An application of Terrain and Environmental Modelling in a Large Scale Forestry Experiment

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Abstract One of the difficulties facing forestry researchers in the design of field trials is to overcome within-site heterogeneity, particularly of soil and climatic variables. Forest soils are notoriously variable and subtle changes in soil properties can have a large impact on tree productivity. Likewise, within-site variation in micro-climate is known to influence growth. Within a particular climatic envelope, this variation is controlled to a large extent by terrain shape. In this study a range of terrain-derived attributes and indices was calculated for each of 40 growth plots from a digital elevation model (DEM) in an attempt to quantify these effects and establish whether they improved the interpretation of data from a field experiment. In addition, selected soil profile measurements were analysed for their impact on tree growth and correlated with calculated terrain attributes. The presence of gleying (evidence of waterlogging) in the profile accounted for a significant proportion of the residual variation in growth response after treatment effects were removed. A combination of predicted erosion index (*ei*), relative available soil water (*raswc*), dynamic wetness index (*dynwet*) and tangential curvature (*tancurve*) contributed to significant improvements in model predictions of growth. A physiologically-based model of tree growth (PROMOD) was applied to the site to model the effect of these variables on tree growth. We found that by using a terrain-derived waterlogging or gleying variable as input, PROMOD could successfully account for variation in tree growth due to waterlogging (gleying) and some additional between plot variation on growth due to soil depth.

1. INTRODUCTION

Most field experiments in forestry and ecology are spatial in nature and it can be difficult to find suitably large homogenous areas of forest or available land for many such experiments. Consequently, true replication may be unattainable and there is a risk that environmental variability may mask the treatment effects the experiment is designed to detect (ver Hoef and Cressie, 1993).

Randomised blocks are a simple way of minimising the effects of spatial heterogeneity. However, there is no guarantee that the chosen block size matches the scale at which the environment is varying. If mismatched, blocking will reduce the power of analysis without removing much of the effect of spatial heterogeneity. In some forestry experiments there is a minimum treatment size (machinery operation or burning for example). Also, cost of treatment applications and the inherent mosaic structure of many forest areas limit the extent to which treatments can be replicated without extending experiments into forests of different structure or history, or that are growing in markedly different environments. In these cases reformulation of hypotheses into more testable or affordable contexts is preferable. If this course of action is not chosen, or is not possible, the incorporation of spatial information into data analysis can reduce the "noise" in data and improve the estimate of treatment effects. Provided that there is no interaction between treatment effects and the spatial heterogeneity in the environment (a standard condition for the incorporation of covariates, [McPherson, 1990]) the use of environmental covariates will reduce the possibility of incorrectly assuming treatment effects due to an underlying environmental correlation.

Site productivity at broad-scales is determined by climate and geology (Eagleson 1982, Austin *et al.*, 1983, Blake *et al.*, 1990; Boomsma and Hunter 1990). At the single plot scale the effect of these determinants of forest growth is modulated by the influence of topography and, through this, soil factors (Conry and Clinch 1989, Honeycutt *et al.*, 1990). It is variation in topography and soils that typically result in spatial heterogeneity in field experiments. Topography affects site productivity by controlling soil forming processes (Jenny 1941; Jaiyeoba and Ologe 1989; Weaver 1991), and by determining the distribution and frequency of radiation inputs (Tajchman and Lacey 1986; Takahashi 1987; Moore *et al.*, 1993a), waterlogging (Blake and Reid 1981, Setter and Belford 1990), cold air drainage (Turnbull *et al.*, 1997) and the import or export of organic matter and nutrients (Grier and Running 1977; Jones *et al.*, 1989; McNab 1989).

It is possible to collect detailed site information to supplement field experiments from a range of variables (including weather variables, and soil variables such as hydraulic conductivity, porosity and soil water content).

The cost of repeated measurement to assess the duration that these factors exert an influence on growth (e.g. the proportion of a year a site is waterlogged) can be prohibitively expensive. Furthermore, because plant growth is synergistically affected by these factors it can be difficult to know how to use them meaningfully as covariates in experimental models. Consequently, for environmental covariates to be applied to broad-scale field experiments it is important that they be obtainable using remote sensing or through the use of existing digital surfaces. Such covariates usually require a process-based re-interpretation before they can be applied usefully.

