Spatial Terrain Analysis for Matching Native Tree Species to Sites: A Methodology

Robin N. Thwaites

Abstract.—Predicting the distribution of preferable biophysical sites for three of the favored plantation species—*Araucaria cunninghamii*, *Eucalyptus cloeziana*, and *Flindersia brayleyana*—is necessary for private land rehabilitation in tropical north Queensland. The distribution of these predicted sites is expressed in a spatial and quantitative form. Sites are characterized by soil and terrain qualities, within known climatic parameters, using spatial analytical techniques afforded by the predictive capacity of digital terrain models (DTM's) and conceptual regolith-terrain relationships in an explicit approach.

Knowledge-based relationships and recorded soil-topographic data are used to create conceptual models of climatic, terrain, and parent material interaction. These guide the algorithms for digital terrain analysis through use of pedotransfer functions and topographic DTM derivatives. The spatial arrangement of potentially favorable sites is classified through fuzzy means. This form of classification provides multiple membership values for given regolith-terrain attributes for each raster cell in a GIS.

Degraded and poorly utilized pasture lands in the Atherton Tableland region of north Queensland's "Wet Tropics" are being planted with native rainforest and allied timber species. This is an attempt at maintaining biodiversity and rehabilitating degraded lands under private ownership, as well as providing alternative commercial productivity (CRC-TREM 1998). The federal government introduced the Community Rainforest Reforestation Program (CRRP) to help implement and develop this initiative because of the loss to the forestry and timber industries in and around the World Heritage Area national park declaration (CRRP Annual Report 1992-1993 unpublished).

The CRRP has environmental information of variable quality to work with; one of the most critical types is soil information. Soil surveys of varying ages, scales, and relevance have been undertaken for the developed areas of the southern Tablelands but not for the native forest regions. Therefore, knowledge of physical site preferences for most of the target species being recommended for planting (14 in all) is limited. Geological information is being used as a surrogate for soil data, a practice that is inappropriate for several philosophical and practical reasons (Thwaites 1998). The current belief from interpreting current and previous trials is that rainforest site quality is influenced by mesoclimatic and topographic factors as well as parent material and soil moisture (R. Keenan, Queensland Forestry Research Institute, unpublished data; A. Irvine, CSIRO, unpublished data). This ideology forms the basis of this study.

The intention of this study is to predict the distribution of preferable biophysical sites in the Atherton Tablelands for 3 of the 14 species favored by the CRRP: hoop pine (*Araucaria cunninghamii* Aiton ex D. Don), Gympie messmate (*Eucalyptus cloeziana* F. Muell.), and Queensland maple (*Flindersia brayleyana* F. Muell.). There is little recorded information on the site preferences of these species, and even less on the other 11 favored species. Current indications are that an unsatisfactory proportion of the CRRP plantings are showing poor early growth. The individual site characteristics are not known and, therefore, are not being managed appropriately. More confidence is required in choosing appropriate species for sites and in deciding how to manage them for optimal growth and yield.

This paper outlines a methodology for forest site characterization, which is not only explicit and replicable for the information user, but also makes full use of current knowledge environmental and geoecological processes in a scientific analytical framework.

The process involves the use of digital terrain analysis as it is related to field regolith-terrain[1] analysis. The forest-species sites (here termed "toposites," because of their

Lecturer in Land Resource Science, Faculty of Natural Resources, Agriculture and Veterinary Science, The University of Queensland, St Lucia, Queensland, Australia.

[1] *The regolith is the complete unconsolidated material within and beyond the solum (the A and B horizons of soil) and is inherently linked to geomorphological surface form and process of the terrain.*

generation through terrain analysis) are determined in a spatial and quantitative form. This is compatible with modeling the species' site suitability over the area using GIS (geographic information system). These toposites are characterized by regolith (including soil) and terrain qualities using DTM's (digital terrain models) involving soil-landscape relationships in an explicit and objective way (Thwaites 1998). Much of the supporting data to define species preferences has to be synthesized from expert knowledge using notional relationships and integrated with the spatial "hard" data on regolith and terrain. Notional relationships are expressed at the empirical level as two-dimensional cause-and-effect notions about species for which there is little real empirical data available to provide statistical predictions. The relationships are expressed through two-dimensional response curves—of the kind: "more is worse/better," "extremes are worse/better," etc.—that are now commonly used in multi-objective decision support systems (MO-DSS) using personal knowledge (El-Swaify and Yakowitz 1998, Lane *et al.* 1991).

