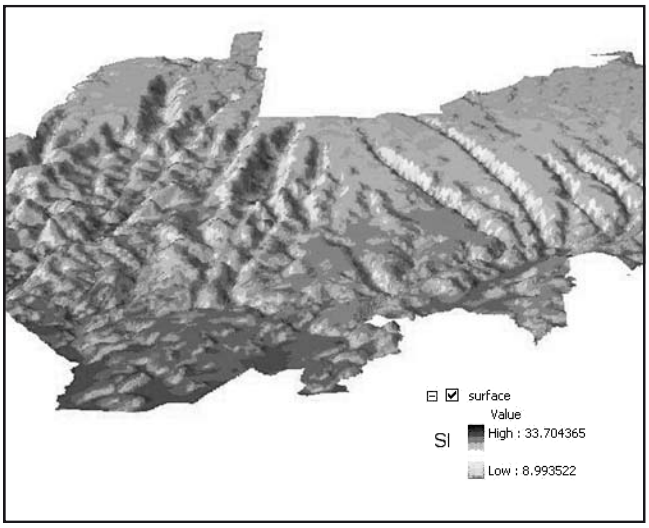


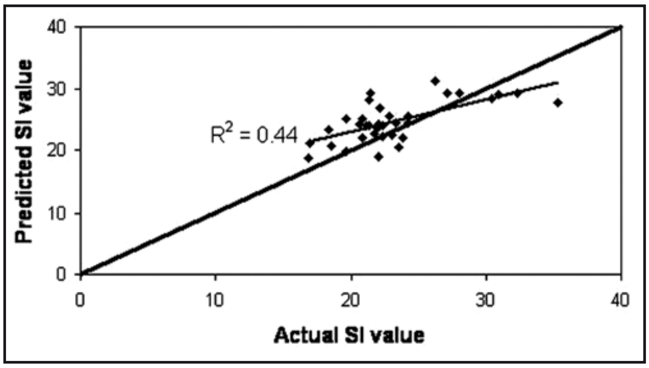
Figure 4. MAI-300 productivity surface for part of the North Kinleith Forest (oblique view from the West).

only 44% of the actual MAI-300 can be explained by the predicted MAI-300. Ideally, for model verification, an R^2 close to 1.0 and a regression line slope close to 1.0 are desired. However, in this case the model appears to under-predict especially at high MAI-300 values and over-predict in lower values. For example, if the highest MAI-300 data-point is removed from the verification exercise the coefficient of determination rises to 0.46. Of interest is that the removal of this highest data-point also resulted in the slope of the regression line being not statistically different from 1.0. Hence it was considered that despite the R^2 being less than ideal, the underlying model of site productivity nevertheless appeared reasonable.

The Application of the MAI-300 Surface to Forest Management

Pods are the areal units used in the management of planting and harvesting; i.e. a pod is planted at one point in time with the same genotype of tree, is subject to the same thinning and pruning practices, and all the trees in the pod will be harvested together. However, biophysical attributes such as soil units or landform elements, may not underpin pod layout or design. Instead, historical or reasons of convenience such as proximity to roads and the position of existing pods can influence pod boundaries. Therefore, pods are an example of what are referred to as "virtual boundaries" in GIS. Such a boundary defines a discrete unit, which may have very precise units of measurement stored against it in the GIS, but may represent an artificial delineation in a continuum, or may in fact have a sometimes unexpectedly high within-unit variation when applied to reality. These boundaries, however, delineate an important concept for management, and so the MAI-300 surface was used to test the usefulness of these boundaries for delineating areas of forest productivity.

Firstly, the MAI-300 surface was compared to the S.I. of the inventory plots to verify if the modelled MAI-300



Mean of Actual Index	=	23.18
Standard Deviation of Actual Index	=	3.99
Mean of Predicted Index	=	24.59
Standard Deviation of Predicted Index	=	4.08

Figure 5. Plot of predicted MAI-300 against actual for the 40 retained plots.

surface followed the same spatial trend as the measured S.I. While these are two different indices, they are known to the authors to be not unrelated to one another. The two indices were compared at each of the 450 inventory plot locations. While the inventory S.I. values had a higher mean than the MAI-300 values (29 vs 23), the standard deviations of the two datasets were similar (1.3 and 1.9 respectively). The inventory plot data was slightly more leptokurtic (a kurtosis of 14 compared to 4). It was decided to compare the variance of site indices within a pod to the variance of the virtual MAI-300 surface in the pod in order to determine if it is possible to rearrange pod boundaries in such a way as to minimise within-pod variance; in effect relating them better to terrain and microclimate conditions.

In the northern Kinleith study site, pods cover a range of different terrain types and a certain amount of variation in site productivity within individual pods would be expected, depending on the size of the pod and the degree of terrain heterogeneity within that pod. If terrain-based attributes are drivers of site productivity, then terrain can be used in the design of pods to minimise within pod variance and allow more effective operational management practices and forest valuation. For example, it is advantageous if growth models can more accuratelly predict growth and value for all the trees in the pod. The degree to which this is feasible will depend on the nature of the terrain and the variability of site productivity related specific terrain elements within a given management unit.

