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The uncertain impact of climate change on forest ecosystems — How qualitative modelling can guide future research for quantitative model development

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ABSTRACT

Climate change could significantly alter forest productivity and climax states. Hence modelling productivity under climate change will need to account for many alternative ecosystem states. We apply qualitative modelling to identify the most likely ecosystem representations for a well-researched Tasmanian forest. Its main ecosystem is a tiered forest with rainforest, wet sclerophyll and myrtaceae components. Interactions between these components are uncertain, especially under additional pressures from climate change. Qualitative modelling is a structured method to analyse these uncertainties. We identify the most appropriate models and research efforts for model development. Further, we identify research needs for interactions between root pathogens and forest components, with research on some impacts of system components on fire being ruled out. The qualitative modelling approach applied here was useful in identifying research priorities for modelling complex ecosystems, even under uncertain system understanding or deficiencies in quantitative data.

1. Introduction

Climate change could cause significant changes to forest productivity, ecosystem function and processes, community composition and structure, and forest types and ecotones. The rapid nature of current climate change, and the fragmented nature of the forested landscapes, makes it difficult for species to respond by migration and genetic adaptation (Hannah et al., 2002; Hilbert et al., 2001; Luckman and Kavanagh, 2000). This limitation in natural responses to climate change has consequences for estimating net primary production (NPP) and carbon storage in forests.

Forest NPP is difficult to measure. The methods provide considerable challenges, and estimates of NPP are sparse both spatially and temporally. The main methods revolve around either monitoring changes in biomass or measuring CO_2 fluxes in chambers or the atmosphere (Clark et al., 2001). Current NPP quantification over large areas relies on mathematical modeling that incorporates empirical data and process understanding of plant-material growth and losses. NPP modeling generally takes into account some measures of CO_2 concentration, radiation and adsorption, nutrient availability, soil conditions, water availability, temperature and humidity. Current models are based on limited data and are poorly validated, and predictions can vary widely (as much as a factor of 5) between models (Roxburgh et al., 2004). Predicting these changes under climate change becomes even more challenging because of the need to include additional disturbance events, such as the effects of pests and fire. While CO_2 concentration in Australia are predicted to double by 2100 (Howden and Gorman, 1999), additional uncertainty stems from our limited ability to forecast the regional changes in temperature and rainfall (Hennessy et al., 2007; Pinkard et al., 2011).

The challenges for estimating the impacts of climate change on forest NPP illustrate the need for well-targeted research to support the development of models (Hannah et al., 2002). Identifying

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research priorities to improve NPP model development is difficult when there is uncertainty associated with ecosystem responses. In situations where parameterisation data are unavailable or too costly, there is need for approaches that enable the incorporation of our limited and imprecise understanding of an ecosystem (McIntosh, 2003). In this context, it is important to develop a limited number of hypotheses that define the key components and interactions of the ecosystem. From these, identification of the most credible hypotheses then provide priorities for future research efforts in support of model development (Walters and Holling, 1990).

Qualitative models (Levins, 1966) are a complementary approach to quantitative modelling, especially when data limitations arise (Levins, 1974; Puccia and Levins, 1985). They provide a formalized way for assessing the implications of different assumptions on the structure of ecosystem models, which helps to reduce model uncertainty and to focus future research efforts. The high mathematical rigor of the analyses, testability of their predictions, and emphasis on generality and realism makes qualitative model outcomes broadly useful and readily understandable by both scientists and managers (Dambacher et al., 2009; Levins, 1966). They provide the ability to evaluate hypotheses about ecosystem structure and the key processes and interactions among species including feed-backs (Dambacher et al., 2002). In addition, when perturbations occur in ecosystems, indirect effects can oppose and outweigh direct effects, resulting in counter intuitive outcomes and indeterminacy (Yodzis, 1988). Qualitative modelling is well suited to exploring the relative balance between direct and indirect effects in ecosystems, thus providing a means of exploring perturbation outcomes.

In this work we use qualitative modelling to identify research priorities for quantitative process models of NPP in *Eucalyptus obliqua* forests, a common forest type in Tasmania and mainland south-eastern Australia. Most information for the model development comes from the Warra Long-Term Ecological Research (LTER) forest, and despite this forest ecosystem being well researched, there are several knowledge gaps about the interaction of the ecosystem components, especially under climate change. The qualitative modelling approach allows us to canvass these knowledge gaps and provides information on the most likely direction of these interactions. Further, we explore the possible consequences of climate change, including disturbance events, on forests. The work examines key uncertainties in responses to climate change and uses them to identify the most important knowledge gaps. Subsequently, these are evaluated for their ability to improve quantitative predictions of forest NPP under climate change.