THE STUDY AREA

The targeted region for this study is part of the Atherton Tablelands inland of the high coastal range in the "Wet Tropics" of northern Queensland. The study area encompasses approximately 990 km^2 of upper catchments of the Barron and North Johnstone Rivers adjoining the World Heritage Area rainforests. Hence it is termed the Upper Barron/Upper Johnstone (UB/UJ) Key Area. Summary details of the area are given in table 1. Much of this region, which adjoins and includes some of the rainforest conservation areas, is given over to dairy cattle grazing and some beef cattle grazing. Parts of this grazing land are rugged, with short, steep slopes (ranging up to 80 percent gradient) and susceptible to surface erosion - dependent upon soil type and rainfall characteristics.

SITE PREFERENCES FOR TARGET SPECIES

Site preference information for the three species had to be ascertained without the benefit of long-term, specifically designed trial work. It comes from currently available recorded information and expert knowledge. This then can be associated with the notional relationships of the soil-landscape to these species to provide a provisional land suitability model (fig. 1).

Environmental factors that influence the growth of the target species that can be readily ascertained depend on prior trial work and observations of species presence in the course of botanical survey. An environmental profile for each species was developed using known relationships in plantation trials and derived relationships from deductive environmental modeling (Sneddon 1997). The results of the climatic analysis (discussed below) are then used with soils and other environmental data from prior trials to construct a comprehensive environmental profile for each of the three species through the Plantgro computer model. Plantgro 2.1 (Hackett and Harris 1996) expresses the growth potential for any usable species under defined environmental conditions. It is a decision-support system that provides expert systems for recording personal knowledge and combines experimental data to predict overall plant performance at an empirical level at the appropriate, but relatively coarse, local scale (Hackett 1995a). It can therefore be used at the end of the site prediction process to predict growth potential of species in plantation in any individual site. It is not a spatial model and cannot, therefore, be integrated directly with the GIS framework of this site-prediction methodology, although it can be linked to GIS by replicating the spatial distribution of like sites. Plantgro uses a starter data-set system called "Infer" to generate initial species preference characteristics (Hackett 1995b). Little work has previously been undertaken in producing environmental

Table 1.—*Environmental information for the UB/UJ Key area*

Elevation range: 1,100-1,200 m (3,630-3,960 ft) in south and west to 600 m (1,980 ft) in north. Common relative relief range: 100-200 m (330-660 ft).

Landform pattern: Undulating on old basalt plateau, through rolling low hills in the metasediments and midage lavas, to rolling to very steep hills in the recent basalts.

Climatic zone: Subtropical, strongly summer seasonal rainfall with a strong gradient from 3,500 mm in the southeast mountain zone (Johnstone River gorge) to 1,200 mm in the northwest tablelands zone (the town of Atherton). Eighty-five percent falls between November and April (heavy rain January-March). The "critical rainfall deficit" period is October-November, which if dry (after the winter dry), restricts the distribution of many rainforest and allied species.

Geology: Succession of basalt flows in three provinces: "Old," "Middle-age," and "Recent"; Scoria/volcanic materials from Pleistocene eruptions; Low-grade metasediments; Acid volcanics (dom. Rhyolite) around; and Granites in the southern part.