To test the ability of the MAI-300 surface to improve pod management, the pod boundaries were redesigned to reduce within-pod variance. By splitting a pod with a site index variance of 3.76 into two, a new pod with a site index variance of 1.5 and the remaining pod with a variance of 3.2 were created (Figure 6). With a certain amount of pod redesign the variation in site index across a management

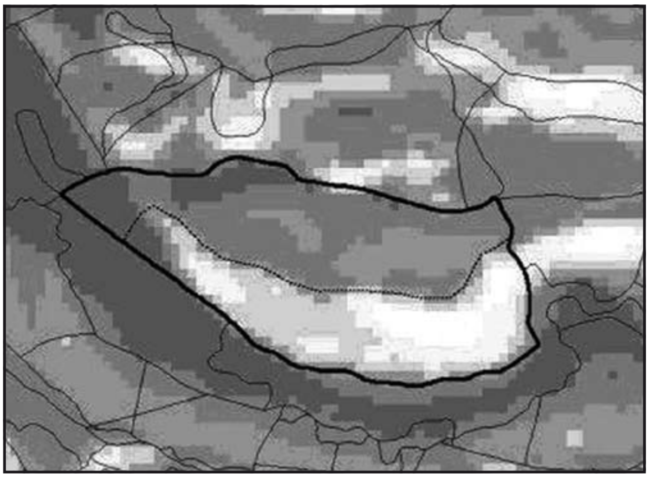


Figure 6. Pod redesign using the variance in MAI-300. An example of a pod (dark outline) being split into two (dotted line) based on the underlying site productivity surface where the lighter shade represents higher productivity.

unit could be reduced (without reducing the size of the management units too much) and so delineate a more uniform stand of trees.

There is of course a balance between reducing variance and making the units too small for effective forestry operations. However, it is possible to reorganise these spatial units without making units smaller so the within pod variance is substantially reduced. For example, in another case from 8 redrawn pod boundaries the average reduction in within-pod productivity index variance was 48%. In addition, where a new area is being developed, a productivity index model could aid the planning of the pods. Using a series of standard GIS operations for neighbourhoods on the site productivity surface facilitates the process of creating pod boundaries. Interpreting the productivity surface may be improved by what is known as clumping and sieving techniques. These neighbourhood operations utilise spatial filters to remove noise from extraneous cell values and assign similar values to like classes based on the values of neighbouring cells. Hence management units may be identified and pod boundaries fitted without further specialisation.

The pods also provide an opportunity to further verify the site productivity surface. For each pod the topographic roughness index (TRI), a parameter developed to express the magnitude of elevation difference between adjacent cells of a digital elevation grid (Riley *et al*. 1999), was compared to the within-pod variance of the site index surface. The TRI is a good measure of the heterogeneity of the topography and, if productivity relates to topography, then where the site index is highly variable within an area such as a pod, we would expect the roughness index of the pod to be high also. In this case the variance of MAI-300 index and the TRI for the pods was significantly correlated with an R^2 of 0.53.

Discussion

The productivity surface makes physical sense; that is, it conforms to what is known about the drivers of *Pinus radiata* growth[4]. Soil nutrients and water availability are negatively correlated with slope angle; the availability of solar radiation, the energy input to the system driving photosynthesis and respiration, will mean that trees on sunny sites will tend to do better than those subject to more shading. The inclusion of elevation as an explanatory variable may well relate to the effect of elevation on temperature, another driver of photosynthesis.

The ability to explain over 40% of the variability of the productivity surface over a large area by a terrain-based model accords with results from other studies which have used a similar type of methodology (Brubaker *et al*. 1994; Curt, 1999). For example Curt (1999) was able to explain 42% of site index variations for Douglas-fir using soil landscape units, while Brubaker (1994) developed models based on terrain properties for pH and organic matter with R^2 values of about 0.50. Moore *et al.* (1993a) and Mcnab (1993) have had similar results using terrain based models to predict edaphic or plant growth variables. Improvements might be gained by increasing the spatial resolution of the data, both the elevation and the site quality data but there is a point at which the cost would outweigh the benefit. A high spatial density of sampling would enable better predictive surfaces to be generated, but there is a balance between achieving model accuracy and directly measuring the target domain in the field, which would be prohibitively expensive. The purpose of modeling is that we can obtain a robust representation of the real world from the minimum of sampling. The principle of parsimony suggests that we should select, from a set of otherwise equivalent models of a given phenomenon, the simplest one (Burnham and Anderson, 2001).