In this paper we examine a forestry field experiment with a typical design (Turnbull *et al.*, 1997). This experiment has limited replication and treatments are confounded with aspect and topography. It is unclear whether this has affected the results, and confidence in the conclusions is consequently reduced. We collect site information for each of the experimental areas. These were tested for significance in a stepwise regression model incorporating the treatments as categorical variables to see how they affected our interpretation of the experiment and how the estimates of treatment effects were altered by these site factors. Waterlogging was the principal soil attribute found to influence tree growth. Because waterlogging was difficult to measure in the field we examined whether it could be predicted using a digital elevation model and landscape process models. Finally, we tested to see whether integration of all the environmental attributes with a process-based model of tree-growth provided an improved means of synthesing the enviromental information into a covariate that could be used to adjust for spatial heterogeneity in the field experiment.

2. MATERIALS AND METHODS

The study site of 83 ha in SE Tasmania (Lat 43° 21'S, Long 146° 54'E) is an inherently high productivity, (average MAI >20 m^3 ha^{-1} a^{-1}) intensively managed, experimental plantation of *Eucalyptus nitens* (Deane and Maiden) established in winter 1989. Elevation across the site ranges from 90 to 150 m above sea level (a.s.l.) with a mean elevation of 109 m a.s.l. Slope ranges from 2 to 25% and aspect 40° to 226° from North with means of 9% and 146° respectively.

The climate at the site is cool-temperate with significant rainfall occurring in both summer and winter. Long term climatic means (see Table1) were estimated from the interpolated climate model ESOCLIM (McMahon *et al.*, 1997). These estimates were used as input to the plantation productivity model PROMOD (Battaglia and Sands 1997).

Table 1. Mean annual maximum & minimum temperatures, rainfall, radiation, evaporation and number of rain days.

Source	Maximum Temperature °C	Minimum Temperature °C	Rainfall mm	Radiation MJ m^{-2} d^{-1}	Evaporation mm d^{-1}	Rain days d
ESOCLIM for Creekton	15.8	6.6	1254	12.7	2.3	204
Geeveston[1] (40 m asl)	16.8	5.8	872	n/a	n/a	199

[1] Geeveston. (43° 09' S. 146° 55' N) is a Bureau of Meteorology weather station site approximately 22.5 km north of the Creekton plantation.

Soil was sampled during winter 1996. Samples were taken in the centre of each of 40 growth plots by augering to a depth of at least 100 cm where this was possible and recording the presence/absence of surface water, thickness of the A horizon and depth to B horizon, variations in colour and texture, stoniness, presence/absence of mottles and presence/absence of gleying (gley) in the profile. Sampling locations also were recorded with a Global Positioning System (GPS) in differential mode and later geo-referenced to the base map (in UTM coordinates).

The study area principally covered one geological substrate, Jurassic dolerite. The soil was a yellowish-brown to red-brown mottled clay (Australian Soil Classifications: Mottled, Brown Ferrosol) characteristically developed unaer wet forest with annual rainfall > 1000mm (Grant et al., 1995). Average soil depth was typically greater than 100 cm, soil pH was between 4.3 to 5.0 prior to establishment and organic matter in the upper 100 cm was 2.0 - 4.2% (Turnbull et al., 1997). Mean thickness of the A0 horizon was 10 cm and mean depth to the B horizon 30 cm. Significant surface and sub-surface dolerite rocks and boulders were limited to the steeper, south-facing slopes. Middle and upper slope soils tended to have better structure, were more friable and in many cases obviously better drained than neighbouring soils at the base of slopes or in flatter areas where soil in the A horizon was generally silty-clay rather than clay-loam and tended to massive clay in the lower B horizon. In many cases on the lower sites surface water was also retained in local depressions.

Saturated hydraulic conductivity (K_s) and porosity were estimated for the purpose of landscape modelling from soil texture after Rawls et al., (1982). The A horizon profile ranged from silt loam (K_s = 6.9 mm h-1, porosity = 48%) to clay loam (K_s = 2.3 mm h-1, porosity = 39%). B horizon profiles ranged from clay loam (K_s = 2.3 mm h-1, porosity = 39%) to medium to heavy clay loam texture (K_s = 0.6 mm h-1, porosity = 38%). However, as the hydrologically active zone generally corresponds to the A horizon (Moore et al., 1993b) the average K_s was taken as the mean of these two values ($K_s = 4.58$ mm hr-1). Effective porosity was set to 43%. For the purposes of this study we have assumed that K_s and porosity are spatially invariant.

