

The impact of climate change on the cost of insect related dieback of rural woodlands

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Abstract Dieback of forest trees is an international phenomenon with multiple causes that vary in different places. In Australia dieback has mostly been associated with intensive use of land for agriculture or grazing. A succession of dramatic events has led to community concern and investigations into the causes and cures. Unfortunately, a combination of long lag times, numerous potential driving forces, strongly interacting influences and insufficiently long runs of detailed observations have made it difficult to attribute the problems to specific causes. In this analysis an attempt is made to estimate the cost of dieback in rural woodlands in the New England area and to examine how the incidence and severity of dieback events may be affected by climate change. The CLIMEX model was used to develop a species-specific index of dieback risk in relation to climate. The results were used to compare the likely incidence of dieback using sensitivity analysis. A range of likely changes in temperature and rainfall to the year 2030 was used, based on climate change scenarios provided by CSIRO. The costs of dieback were estimated by interviews, a survey of the literature and an economic model. The results indicated that a wide range of outcomes was possible, given the contrasting rainfall scenarios provided by the CSIRO coupled and slab global circulation models. Increased rainfall is expected to increase the incidence of severe dieback events while a drier climate will reduce the incidence. The total annual cost of dieback in New England under current conditions was estimated to be \$484m, using a discount rate of 6%. This value acted as a benchmark for the estimates of climate change. Using the results from the sensitivity analysis, the annual cost of dieback increased by up to \$100m with the wetter scenario, and decreased by a similar amount with the drier scenario.

1 INTRODUCTION

Dieback of forest trees is an international phenomenon with multiple causes that vary in different places, but often appear to be associated with stress induced by extreme climatic events or other agents such as salination. In Australia dieback has usually been associated with intensive use of land for agriculture or grazing resulting in fragmentation of the vegetation. A succession of dramatic dieback events has led to community concern and investigations into the causes and cures. Unfortunately, a combination of long lag times between triggers and observable symptoms, numerous potential causes, strongly interacting effects of land use, climate and biota, and insufficiently long runs of detailed observations have made it difficult to attribute the problems to specific causes.

A common feature of most dieback events is the presence of severe insect infestation. A continuing controversy exists as to whether the insects are the cause or the result of tree stress (Davidson & Davidson 1992). A common theme has been that insects build up after a loss of vigour of trees and an increase of nutrients in the feeding tissues following severe climatic events, such as drought or flood (White, 1986) or frost (Auclair *et al.*, 1995). Other claimed causes of stress include salination (Wylie and Bevege, 1980), and redistribution of soil nutrients by grazing animals (Landsberg *et al.*, 1990). In this paper we summarize an analysis of the potential role of climate in triggering dieback in the New England area of Australia and then explore the likely impact of climate change on the frequency and severity of dieback events.

Species-specific Dieback Index

The first step was to develop stress indices that would reflect the different responses of species of *Eucalyptus* to the same climatic conditions. White (1986) used a stress index to describe the relationship between the incidence of eucalypt dieback in the New England Dieback Tablelands and rainfall. Although simple and useful, the index does not take account of the different is not related to the physiological stress-responses of different species of trees Eucalyptus to extreme rainfall events. The existence of CLIMEX (Sutherst & Maywald 1985; Sutherst, Maywald & Skarratt 1995), a dynamic model linking distributions of species to climate, provided an opportunity to develop more sensitive and species-specific stress indices (Mo and Sutherst in prep.). CLIMEX generates weekly indices that measure the potential for population growth in the favourable season (Growth Index) and the severity of climatic stresses that limit the species ability to survive through the unfavourable season and hence persist in a given location (Cold, Hot, Wet and Dry Stress Indices.)

CLIMEX parameters were iterated until they matched the geographical distribution - and hence by inference the climatic preference - of each of the species of *Eucalyptus* that had been reported as being affected by dieback in the New England Tablelands. Geographical distributions of the species were obtained from the ERIN Web Page of Environment Australia ([http:// Error! Bookmark not defined.](http://Error! Bookmark not defined.) CLIMEX was then run using historical rainfall data for the last century to

generate weekly stress values. Those weekly stress values greater than 100 (the CLIMEX value calculated from long-term average data, above which the stress is considered to be limiting to the long-term survival of the species) were summed to estimate the annual stress for each year of meteorological data. Prolonged periods of severe stress were identified from the time series of annual stress indices. Severe stress was mostly related to excessive rainfall but some drought stress was also evident. CLIMEX was also used to estimate the annual climatic suitability of the region for two species of Christmas beetles (*Anoplognathus* spp.) that were representative of the phytophagous insects attacking the affected trees in the New England Dieback. The overall suitability of each year and location for the beetles was indicated by the CLIMEX Ecoclimatic Index (EI), which combines the Growth and Stress indices, and gave a measure of the expected relative abundance of the defoliating insects in relation to climate each year.