The subsequent text of the paper is structured as follows: The methods sections (Section 2) describes the relevant components of the Warra LTER ecosystem and provides an overview of qualitative modelling. In Section 3 we present the results for assessing future climate change research priorities in two parts. In the first part we develop qualitative models for the present state of the ecosystems in the Warra LTER (Section 3.1), and in the second part we add the future climate change components (fire and pests) to these models (Section 3.2). After discussion of the analyses outcomes in Section 4, we provide a conclusion in Section 5.

2. Methods

There are several steps in canvassing the impact of climate change on the Warra LTER forest ecosystem to guide future research. In the first step, experts develop a conceptual understanding of the Warra LTER forest ecosystem through consensus and reference to the literature. This yields the present state models of the current forest ecosystems. In the second step we incorporate information (including literature) that justifies the model components and linkages where there is sufficient knowledge. Where the experts disagree or are uncertain, we highlight these areas and provide alternative model representations. The alternative models are analysed qualitatively to find the most plausible models. Sections 3 and 3.1 provide the outcomes from Steps 1 and 2. In the third step we consider a climate change scenario (Section 3.2). Here uncertainty becomes much more prevalent as the role of new elements, like pests and pathogens, are considered within the conceptualization of the forest ecosystem types. In the fourth step, we rely on perturbation response analysis and associated predictions from the matrix mathematics to identify where the uncertainties are (Section 4). In Step 5 we identify which uncertainties are most important and which are of limited consequence (Section 5).

The first subsection (Section 2.1) of the methods describes the study site and details the forest ecosystems types and the fire regimes that drive ecosystem patterns. In Section 2.2 we provide a brief overview of qualitative modelling. This includes perturbation response analysis and details of qualitative modeling terminology to aid an understanding of the modeling outputs.

2.1. Study site description

The Warra LTER is a forest in southern Tasmania (http:/www.warra.com/warra/about.html). It is a core site in the International Biodiversity Observation Year global long-term monitoring network, and encompasses both Tasmanian State forest and World Heritage Area. The Warra LTER, located in 146° 40′ east, 43° 04′ south, is mostly covered in sclerophyll (broadleaf) forest, mainly consisting of members of the plant family Myrtaceae (subsequently referred to as myrtaceae forest), and also has smaller areas of moorland, rainforest, conifer forest and shrubs.

There is much information on the Warra LTER ecosystem readily available, including an inventory and baseline data on flora, fauna, fire and forest use. Plots providing complete vegetation and geology survey, logging data, and recent fire history dating back to the late 1960s, exist. Detailed information on the myrtaceae pests in the area, including damage impact, and dynamics of coarse woody debris is available (Brown et al., 2001; Grove, 2004).

Fire is an important driver in the Warra LTER. Interaction of fire and forest management produces patterns of growth conducive to low intensity burns and the suppression of wild fires through limiting fuel loads. This resulted in establishing a wet myrtaceae forest (Marsden-Smedley and Slijepcevic, 2001). Such interaction, however, may change under possible climate change scenarios where reduced humidity and higher fire intensity may favour rainforest components or scrub-like climax states. The Warra LTER site covers an area of 15,900 ha, and provides an extensive area of *E. obliqua* forest in a variety of successional stages (Corbett and Balmer, 2001). Warra LTER is representative of the range of environments in which *E. obliqua* forests grow. The main forest types are (Neyland, 2001):

- *E. obliqua* wet forest with a wet sclerophyll understorey dominated by *Leptospermum lanigerum, Melaleuca squarrosa, Nematolepis squamea, Bauera rubioides* and *Gahnia grandis*;
- *E. obliqua* mixed forest with an understorey of rainforest species typical of thamnic rainforest (i.e. with shrubby understorey dominated by *Anodopetalum biglandulosum*, *Atherosperma moschatum* and *Nothofagus cunninghamii*);
- *E. obliqua* mixed forest with an understorey of rainforest species typical of callidendrous rainforest (i.e. open understorey with a tall elevated stratum dominated by *N. cunninghamii* and *A. moschatum*).

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