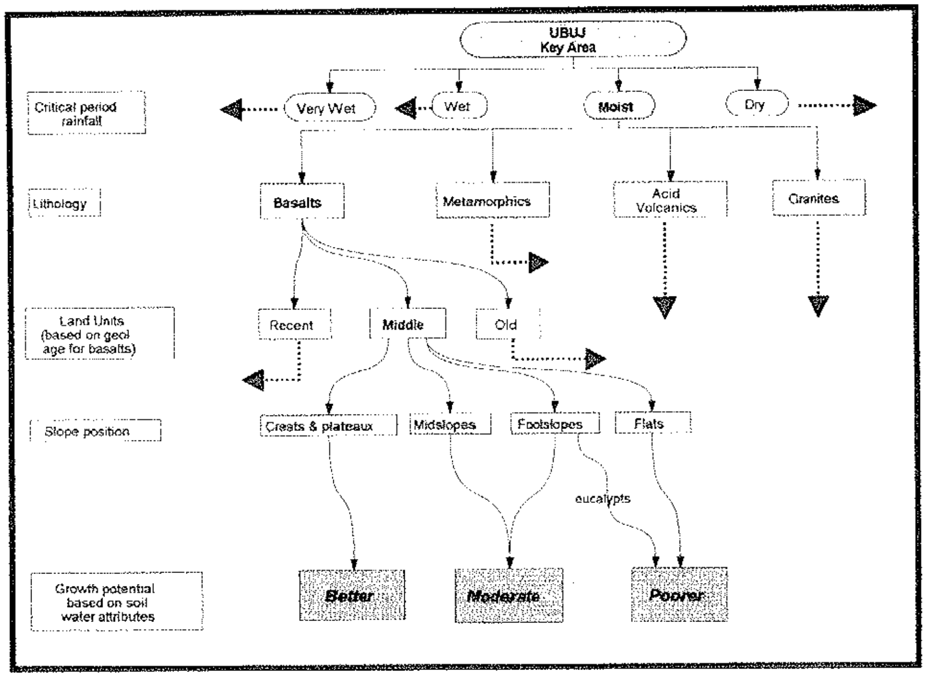

Figure 1.—*Part of the conceptual model used to combine trial information and expert notional relationships to develop rainforest species suitability in N. Queensland which is quantified for running in Plantgro. This example emphasizes the Basalt "geological zones" in the "Moist" climatic zone.*

profiles for native tree species. Plantgro is valuable in this situation because it is a knowledge-based system that helps formalize and quantify expert knowledge in the form of notional relationships.

Climatic Analysis

Using spatial data of species presence only, the natural climatic envelope for each of the target species was ascertained using BIOCLIM, a package within the ANUCLIM 1.2 suite of climatic modeling packages (McMahon *et al.* 1997), and a 10-second resolution digital elevation model (DEM) of Queensland produced by the Queensland Department of Natural Resources (QDNR). BIOCLIM is a two-part package that can calculate bioclimatic values at a set of sites to generate a bioclimatic profile using up to 35 climatic parameters. Not all parameters are possible to use because of restrictions in reliable climatic data recorded. All parameters relate to the following five meteorological variables that strongly influence the distribution of plant species: Max. temperature; Min. temperature; Rainfall; Radiation; and Evaporation. Monthly time steps to create climatic surfaces were selected for the UB/UJ Key Area (Sneddon 1997).

The second part of BIOCLIM is BIOMAP, a stand-alone program that matches the bioclimatic profile generated in BIOCLIM to the bioclimate at any nominated points on a regular grid (McMahon *et al.* 1997). This generates the bioclimatic predictions of spatial distributions of the target species in a bioclimatic context extrapolated from known natural occurrences of the species.

There is a striking meteorological gradient over the Atherton Tablelands associated with the range of relief from 1,600 m elevation at the coastal Bellender Ker mountain range to 600 m elevation at the Barron River near the town of Atherton. Because of this strong gradient, further automatic meteorological stations were recently installed to improve the reliability of climatic modeling through ANUCLIM. New data from these stations will augment the current climate surface modeling in the region, including the UB/UJ Key Area.

REGOLITH-TERRAIN RELATIONSHIPS AND DIGITAL TERRAIN ANALYSIS

The bioclimatic surfaces created through ANUCLIM were used to stratify the UB/UJ Key Area. From this stratification at the broader, regional scale, the most potentially suitable areas for growing the three species were identified, which then became foci for toposite prediction through regolith-terrain and digital terrain analysis at the more detailed landscape scale.

Broad-scale geology maps (1:250,000) of the area have been used by CRRP and QDPI (Queensland Department of Primary Industries) practitioners for gauging soil character, although some previous soil mapping of the region has been undertaken—primarily that of Laffan (1988) at 1:100, 000 scale. Recent soil mapping of the Atherton Tablelands by the QDNR has been completed at 1:50,000 scale (Malcolm 1998). This scale is still too coarse to characterize sites meaningfully for small-scale forest plantation planning. Nonetheless, this soil mapping has aided the development of regolith-terrain models for the UB/UJ Key Area by identifying parent-material provinces and soil-slope relationships. This soil information, augmented by field analysis of regolith exposures and associated terrain characteristics, provides the basis for conceptual regolith-terrain models of the landscapes for the parent-material provinces (fig. 2). These conceptual models guide the algorithms for digital terrain analysis through use of field pedotransfer functions and digital topographic derivatives from simulation of terrain-surface form and process by DTM analysis.