2.1 Terrain modelling

A Digital Elevation Model (DEM) was constructed using ANUDEM version 4.0 (Hutchinson 1995). ANUDEM uses a drainage enforcement algorithm coupled with a finite difference interpolation technique that eliminates spurious depressions in DEMs based on scattered, surface-specific point or contour elevation data and stream-line data. The DEM data were derived from digital contours and hydrography supplied by the Tasmanian Department of Environment and Land Management. These data were digitised by that Department from the 1:25 000 series topographic maps Raminea and Hastings (TASMAP Map numbers 4820 and 4819 respectively). The horizontal accuracy of the base contour data is stated to be ±12.5 m for 90% of the coverage, and 90% of the elevations are within 5 m of their true positions. The DEM was constructed on a 12.5 x 12.5 m grid using existing hydrography (streamlines) to ensure a hydrologically sound (depressionless) DEM and then re-sampled to a 25 m x 25 m grid. A basin delineation procedure (the WATERSHED function in ARC/INFO) was used to identify the catchment surrounding the Creekton plantation. A rectangular DEM completely containing this catchment was then extracted and used for all subsequent analyses.

The TAPES-G package (Gallant and Wilson 1996) was used to derive various topographic and hydrologic attributes for the Creekton catchment. TAPES-G is a suite of grid-based terrain analysis programs that computes slope, aspect, upslope catchment area, profile and plan curvature and several other topographic attributes. These topographic attributes may be divided into primary and compound attributes. Primary attributes that were directly calculated from the DEM included: slope, aspect, plan, profile and tan curvature, flow direction, flow path length, and upslope catchment area. Compound attributes are indices that involve combinations of the primary attributes such as the erosion index and wetness index that were calculated using the EROS (Wilson and Gallant 1996), SRAD, WET (Moore et al., 1993a) and DYNWETG (Barling et al., 1994) programs.

The following attributes and indices were calculated from the DEM using the TAPES-G package:

- variation in radiation and temperature across the plantation. SRAD takes into account slope, aspect, topographic shading and monthly variations in cloudiness, atmospheric transmissivity and several vegetation properties such as variation in leaf area index and reflectance characteristics for different vegetation types. It computes a radiation balance using incoming short wave radiation and incoming and outgoing long wave radiation, and also extrapolates minimum, maximum and average temperatures across the surface based on temperature records from a nearby weather station. SRAD was used to derive radiation estimates for the site modified by slope, aspect and topographic shading.
- the erosion index (*ei*), a dimensionless sediment transport capacity that is a non-linear function of specific discharge and slope. A positive grid cell value indicates net deposition and a negative value indicates net erosion (Wilson and Gallant, 1996).
- relative available soil water content (*raswc*), the estimated average long-term water balance of a grid cell and is controlled by precipitation, topography and radiation. The water inputs to each grid cell are rainfall and run-on, and the outputs are deep seepage, evapotranspiration and run-off. A *raswc* =1 represents field capacity and a *raswc* =0 represents plant wilting point (Moore et al., 1993a).
- the dynamic wetness index (*dynwet*) which predicts subsurface soil water re-distributions in the landscape using specified catchment drainage times. It is a function of saturated hydraulic conductivity, drainable porosity, slope and specific catchment area. Actual soil water storage for each grid cell is assumed to be linearly related to the dynamic wetness index (Barling et al., 1994).
- tangential curvature (*tancurve*) which represents convergence (valleys) or divergence (ridges) of the land surface in the direction of flow and is obtained using a plane normal to the flow path (in three dimensions) and calculated using finite differences. A positive value for tangential curvature indicates convergence and a negative value divergence (Gallant and Wilson 1996).

The final environmental covariate generated was a site index (si) for eucalypt growth. This was generated using ProMod (Battaglia and Sands 1997) , a simple physiologically based model that predicts the productivity of a plantation following canopy closure. It uses readily available site inputs, ESOCLIM derived climatic data, slope and aspect and a simple soil classification of depth, texture, stoniness, drainage and fertility.

