Regional Modelling of Vegetation Distributions in Australia – and climate impacts

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Introduction

Dynamic Global Vegetation Models (DGVMs) are being developed and used to predict broad, global vegetation patterns and are linked with General Circulation Models (GCMs) to understand the role of terrestrial vegetation in the mass and energy balance of the planetary boundary layer. When fully couped with a GCM, DGVMs attempt to predict how terrestrial vegetation may change due to changes in future climate and elevated CO_2 concentrations. However, currently, the predictions of these models – *even for current climate and CO_2* – do not represent well the vegetation (structure or processes) in Australia, even at a continental scale. Consequently, these models are of no use for predicting the finer-scale patterns of vegetation of even quite large regions where immediate knowledge of possible climate change impacts is critical to inform policy and long-term management actions. Thus, alternative approaches that are demonstrably successful must be developed and applied regionally at the same time that the long-term development of DVGMs is attempted.

Approaches to regional vegetation modelling are generally empirical and use a range of statistical and machine learning techniques such as General Additive Models (GAM), Generalized Linear Models (GLM), Classification and Regression Trees (CART) and Artificial Neural Networks (ANN).

Here, I outline what is required for successful modeling of regional vegetation and its response to climate change in the near future. I concentrate on what is perhaps the most detailed modelling of climate impacts on regional vegetation in Australia - the Wet Tropics Bioregion of NE Queensland. In doing so, I illustrate the usefulness of carefully designed empirical modelling, incorporating local knowledge and ecological insight, for elucidating climate-vegetation interactions in a rapidly changing climate. I also challenge the global, so called " mechanistic", vegetation modelling community to demonstrate the ability of their methods to reproduce even the current vegetation of Australia, much less the regional vegetation that is of concern now. Given the extremely poor ability of the current, so called "mechanistic" DGVM models to represent the broad patterns of vegetation in Australia and its dynamics, and their complete lack of statistical testing, I suggest that the DGVM approach and its proponents need to justify with examples of their approaches' usefulness in Australia (at least), and indicate how (if at all) this approach has influenced any regional, State or Commonwealth policy.

Requirements for regional success

There are several key issues for successful regional vegetation modelling:
    1. A useful vegetation classification for the objectives

2. Climate, terrain and soil data of an appropriate scale and resolution.
3. An appropriate modelling method for the objectives
4. Careful data selection for training/fitting including an appropriate range of environments and vegetation types
5. Careful verification and awareness of the model's limitations
6. Creative use of the model incorporating ecological knowledge and a range of climate scenarios as appropriate.

Each of these issues is briefly described below.

A useful vegetation classification for the objectives
It is generally agreed that plant communities are not stable with climate change since species respond individually to climate and other environmental factors. There are at least three options available: plant functional types as used in DVGM's; individual modelling of many species (e.g., Austin ???), and structural/physiognomic classification of vegetation units that are not floristically based (e.g. Webb …). My research in the Wet Tropics illustrates the latter option.

Climate, terrain and soil data of an appropriate scale and resolution
In the biogeographic community, vegetation pattern at regional scales is well known to be determined by both climatic and edaphic factors. So these variables must be mapped at a fine enough scale to account for the range of vegetation – appropriately defined – within the region of interest.

An appropriate modelling method for the objectives
This may be the least constraining issues because there are several well established methods and the specific method may be less important than other issues. It is better to have the right combination of ecological expertise, local knowledge and statistical skills in the team than to be using the current "best method" (Austin et al. 1995).

Careful data selection for training/fitting including an appropriate range of environments and vegetation types
In the Wet Tropics modelling, we carefully evaluated the scale and probable accuracy of each of the available independent and dependant variables. Climate variables produced by ANUCLIM were inspected closely and some were rejected when their predicted pattern was not consistent with local knowledge, others were chosen because of their consistency and known importance for the vegetation and with regard to applications to past and future climates. The vegetation mapping, while based on a well developed structural/physiognomic system, included some mapping types that include local, floristic dominants. Consequently, 27 mapping types were aggregated to 15 classes that coincide more consistently with vegetation structure only.

Careful verification and awareness of the model's limitations
One value of empirical models is their potential for relatively high accuracy, so careful statistical evaluations of their performance is necessary and universally performed. This goes far beyond "producer" accuracy. For example, I intentionally included one non-equilibrium vegetation class (Tall Open Forests converting to various classes of rainforest). This vegetation class had, by far, the least predictability but the "errors" were consistently correct in predicting the type of rainforest they are now converting to. While this reduced the model's overall accuracy, this added to the ecological, *post hoc*, confidence in the model.

Empirical models are presumably less reliable when extrapolated to new conditions. Thus, it is important to identify when and where extrapolation occurs, identify the model's responses outside of the training data domain and take these into consideration in analyses of the model's responses to climate change.