One dieback index was produced with climate-induced stress alone and another integrated index was derived to include the combined effects of both climate-induced stress and insect-induced stress on each species of *Eucalyptus*. A positive feedback loop for insect feeding was included in the integrated dieback index, with stressed trees becoming more susceptible to insect attack. Stress in trees not only reduces their resistance to insect attack but also increases the nutritional value of the foliage for the insects.

Once the dieback indices had been calculated for a species of *Eucalyptus*, the frequency and severity of predicted dieback events were calculated for the duration of the historical record. In order to evaluate the potential impact of climate change, the CSIRO 1996 VMGW-DARLAM climate change scenario for the year 2030 (Anon. 1996) was used to choose the range of variation in temperature and rainfall to be examined in a sensitivity analysis. These values ranged between $\pm 1^\circ\text{C}$ maximum and minimum temperatures and $\pm 10\%$ rainfall. The use of sensitivity analysis instead of the scenarios was preferred because of the high levels of uncertainty associated with the model outputs. The rainfall projections from the different global climate models varied widely and were compounded by strong spatial variation at the regional level.

The likely effect of climate change on the geographical distributions of the *Eucalyptus* species was examined first by applying the projected range of rainfall and temperature change to the long-term average climate data in the CLIMEX model. Secondly the range was used to modify the historical rainfall and temperature data for the representative locations in New England. Historical temperature data were not available so it was necessary to use average data. As the CLIMEX analysis had indicated that the trees were not limited by temperature, the use of averaged temperature data had little effect. The dieback indices were then recalculated to estimate the likely change in frequency and severity of dieback events under the different temperature and rainfall conditions (Gaines & Denny, 1993).

The changes in the indicated incidence of dieback were then fed into an economic model of the different usages for rural woodlands in New England (Harrison *et al.* in prep). These valuations included market and non-market

measures, derived from the literature and a short survey of residents in the area.

Results

A brief summary of the preliminary results is presented below.

High CLIMEX Wet Stress values featured more prominently during the historical period than high Dry Stress values for the four eucalypt species involved. Dry Stress values were low for *E. blakelyi* and absent for *E. melliodora*. However, relatively high levels of Dry Stress were detected in 1965 for *E. nova-anglica* and *E. viminalis*. The 1965 drought was widespread in eastern Australia (Pook, 1981).

The derived 'Dieback Indices' satisfactorily correlated with the reported dieback events involving the four *Eucalyptus* species in the New England Tableland during the 1960s and 1970s. The indices peaked during the late 1970s when dieback was most severe (White, 1986). An earlier dieback event (Norton, 1886) was also partly reflected by the indices. The integrated dieback index, incorporating the effects of defoliating insects, appeared to be more successful in describing the dieback process than the index considering climate-derived stress alone. The predicted historical frequency of dieback was highest for *E. nova-anglica*, followed by *E. blakelyi*, *E. melliodora*, and *E. viminalis*. This was in accord with the observed sequence shown by surveys (Clark et al., 1981; Williams and Nadolny, 1981). Differences in the incidence of dieback among the species reflected their different climatic requirements, as inferred from their geographical distributions. Species with wide geographical distributions, such as *E. viminalis*, are likely to be less sensitive to climate induced stresses than species, such as *E. nova-anglica*, with very restricted geographical distributions and hence less implied tolerance of different climates. Site factors may also have contributed to the higher dieback intensity of *E. nova-anglica*. The affected specimens of the latter species were mostly found in flat, low-lying and poor draining areas (William and Nadolny, 1981), and consequently were more vulnerable to stress from excessive rainfall with the resultant runoff from higher surrounding areas.

The wetter scenarios led to substantial increases in the risks of dieback, caused by an increase in the frequency and severity of excessive rainfall events. Up to three-fold increases in the value of the integrated climate/insect dieback index were produced in the analysis when higher temperatures and rainfall were used. Under the drier scenarios, lower dieback frequency and intensity was predicted for *E. blakelyi*, *E. melliodora* and *E. nova-anglica*. No dieback was predicted for *E. viminalis* in the range of climates considered.

The current annual cost of dieback was estimated with the economic model for the New England area, including major items for repair of damage to trees, loss of wildlife habitat, land degradation, wool production and tourism. The total annual loss under current conditions equalled \$484m, using a discount rate of 6%. This value acted as a benchmark for the estimates of climate change. Using the

results from the sensitivity analysis, the annual cost of dieback increased by \$75-100m with the wetter scenario, and decreased by a similar amount in the drier scenario.

