Growth and yield modelling in a climate of change: How can we make good use of data from past epochs?

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Abstract

Changes in climate projected by the National Institute of Water and Atmospheric Research imply that either past records from permanent sample plots (PSPs) will be redundant, or that we need to adopt some new approaches to growth and yield modelling. The heart of the issue is that traditional mensurational models employ time as a surrogate for inputs of radiation and changing capacities of plants to intercept and use radiation. If climatic conditions change, then time no longer has the same meaning within the context of such a model. This might not matter if climate change occurred at one point in time, outside the time period covered by a rotation. If the influence of time changes within a rotation, then traditional mensurational models will provide biased estimates. A new approach to mensurational modelling has been developed that employs radiation sums in mensurational equations instead of time. These sums are modified by impacts of monthly climate on a tree’s ability to make use of intercepted radiation. The new approach was tried using data from PSPs in radiata pine plantations in the Central North Island for models of mean top height and basal area/ha. Fits using the new approach were more precise than those using equivalent models based on time.

Introduction

Climate change during a rotation may introduce bias into simulations from traditional mensurational growth and yield models, and it is important to find ways to avoid bias if it is of practical significance.

Climate change

The New Zealand National Institute of Water and Atmospheric Research (NIWA) has published estimates of climate change in New Zealand that will result from anthropogenic introductions of fossil fuels into the atmosphere (Mullan et al. 2008). A few people dispute whether or not anthropogenic climate change is real (Brown et al. 2009) but this paper does not address that question. Instead, I examine the implications for growth and yield modelling, assuming that change occurs. Whether or not the change is anthropogenic is immaterial to this analysis.

NIWA’s estimates can be used by resource management professionals, given appropriate models, to estimate likely impacts on crop production, changes in site suitability, and likely changes in pathogen or weed distributions. Estimates for the Central North Island region, for instance, are for a 1 degree C increase in summer and autumn temperatures, 0.9 degrees C in winter temperatures, and 0.8 degrees C in spring temperatures between 1990 and 2040.

Traditional mensurational models

At the present time most plantation managers rely on highly abstract models loosely called ‘growth and yield’ models. Nevertheless, they have proven to be surprisingly accurate predictors of future forest yield. They are used primarily for making silvicultural decisions and for harvest planning. Forest growth is empirically depicted by sigmoid yield-age functions (Zeide 1993). Differentiation of any such equation defines the corresponding growth curve. Growth and yield models typically represent changes in height, basal area (or in some cases individual tree diameter) and mortality. In addition they often represent distributions of tree sizes and shapes at future times. Independent variables generally include tree sizes at some initial time and the time period over which the simulation should be run. The initial state of the forest at a particular time defines site quality in these models, determining which curve best represents the future growth of any particular stand or plot. The set of curves for any region is created by fitting curves against data from permanent sample plots (PSPs).

Traditional mensurational growth and yield models are those that employ time as a principal independent variable, as a surrogate for inputs of solar radiation and factors such as nutrition, moisture and temperature that influence the use of that radiation. Using time as a surrogate for these causal influences makes these models insensitive to climate change. However, it is not clear how important this problem is. In addition, as they represent site quality by using tree sizes and shapes at future times. Independent variables generally include tree sizes at some initial time and the time period over which the simulation should be run. The initial state of the forest at a particular time defines site quality in these models, determining which curve best represents the future growth of any particular stand or plot. The set of curves for any region is created by fitting curves against data from permanent sample plots (PSPs).

The objectives of this paper are to:

1. examine the likely consequences of using traditional growth and yield models under conditions of climate change; and
2. Describe a new approach to growth and yield modelling that can make good use of PSP data from previous epochs, when climate may have been somewhat different from current and future climate.

Impacts of climate change on simulations from traditional models

Examining the impacts of climate change on model simulations involves three questions, one with an obvious answer and two that are more subtle.

**Question 1: Will a long term simulation, during which productivity changes, result in biased future yield estimates?**

An increase in productivity can be represented as a reduced time to get to a particular yield, and so it is feasible to test existing growth and yield models under simulated conditions when productivity changes.

For the study reported here, I chose to use a stand-level basal area model for radiata pine in the Central North Island developed by Ricardo Methol as part of his PhD project (Methol 2001). Methol’s model uses time and yield at a particular starting time as independent variables, but also includes elevation. The latter variable is strongly related to productivity in the Central North Island region (Mason 2001; Mason and Whyte 1997; Mountfort 1979), but in Methol’s model it serves only to subtly alter the shape and asymptote of the sigmoid curves used to represent basal area/ha.