In my opinion, so called "mechanistic" models such as DGVM's need to be evaluated formally and statistically and meet similar expectations for accuracy and ecological realism that are required of empirical models, while acknowledging differences in scale. From the presentations at the workshop it does not appear that this is the case – DGVM's "mechanistic" and ecophysiological basis seems to so important that normal requirements for accuracy or even broad ecological consistency are ignored.

Creative use of the model incorporating ecological knowledge
Often the output from empirical models is more complex than the simple mapping of vegetation classes. When possible, the full range of output can be considered and used to, partially, overcome the static limitation of these approaches. For example, I developed an index of stress to existing forests due to rapid climate change that recognizes the inertia to change in systems dominated by long lived trees (Hilbert and Ostendorf 2001, Hilbert et al. 2001). Due to the large uncertainty in GCM projections about future rainfall, I have also used a wide range of precipitation scenarios that are then combined into an index of local sensitivity (Figure 1), given a warming scenario combined with many rainfall scenarios – how many of the rainfall scenarios predict that the local environment becomes more suitable to a different forest type.
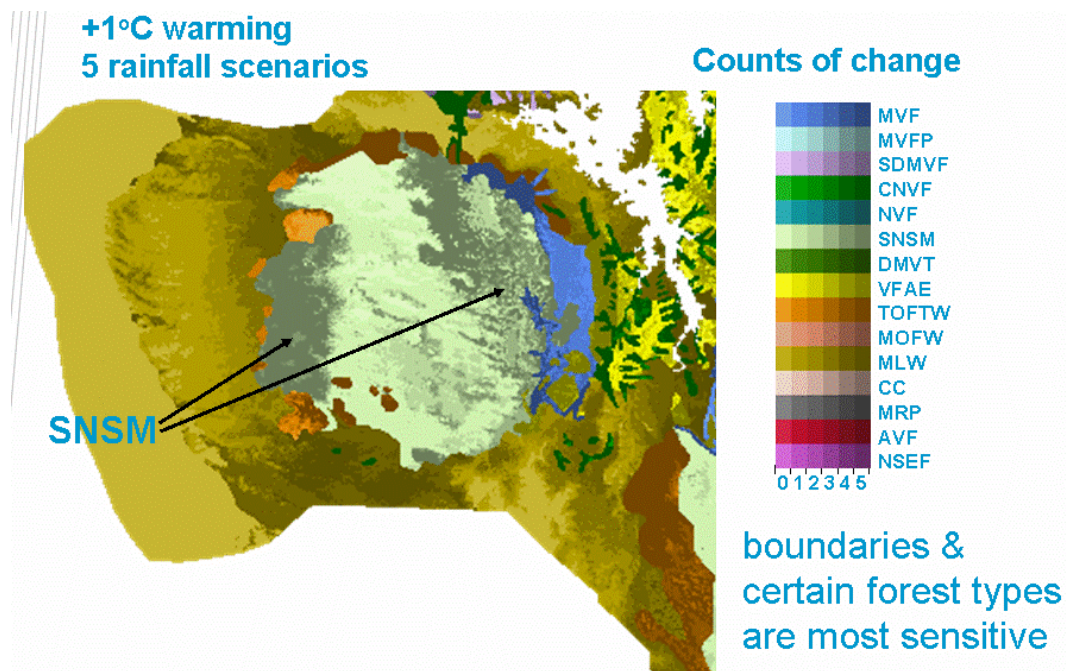

Figure 1. Sensitivity to changes in rainfall (-10% to +20%) with 1 deg. C of warming on the Windsor Tableland in NE Queensland (modified from Hilbert et al. 2001). The upland rainforest types, Simple Notophyll and Simple Microphyll Vine Forest (SNSM), are indicated and they show a high propensity to change, irrespective of uncertainty about rainfall changes, with only minor warming. Some vegetation types are more certain to be affected as well as, not surprisingly, boundaries between

vegetation types. Note the grain size of predictions in this figure is 1 hectare versus 0.5 X 0.5 degrees for even "down-scaled" GCMs and DGVMs.

Utility of Empirical Approaches Illustrated by Modelling of the Wet Tropics Bioregion

In the Wet Tropics Bioregion (as in many high-diversity regions) there are more than 800 species of tree species in c. 80 families. Not all species are formally described and named, there is limited biogeographic information, non-existent ecophysiological or autecological knowledge even for the best studied, economically important species, no useful plant functional type classification within rainforests and a lack of predictive theoretical models. Because of these factors, mechanistic approaches are not now possible although empirical approaches, carefully focused on vegetation structure are demonstrably useful.   Consequently, I used an empirical, ANN approach that demonstrates the usefulness of this type of model that has been very informative and has influenced policy at regional, state and commonwealth levels. Arguably, unlike empirical and regional vegetation modelling, DGVM's are not yet good predictors of vegetation patterns in Australia, despite their presumed greater generality and "scientific" credibility, and consequently have had little or no impact on policy or management within Australia.