1.4 Conclusions and Recommendations

The analyses reported above have provided a new approach to interpreting the causes of tree dieback by the development of species-specific risk indices. They have also demonstrated one approach to the problem of integrating economic evaluations of non-market values into integrated climate change impact assessments.

The results showed that dieback is a major cost to the local community in the New England Tablelands and that the incidence of dieback is likely to be affected substantially by climate change. Trees that currently occur in their natural habitat will suffer stress as the climate changes, especially if the tree population is close to the edge of its geographical distribution. The wide range of results from the global climate models indicates that there is a high level of uncertainty surrounding the direction of change in rainfall in particular. This inevitably leads to a high level of uncertainty about the future incidence and estimated costs of climate change effects on dieback because the direction of change in the incidence of dieback is particularly sensitive to the rainfall change.

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Long-range dependence and singularity of two-dimensional turbulence

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Abstract This paper proposes a class of models to represent, in the same framework, the long-range dependence and singularity/intermittency of 2-D turbulence. A method is given to estimate and separate these two effects. Application to a vorticity field indicates that the resulting energy spectrum follows the power law, in the low-frequency as well as the high-frequency inertial range, predicted by Kraichnan's theory of 2-D turbulence.

1 Introduction

Kraichnan's theory of two-dimensional turbulence predicts an inverse energy (L^2 -norm of velocity) cascade which gives rise to the power law $E(\lambda) \sim |\lambda|^{-5/3}$ for the energy spectrum in the low-frequency inertial range (Kraichnan, 1967). This theory also predicts a direct enstrophy (L^2 -norm of vorticity) cascade which leads to the power law $E(\lambda) \sim |\lambda|^{-3}$ for the high-frequency inertial range. It is known that the energy spectrum $E(\lambda)$ of the velocity field is related to the enstrophy spectrum $Z(\lambda)$ of the vorticity field via the formula $Z(\lambda) = |\lambda|^2 E(\lambda)$, $\lambda \in \mathbb{R}^2$ (Do-Khac *et al.*, 1994). Consequently, the above scaling laws can be written for $Z(\lambda)$ as

$$Z(\lambda) \sim \begin{cases} |\lambda|^{1/3}, & |\lambda| \rightarrow 0, \\ |\lambda|^{-1}, & |\lambda| \rightarrow \infty. \end{cases}$$

Self-similarity theories, in particular that of fractional Brownian motion (fBm), have been commonly used to model the $|\lambda|^{-3}$ scaling of the velocity field. The scaling $|\lambda|^{1/3}$ in the low-frequency range means that the vorticity field does not display long-range dependence (LRD), and, due to lack of an appropriate method, its validation does not seem to have received much attention in laboratory as well as numerical experiments (Farge *et al.*, 1996). Also, to our knowledge, there has been no previous work reporting on the estimation of both scaling laws in the same setting.

In this paper, we propose a method to estimate

both scaling behaviours (at low frequencies as well as in the high-frequency range) for the vorticity field. As a result, we advocate that the scaling $|\lambda|^{-3}$ in the energy spectrum is the contribution of both singularity / intermittency and LRD of the velocity random field. It is then essential to be able to separate these two effects. This separation is based on a class of models which represent simultaneously the LRD and singularity / intermittency of 2-D turbulent flows. In the simplest setting, the increment random fields of this class have spectral density of the form

$$f(\lambda) = \frac{c}{|\lambda|^{2\gamma} (1 + |\lambda|^2)^\alpha}, \quad c > 0, 0 < \alpha \leq 1, \quad (1)$$
$$-1/2 < \gamma < 1/2, \quad \alpha + \gamma > 1/2, \quad \lambda \in \mathbb{R}^2.$$

The imposed conditions on γ and α mean that the spectral density (1) is properly defined and the resulting increment random field is stationary. In other words, the random fields are not assumed stationary, but have stationary increments with spectral density (1). It is noted that $f(\lambda) \sim |\lambda|^{-2\gamma}$ as $|\lambda| \rightarrow 0$ and $f(\lambda) \sim |\lambda|^{-2(\gamma+\alpha)}$ as $|\lambda| \rightarrow \infty$. Hence, the LRD is represented by the exponent γ , while the singularity / intermittency is indicated by the exponent α . Fractional Brownian motion is a special case of (1) when $\alpha = 1$. The component $|\lambda|^{-2\gamma}$ is the Fourier transform of the Riesz kernel, while $(1 + |\lambda|^2)^{-\alpha}$ is the Fourier transform of the Bessel kernel (Anh *et al.*, 1997b). The existence of random fields with spectrum of the form