Pedotransfer functions (see Bouma and Van Lanen 1987 for a discussion of the concept) are used as surrogates for soil/regolith parameters that have not been recorded in the process of soil survey, or are impractical to record on any operational scale. An example for soil moisture properties used here is the substitution of soil field texture, structure, organic matter (OM) content, and horizon (or soil layer) depth in a known functional relationship for the measurement of soil bulk density. More complex parameters such as hydraulic conductivity or soil moisture retention can likewise be substituted with more easily, and regularly, measured soil properties in known functional relationships.

The digital topographic derivatives used here include slope curvature in plan, profile and tangential form, aspect and shade, as well as that of the topographic wetness index (TWI), a specific-area contribution formula using a flow-routing algorithm (see Moore *et al.* 1993).

$$\text{Wetness Index} = \ell n(A_s / \tan\beta)$$

Where A_s is the specific catchment area (the upslope area draining to any point), and β is the slope angle.

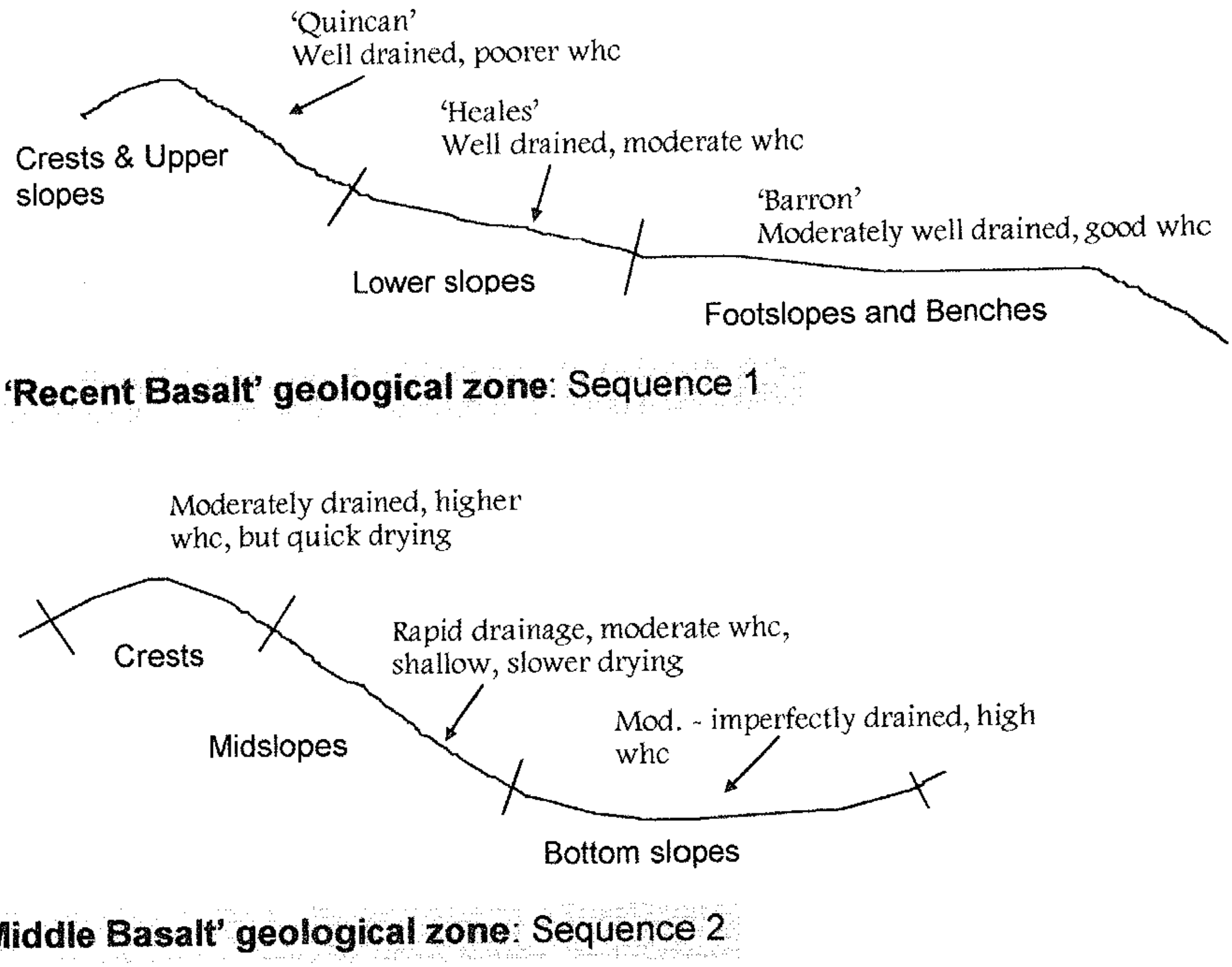

Figure 2.—*An example of the conceptual model of topographic, soil, and parent material relationships for part of two of the Basalt geological zones in the UB/UJ area. (whc: water holding capacity).*