The ANN model is well documented (Hilbert and van den Muyzenburg 1999, Hilbert and Ostendorf, 2001, Hilbert in press 2007). It uses nn independent, environmental variables representing climate, terrain and soil variables to predict 15 forest environments from low woodlands to complex rainforests and coastal wetlands. The model's ability to predict current vegetation patterns at a one hectare scale is quite good (Hilbert and van den Muyzenberg, 1999) as is it's ability to predict pre-clearing vegetation (assessed from independent mapping of vegetation fragments, Hilbert, in press 2007) and vegetation since the last glacial maximum (Hilbert et al. 2007). Arguably, a model or modelling approach for bioregions that can represent the current vegetation, the pre-clearing vegetation and vegetation in the recent geological past is useful for assessing regional climate change impacts in the near future. Arguably, approaches that can not do so, such as current DGVM models, are not effective for regional vegetation projections even though they claim a higher relevance due to their presumed mechanistic basis.

Applications of the regional, empirical model to climate change

       Palaeo-distributions
Using the ANN model, Hilbert et al. (2007) mapped the environments characteristic of forest classes in four climate regimes (the present and three past climate scenarios), quantified the changes in area of these environments in response to past regional changes in climate and identified areas that would have been environmentally suitable for rainforests at last glacial maximum (glacial refugia). They also identify areas that would have been suitable for upland and highland rainforest classes during the warmest parts of the interglacial (interglacial refugia) and map locations that consistently remain favourable to specific forest classes despite large changes in climate. The predictions are consistent with macro-fossil evidence (charcoal) and detailed palynological studies in the Wet Tropics.

Future climate change

Using the ANN model, Hilbert et al. (2001) demonstrated that rainforests in Australia are highly sensitive to even small changes in climate. The distribution and extent of environments suitable for fifteen structural forest types were estimated, using the model, in ten climate scenarios that include warming up to one degree and altered precipitation from –10% to +20%. Large changes in the distribution of forest environments are predicted with even minor climate change. Increased precipitation favours some rainforest types while decreased rainfall increases the area suitable for forests dominated by sclerophyllous genera like *Eucalyptus* and *Allocasuarina*. Rainforest environments respond differentially to increased temperature. The area of lowland, Mesophyll Vine Forest environments increases with increased temperature while upland, Complex Notophyll Vine Forest environments respond either positively or negatively to temperature, depending on precipitation. The highland rainforest environments (Simple Notophyll and Simple Microphyll Vine Fern Forests & Thickets), the habitat for many of the region's endemic vertebrates, decrease by 50% with a one degree warming.

Estimates of the stress to present forests resulting from spatial shifts of forest environments (assuming no change in the present forest distributions) indicate that several forest types would be highly stressed by a one degree temperature increase and most are sensitive to any change in precipitation. Most forests will experience climates in the near future that are more appropriate to some other structural forest type. Thus, the propensity for ecological change in the region is high and, in the long-term, significant shifts in the extent and spatial distribution of forests are likely. A detailed, spatial analysis of the sensitivity to climate change indicates that the strongest effects of climate change will be experienced at boundaries between forest classes and in ecotonal communities between rainforest and open woodland.

Linking with Cellular Automata

We have evaluated how the spatial arrangement of forest pattern may constrain vegetation change as predicted by the static artificial neural network (ANN) model (Ostendorf et al. 2001). We relaxed the equilibrium assumption and considered spatial dynamics using a cellular automata approach. The ANN model quantifies a most suitable forest type based on the conditional probability of vegetation in the environmental space, whereas the cellular automata model imposes spatial constraints on the transition to the best-suited type. We adapted the cellular automata algorithm to successively increase spatial and ecological constraints, hence relaxing the POCEC assumption. A comparison of predictions of vegetation change with the different models indicates that the spatial arrangement of vegetation in the Wet Tropics may impose relatively few constraints for the region's potential change. Depending on the strength of spatial effects included in the models, the predicted future vegetation patterns differ from 1 to 10% in the study area. However, if ecological constraints also are considered (e.g. prohibiting several transitions), the predictions differ by as much as 27%, showing a relatively strong dependence of predictions on assumptions about patch-level processes.

Conclusions
- Regional modelling of vegetation distributions is usually empirical, often by necessity due to scale issues and limited basic understanding that render the presumably superior mechanistic approaches unusable at the present time.
- The specific modelling method is less important than the range of skills and data that are available.
- Careful empirical modelling, coupled with local ecological knowledge, good biogeographic data and creative analyses can be very informative, both scientifically and for management and policy development.
- So called "Black box", empirical approaches have demonstrated value when coupled with ecological insight and are essential in the many circumstances where mechanistic models are not yet capable of addressing very important regional issues about climate change.

This research has had very significant documented, influence on regional, state and national policy. The presumably more sophisticated "mechanistic" approaches have not, as yet, succeeded at representing Australian vegetation at even continental scales and have had little impact, to my knowledge, on commonwealth, much less state or regional policy.

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