2.2 Original experimental design

The original experiment (Turnbull et al., 1997) was designed to evaluate (a) the relative impact of clearing practice on native forest sites and (b) the application of fertiliser on the dynamics of growth throughout the rotation. It consisted of two fertiliser regimes (f1 and f2 with nitrogen added at the rate of 100 kg ha-1 and 300 kg ha-1 respectively) and two machine preparation methods (m1 and m2 using a bulldozer with standard blade and an excavator fitted with finger rake and thumb grab, respectively). The 40 growth plots were each of 30 trees on a 6 x 5 rectangular grid (2 m between trees within rows and 3.5 m between rows) and established in a partially replicated design. The 80 ha site was first divided into two 40 ha machine treatment compartments. Within these, four approximately 20 ha blocks were further divided into two 10 ha fertiliser treatment blocks. Five growth plots were randomly located in each of these blocks. By the start of the third growing season two fertiliser blocks in each of the machine treatments compartments had received 100 kg ha-1 and the remaining two fertiliser blocks had received 300 kg ha-1. Trees were measured annually for tip height and stem diameter at breast height over bark (DBHOB) to age 7 (Turnbull et al., 1997). Because of operational and resource constraints the site preparation treatments in this experiment were not fully randomised or replicated with regard to topography. This resulted in the excavator treatment being located principally on south facing aspects and bulldozer treatments being located on mainly northerly aspects thus confounding these treatments with respect to radiation and therefore temperature and evaporation regimes (see Figure 1)