We do not have a mechanistic model to explain the linkages between these variables and tree growth but we may make the following inferences. Soil nutrients and water availability will be correlated with slope angles because steeper slopes tend to have shallow soils, with sediments and solutes translocated downslope and accumulated at lower positions. Solar radiation is the energy input into the system driving photosynthesis and respiration in plants. Thus when other factors affecting tree productivity are equal, trees on sunny sites will do better than those subject to more shading. Elevation is a little more problematic as an explanatory variable of productivity, except that elevation may be an indicator of other factors. For example, higher elevation terrain may mean less fertile soils; or there may be elevation-based microclimate conditions in the study area. The erosional unconformities are so complex

[4] *For example, see Lavery, P. 1986: Plantation Forestry with Pinus radiata - Review papers, School of Forestry, University of Canterbury, Christchurch, New Zealand.*

across the whole terrain that generalisations based on broad physiography were not possible. Within the study site, elevation correlates with temperature; there is a temperature gradient from west to east just as elevation ranges from 160m to nearly 700m in the same direction. Cooler conditions affect the length of the growing season, defined as the number of days over a certain temperature, as well as the number of frost days and the average seasonal temperatures. Woollons (2000) compared the growth of *P. radiata* over two rotations and suggested the most likely reason for enhanced growth in the second rotation was that the average temperature had risen from 12 to 12.6 degrees Celsius over that period. Higher elevations are also associated with greater rainfall, which would enhance leaching and podsolisation of soils, reducing fertility.

The available data support modelling the landscape as a continuum of quantitative variables, as represented by a floating-point data model in a digital computer. Creating categorical classes of landform elements loses this continuum because such a choropleth model separates the landscape into uniform areas delineated by sharp boundaries. This is a traditional or conventional approach represented by maps or polygons in a vector GIS system. The problem with this framework is that the values of quantitative variables are necessarily assumed to be constant within the delineated areas, or a constant mean with small residual error variation (Burrough, 1987).

Soil maps of the study site were of limited use for analysing local site productivity variations across the terrain. Soil units are spatial entities not necessarily delineated on the basis of fertility but are determined by features of the pedon which are diagnostic in a particular classification system. For example, in the study area the thickness of the tephra layer is a crucial deciding factor. While this may be a useful diagnostic feature for soil classification, it may not in itself have much significance to tree habitat suitability, and so the within-class variability of tree growth can remain high.

Although the general approach may be applied to other forest regions with other soil-landscape systems, the specific form of the regression model is likely to be different.

Conclusion

Digital terrain models enable landscape-wide quantitative analyses of landscape forms and processes. Digital terrain analysis provides the means to model a target domain, in this case the real world landscape, and to conceptualise this at different levels of abstraction right back to a digital binary model on a computer. Landscape forms can be quantified in new ways using geomorphometric analysis, while forms and processes can be integrated into secondary units of measure such as compound topographic indices, which provide insights into other environmental processes operating in the landscape.

Digital terrain analysis was applied to a forest productivity index where it was able to explain over 40% of the variability of the productivity surface over a large and diverse area. It could also be applied to other units of measure such as biomass or total productivity, or in native forests it could be used to analyse species diversity and community structures in relation to broader landscape features. Although natural systems are highly complex, it can be possible for a few parameters to tell us about the most significant components of the behavior of the system, while increasing the number of variables may lead to increasing measurement costs for little additional modeling capability. The shape of the terrain is a major control of water movement and erosion and deposition, i.e. the flux of matter and energy across the surface. Therefore unless we are concerned about the microscale, we may not require detailed information about finer scale attributes in order to be able to simulate processes at the landscape scale. This is particularly relevant to forestry operations, where detailed information about soil chemical and physical properties is often lacking.

That land resource information for forestry is supported by predictive terrain modelling in a GIS framework has been demonstrated. The advantage of modelling site productivity on the basis of terrain is that it is rapid and relatively low cost. High quality digital elevation data is now widely available, and more data continues to be collected using new technology such as airborne laser rangefinders; it may soon be possible to obtain accurate sub one metre resolution elevation data. The fieldwork is minimised, unlike modelling soils. Therefore there is a significant cost advantage, and reduction in the logistical problems associated with data collection in rugged terrain where access may be poor. The information provided by this digital terrain modelling approach can provide the first reconnaissance data for a new area which has not been surveyed and for which there is no available data of any kind. Digital terrain modelling can then assist in the planning of pods and roads through the proposed forest to optimise access and pod orientation.

Overlying existing pod boundaries on the productivity surface enables possible anomalies to be identified; for example, where a pod boundary crosses a wide range of productivity index values. It is therefore possible to redesign the boundaries to encapsulate less variability in each unit, and so improve the delineation of management units. Where the site quality is of a similar range in a pod, more uniformity of tree growth and quality is expected. This then becomes an optimisation model to solve because there are other considerations such as minimum effective size. However, it has been demonstrated, that with some redesign of pod boundaries, the within-pod SI variance can be reduced by about 50%.

In addition to being a useful tool for modelling new forestry sites and for improving the management of existing ones, the digital terrain modelling techniques described may also be useful for the assessment of forest sustainability; an important issue within the industry. The issue of sustainability of forestry plantations is a complex one, and studies in New Zealand to date, such as Woollons (2000), have not found any decline of productivity with subsequent rotations. By using digital terrain modelling for forestry sites across New Zealand, at different altitudes and latitudes, it may be possible to predict future changes in productivity in relation to terrain variable and location. It may be possible to test whether some types of terrain, or specific altitudes at specific latitudes provide more robust environments for long-term sustainable forestry, or whether some types of terrain at certain elevations may be more prone to degradation or may require more inputs to sustain production.

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