These topographic attributes were derived using TAPES-G (CRES 1996), a grid-based program for digital terrain analysis. The resolution of the DEM created for the UB/UJ Key Area is 30 m (cell size). It was extensively corrected hydrologically to eliminate artifacts of mathematical interpolation. This model proved satisfactorily accurate in tests to reconstruct the contours and streamlines data from which it was originally derived. This showed an approximate 10 percent displacement in contour location overall. The DEM can be validated only against the original topographic data, not the actual land form.

MODEL INTEGRATION

Figure 3 shows how the different major modeling components are synthesized to form a predictive model of site characterization for the forest species. This is prior to the classification process for expressing the toposites in fuzzy form.

Scale and resolution issues are important in any environmental synthesis. The integration of data across scales in forestland resource assessment is discussed in Thwaites and Slater (1999). Scale definition is confined here to the concept of broad and fine scales of investigation with appropriate resolution of data. The climatic model provides a broader scale framework to the site prediction process, but the regolith-terrain analysis provides the finer scale toposite characterization. It is the site preference analysis that provides the predictive capabilities of the overall model.

One of the main reasons for using digital classification techniques is the ability to implement *a posteriori* classification, i.e., "classify last." The identification and use of individual regolith-terrain attributes focuses on what is measurable or estimable without relying on, and being influenced by, *a priori* generic soil or site classification systems, such as soil "types" or geological "formations." No *a priori* classification of sites (e.g., by soil