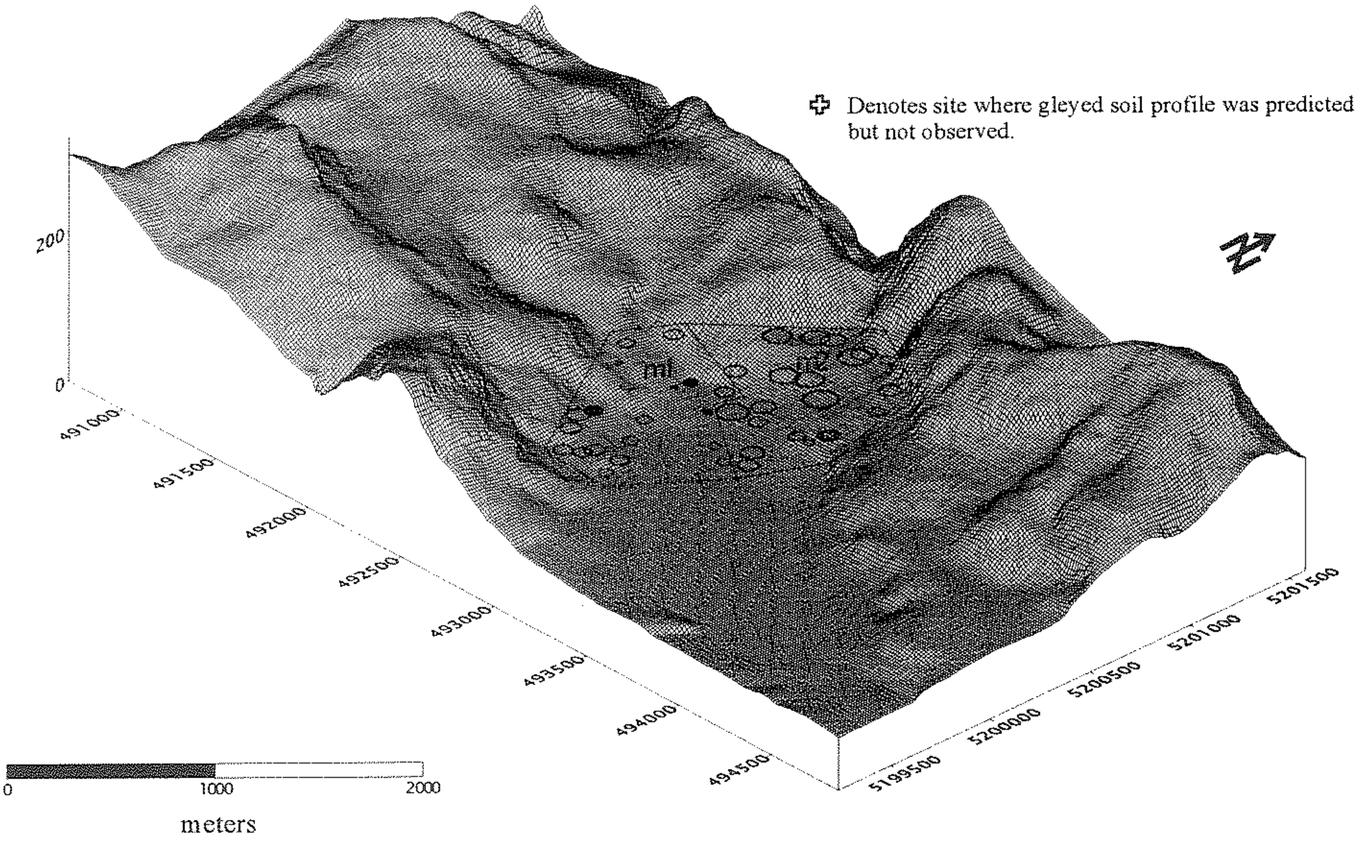

Figure 1. Plot volumes at age 7 draped on topography showing two preparation treatment blocks (m1,m2). Plots with gleyed soil profiles are shown with solid symbol. The size of circular symbols are proportional to plot volumes.

3. RESULTS

Tree volumes were log-transformed (logvol variate) prior to analysis to remove data heteroskedascity. Using generalised linear stepwise regression we found the gley covariate to be the only significant factor influencing growth in addition to the treatment effects. None of the other topographic or environmental factors (slope, aspect, plan or profile curvature, minimum or maximum temperature, net radiation, soil depth) proved significant.

3.1 Rule-based model for predicting gleying

Because gley is difficult to measure in the field a classification tree was constructed from selected terrain variables and developed into a rule-based model to predict the occurrence of waterlogging or gleying in the profile. This model successfully predicted 100% of the observed gleyed sites (n=4) plus one extra site where gleying was not detected in the profile sampled. However at the time of measurement we observed that at least 15% of the plot and much of the surrounding area was covered by surface water ponded in localised depressions.

The rules for predicting the occurrence of gleying (pred_gley) were:

$$\mathit{pred\_gley}=(\mathit{ei}<0,\mathit{raswc}>0.7,\mathit{dynwet}>4.5,\mathit{tancurve}>-0.1) \qquad (1)$$

An erosion index (*ei*) <0 indicated erosive processes may be active. However there was little evidence of actual erosion (e.g., rill or gully formation) at these sites because of relatively low slope, dense understorey vegetation (dominated by the cutting grass *Gahnia grandis*) and clay soil texture. Although actual erosion was likely to have had a relatively minor impact on these sites the water flow being directed and concentrated in these areas would certainly have contributed to the observed leached A2 horizons. Relative available soil water content (*raswc*) >0.7 indicated that these areas may be close to field capacity (*raswc* = 1.0) for much of the year. It is likely that these areas would saturate quickly during storm events given their predicted high antecedent soil water contents and the relatively low estimated mean K_s for these profiles. A dynamic wetness (*dynwet*) >4.5 indicates areas that are prone to early saturation from contributed sub-surface flow during and after storm events and is close to the maximum estimated "dynamic wetness" for the Creekton catchment. According to Gallant and Wilson (1996) tangential curvatures (*tancurve*) >0 indicate areas of convergence (e.g. valleys) in the landscape and tan curvatures <0 divergence (e.g. ridges). Considering the limitations of the DEM, *tancurve* >-0.1 was indicative of areas where flow was generally converging and we would expect greater concentration of both surface and sub-surface water. Equation 1 was applied to the appropriate terrain attribute data for the Creekton plantation to generate the *pred_gley* covariate.

Table 2. Comparison of models examined for predicting growth including the separated least squares treatment means (f1,2 x m1,2) for each combination of treatments.

					Log mean volumes			
No.	Models	r^2	ESS	MSS	f1x m1	f1x m2	f2 x m1	f2 x m2
1	fert x method the analysis of Turnbull *et al.*,(1997)	0.40	1.83	1.21	4.76^{A}	5.24^{B}	4.99^{AB}	5.10^{B}
2	fert x method + gley	0.47	1.62	1.09	4.79^{A}	5.21^{B}	5.02^{AB}	5.07^{B}
3	fert x method + pred_gley	0.45	1.67	1.15	4.77^{A}	5.21^{B}	5.00^{AB}	5.09^{B}
4	fert + method + si(pred_gley)	0.47	1.63	1.06	4.79^{A}	5.21^{B}	5.01^{AB}	5.07^{B}
5	fert + method + si(gley)	0.48	1.59	1.10	4.80^{A}	5.21^{B}	5.02^{AB}	5.06^{AB}

In all models the log transformed standing volume at age 7 (logvol) is the dependent variable. The r^2 value denotes the proportion of variance in the dependent variable (logvol) accounted for by the predictor variables (Wilkinson *et al.*, 1992). ESS and MSS are the error sums of squares and mean sums of squares, f1 and f2 are fertiliser levels 100 kg ha^{-1} and 300 kg ha^{-1} and m1 and m2 are bulldozer and excavator treatments respectively. The four combinations of treatment means were tested for differences by pairwise comparison using the Tukey-Kramer HSD procedure (Wilkinson, *et al.*, 1992). The superscript letters $^{A\text{ and }B.}$ refer to the treatment means that are significantly different for each model tested (n=10 in all cases). Fert represents the two level fertiliser treatments; method represents the two site preparation treatments. Gley is a measured soil property indicating waterlogging in the profile; *pred_gley* is predicted gley generated from the waterlogging model. Predicted gley was used as input to PROMOD to produce the *si(pred_gley)* covariate and *si(gley)* was similarly created using the measured *gley* variable as input to PROMOD.

3.3 Models for predicting tree volumes (logvol)

Analysis of the original experimental design (Model 1 in Table 2) explained only 40% of the variation in the growth response and there was a significant fert x method interaction ($P<0.05$). The *gley* and *si(gley)* models (2) & (5) explain 47% and 48% of the variation in logvol. The slightly better fit for *si(gley)* indicates that PROMOD is taking into consideration other site effects such as water stress that may be occurring in a few plots on shallower soils during the short dry periods. The *pred_gley* and *si(pred_gley)* models (3) & (4) explain 45% and 47% of the variation in logvol respectively. *Si(pred_gley)* is the better covariate in this case, again because PROMOD is picking up those few sites that are suffering from water stress.

Least square mean estimates for treatment combinations are similar for all models and generally lead to the same conclusions. In all cases the use of bulldozers (m1) with lower levels of fertilisation at 100 kg ha^{-1} (f1) resulted in poor growth relative to other treatment combinations. Application of higher levels of fertilisation at 300 kg ha^{-1} (f2) reduced this impact. The best fitting model (model 5) highlights the anomalous result of f1 x m2 being higher performing than f2 x m2. This probably results from residual landscape variation not accounted for in the model and because the inherent site fertility may be masking much of the response to fertiliser in these treatments. Also at high levels of fertilisation (f2) a significant increase in stem deformities and poor form (multiple leaders) has been observed in this plantation (Beadle, et al., 1994). As a general conclusion we found that including landscape covariates refined our estimates of treatment effects but did not substaintially alter the conclusions from the experiments.

4. DISCUSSION

The temperature, rainfall, and inherent fertility of the study catchment suggest that it should be well suited for plantation growth. Estimates of site productivity made using ProMod parameterised with average catchment soil and climate data suggest that the peak mean annual increment should be close to 30 m^3 ha^{-1} a^{-1}. This compares favourably with existing plantations in Southern Tasmania (e.g. Beadle *et al.,* 1995). Radiation and temperature variation over the catchment area caused only a slight variation (about 5%) in predicted yield between growth plots. However, variations in observed soil depth and waterlogging appeared to exert a marked influence and these factors reduced yield by up to 40 and 55% respectively from the predicted climatic potential maximum on some growth plots. These soil properties clearly have the potential to confound experimental treatment effects. Fortunately, while the initial experimental treatments were confounded with aspect, and hence radiation and temperature (due to the lack of sufficient replication of the m1 and m2 treatments) the soil depth and susceptibility to waterlogging were effectively randomly distributed across the treatments. Consequently, treatment effects were estimated with reasonable accuracy cf. Tables 1&2 in Turnbull *et al.,* (1997). The design and analysis of the original experiment leaves some doubt as to the validity of the experimental conclusions of Turnbull *et al.,* (1997). However the removal of the effects of environmental variability in effect "levels the playing field" and provides the spatially uniform experimental area required to give readers confidence in the conclusions.

The proportion of variation in growth over the catchment explained in the original analysis was quite low (40%, Model 1, Table 2). Inclusion of soils and hydrological variables improved the proportion of variation explained from 0.40 to 0.48, an increase of 20%. After the inclusion of all significant landscape variables a considerable proportion of the variation still remained unexplained, although the overall degree of variation explained is comparable to similar landscape-scale studies of productivity (e.g. Borcard *et al.,* 1992; Milner *et al.,* 1996). The nature of this unexplained variation is unclear. In part it may be environmental factors unaccounted for, and in part, stochastic influences.