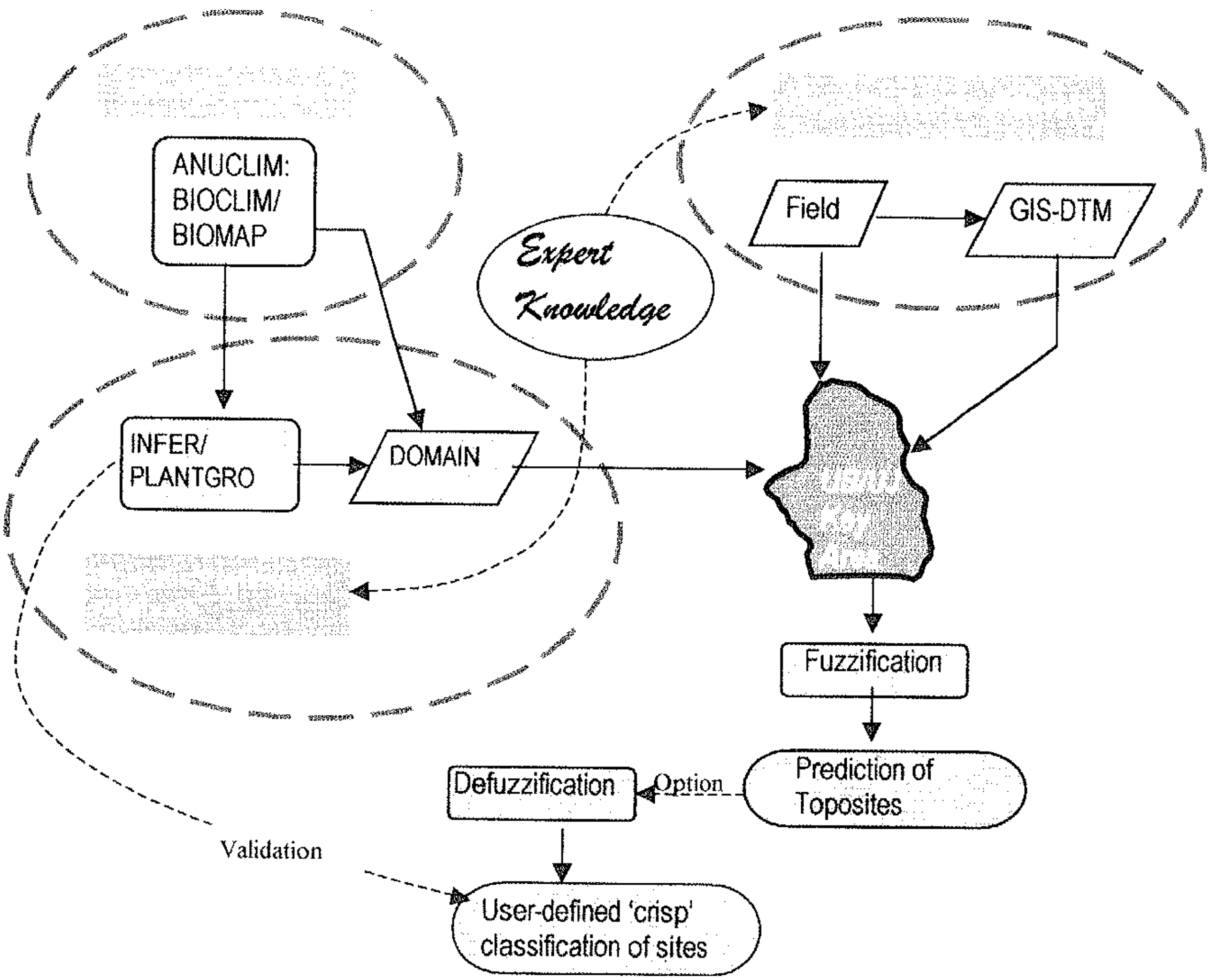

Figure 3.—*Integration of the modeling components to create a site-species matching methodology.*

type, land type, ecological type, ecounits) has been involved in the process of this spatial model development. Generic and technical classification systems only dictate the type of data to be collected and how the data is interpreted if they are applied *a priori* to the model being developed. An *a posteriori* application of a classification system using the attribute data gained during the modeling process has more relevance to the purpose of the exercise, and can be more explicit. One such approach, which is favored here, is the use of fuzzy systems theory (see Burrough *et al.* 1992, Thwaites and Slater 1999)

Fuzzy systems are an alternative to "crisp" set membership in classification. Crisp sets operate through binary logic (i.e., True/False) whereas fuzzy logic allows for trivalued logic (e.g., True/Possible/False). It thereby accommodates imprecision and uncertainty in complex data by invoking functions of "possibility" rather than "probability." The output can be expressed in a series of raster-format plots that relate to the classification of each toposite variable (e.g., plots of shallow, deep, and very deep regolith classes), or combined variable classes can be plotted that are relevant to specific characterization requirements of the toposites (e.g., regolith depth, soil moisture holding capacity). Optionally, these combined classes can then be defuzzified to recreate crisp classes of site quality (e.g., suitability classes—low, medium, high—for each species performance). These then can be expressed as conventional choropleth maps (polygonal units representing classes delineated by well-defined boundaries).

CONCLUSION

The methodology outlined here uses digital terrain analysis in combination with conceptual modeling, within a GIS framework, as an explicit and adaptable approach to site attribute prediction. The major advance of this process is its explicit nature by discerning the relevant attributes that characterize sites for native forest species planting. Unlike traditional soil and site survey and mapping methods, it can be replicated: results are reproducible, and can be subsequently enhanced by further iteration.

Regolith-terrain attributes are used to determine toposites both from field analysis and digital terrain analysis. These measured and generated data must be fitted into conceptual models of the landscape, which cannot be produced without expert knowledge and local wisdom. This is a key aspect of the process. Knowledge-based data (or "soft data") are synthesized with the field data and computer-generated data in a logical and methodical manner through the framework of these conceptual regolith-terrain and site suitability models.

Several computer models are used in combination to reach the desired outcome for a thorough procedure that attempts to overcome the inevitable lack of relevant data at the appropriate scale or resolution. In the case of the climatic surface model, BIOCLIM, and the terrain derivatives model, TAPES-G, the required data are generated to the best possible resolution. Combined with the site-species analysis from previously recorded field data through Plantgro and Infer, and limited field data forming conceptual regolith-terrain models (with the aid of geological and soil maps), a sophisticated picture emerges without lengthy and costly new data acquisition.

The initial work matches toposites to species using the Plantgro output files within the broad climatic stratification of the species, and then the soil map information in conjunction with the conceptual topographic regolith-terrain models. Future work will focus on spatial predictions of regolith-terrain characteristics for potential toposites from the DTM. These are then combined with the species profile information created for Plantgro, particularly the climatic envelopes defined through a BIOCLIM analysis.

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