4.1 Limitations of the digital elevation model

Re-calculating elevation contours from the DEM revealed a high degree of fidelity with the original contour data. Inspection of the residuals from the DEM surface fitting procedure indicated that there were only very minor adjustments made in creating a depressionless DEM of the Creekton site. However the resolution of the DEM may have been insufficient to accurately model finer scale topographic variation and would have undoubtedly contributed to errors in calculated terrain variables and indices. For analytical purposes spatial patterns possessing periods less than twice the size of a regular grid will be lost (Burrough, 1986). In this case growth plot size was approximately 10 m x 14 m whereas DEM cell size was 25 m x 25 m therefore any within cell variations in slope, aspect or curvature would be lost along with any spatial features with frequencies less than about 50 m. Panuska and Moore (1991) and Jenson (1991) demonstrated that slopes, and therefore other secondary DEM derivatives calculated from raster elevation data, vary significantly depending on cell size and data source. It was apparent in the field that in some cases slope, aspect and plan and profile curvature varied significantly over relatively small distances (tens of metres).

While our analysis has considered water movement to predict the occurrence of waterlogging, the effect of run-on and run-off on water supply during the short dry periods of the year has not been considered in detail. Lack of water storage capacity in shallow soils on relatively well drained upper slopes is likely to cause drought stress during summer (Tajchman and Lacey 1986; Takahashi 1987). However, mid and upper slope positions with deep profiles are capable of storing a significant amount of soil water for use during dry periods (Honeysett *et al.,* 1992). In addition sub-surface soil water contributions from up slope may be replenishing soil storage in some parts of the landscape up to several months after the last significant rainfall event (Barling *et al.,* 1994).

Many eucalypt species are known to be sensitive to frost damage (Paton 1981; Hallam *et al.,* 1989; Battaglia and Reid 1993). In addition, waterlogging combined with the effects of cold air drainage and frost is known to have a compounding effect on growth depression in eucalypts (Davidson and Reid 1987). Cold air drainage is known to have adversely affected growth in a nearby catchment (Beadle *et al.,* 1995). This may also have occurred in some areas of the Creekton catchment and may be a contributor to the residual variation. The common flow lines for water and cold air may, however, mean that some of the frost and cold air effects have been subsumed into the waterlogging effect in the model.

The waterlogging predictor developed in this study is comparable with other studies that have used combinations of terrain derived variables for predicting soil and soil water attributes. For example, Burt and Butcher (1986) required a combination of two terrain attributes, wetness index and plan curvature to obtain a reasonable correlation with measured soil water potential and saturated depth. Moore *et al.*, (1988, 1992) used a combination of terrain derived variables, including wetness index, stream power index, aspect, slope and profile curvature, to produce significant correlations with soil water distribution and various soil properties in experimental catchments. Typically these models predict up to 60% of the spatial variation in the property under consideration. However, in the absence of high resolution soils information these predicted attributes will undoubtedly be useful in many site selection studies where some knowledge of soils or other landscape processes is required. As Moore *et al.*, (1993b, pp.217) suggest "One rationale for only using topographic attributes to predict soil water content is that in many landscapes pedogenesis of the soil catena occurs in response to the way water moves through the landscape, so that the spatial distribution of topographic attributes that characterise these flow paths inherently captures the spatial variability of soil properties at the meso-scale as well". Because these topographic attributes are derived from process-based landscape and environmental models they should provide simple, yet physically realistic estimates of a variety of landscape parameters across a wide range of climates and topographies .

The plantation site studied here was small, had limited topographic variation and was located in a fairly optimal climatic regime. Nonetheless, our analysis suggests that, even within the limitations imposed by the available digital terrain data and the establishment of an extensive and necessarily incompletely replicated forestry field trial, the inclusion of terrain derived and environmental variables can lead to a significant overall reduction in residual variation.

Large-scale field trails that cannot be fully replicated due to space or resource contraints are often undertaken. This study has shown that terrain analysis carried out prior to the establishment of the experiment is capable of providing additional site information that has the potential to enhance the accuracy and confidence in the results. This information allows experimenters to identify the confounding influences of various environmental and site heterogeneities before treatments are established. Clearly there are limits to what we have developed. However, for the purpose of deriving appropriate covariates for broad scale forestry experiments and for generating additional site data for use in general landscape productivity screening, the results suggest that the techniques developed here will be useful.

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