Assuming that during each subsequent year it takes 1.5% less time (as a percentage of the base year) to reach a given yield than during the previous year, we can plot “actual” yield and projected yield for a stand at 300 m in the central North Island, starting with a basal area/ha of 5 m² at age 5 (Figure 1). As expected, the curves diverge.

**Question 2: Can traditional growth and yield models adjust, without bias, to an on-going change in productivity because the starting values at any given age would be larger?**

Methol’s model, like most traditional, stand-level growth and yield models, uses tree size at a given time as an estimate of site productivity in order to project size at some future time, and so it is interesting to ask whether or not this type of model would be unbiased if a projection was made from a more advanced age prior to which productivity had increased. We can take the “actual” basal area at age 14 from the stand depicted in Figure 1 and project it forward using Methol’s model, allowing for the fact that the starting yield at age 14 was higher than it would have been had productivity had not changed systematically with time. The result is depicted in Figure 2.

![Figure 2 - Projection using Methol’s model during a period when productivity is increasing, compared to “actual” growth in basal area.](image)

Clearly managers would be faced with biased estimates of future growth and yield if they used a model such as Methol’s when productivity was increasing. Estimates of allowable cut would be biased downwards, and estimates of forest profitability would be understated systematically.

The results presented here point to a more pressing concern, because mensurational models are based on careful fits, with minimal bias, to growth measured in PSPs, and so the underlying data would no longer properly represent reality during a period of changing productivity. Would all past PSP data be redundant? A study of the likely impacts of climate change on productivity presented an alternative way of using PSP data that allows estimates of growth during periods of changing productivity, and this analysis is briefly described below.

**Question 3: Will climate change projected by NIWA result in a change in productivity?**

Estimates of changes in radiata pine productivity in the Central North Island region resulting from modest changes in temperature are substantial (Mason et al. 2008). Estimates were made by using data from PSPs to parametrise a...
A hybrid physiological/mensurational model based on potentially useable solar radiation

**Background**

For more than two centuries we have known that gas absorbed from the atmosphere contributes to biomass (Ingenhousz 1779), and that use of solar radiation is the critical process driving plant growth (Senebier 1788). In addition, circulation of sap (Hales 1727) provides water for photosynthesis and distributes nutrients and photosynthate to where they are needed within a plant. Adding influences of weather on these processes to traditional mensurational models can make the models sensitive to changing climates.

Complex physiological models (McMurtrie and Wolf 1983) are unpopular with forest managers because they operate at too fine a level of resolution to provide robust estimates of stand- and tree-level stem variables in a management context. Typically such models require inputs that are expensive to acquire, and even one of their authors acknowledges that their complexity, while scientifically informative, often results in biased estimates of variables that forest managers are typically interested in (McMurtrie, pers. comm.). Small errors in cyclic sub-models can compound, resulting in large inaccuracies. Moreover, such models do not fully exploit measurements of growth on a particular site prior to the period of simulation, and so long as managers are willing to measure stand dimensions in inventories, simple mensurational models that use measurements of prior growth are hard to beat.

A greatly simplified approach to physiological stand models has recently been proposed (Landsberg and Waring 1997). The 3-PG model exploits the observation that net primary productivity of plants is linearly related to radiation interception when temperature and moisture conditions are held constant (Monteith 1977). Changes in temperature or moisture conditions alter the rate at which biomass is produced for any given amount of intercepted light, and the model contains sub-models that represent these influences on a monthly cycle. Once biomass is produced the model has then to allocate it to roots, stems and canopies so that changes in tree dimensions can be calculated and light interception during the next month can be estimated. In order for the model to be used in different places and at different plant ages, impacts of soil fertility and senescence on light use are also represented. The model has been used by forest managers to simulate stand development of highly productive, short rotation crops of Eucalypts in Brazil (Almeida et al. 2004), where ephemeral variations in growing conditions can significantly impact on profitability. It does not, however fully exploit prior growth measurements on particular sites, and deciding how to estimate foliage surface area and also how to allocate photosynthate to different plant parts can be problematic. Nevertheless, the 3-PG model has some very attractive simplifications, and the notion of relating growth to radiation use underlies the approach described here.

**The hybrid model**

A forest stand modelling strategy was designed that would be sensitive to climate, employ estimates of site-specific prior growth, and be fitted to historical PSP data in a rigorous fashion, but avoid cyclic models and also lack any requirement for allocation of photosynthate. It drew on ideas and some sub-models from the 3-PG model, but also on general principles applied in mensurational growth and yield modelling (Clutter 1963; Clutter et al. 1983). The core idea was to replace time in mensurational models with a modified sum of solar radiation. The radiation sum would be measured at a nearby meteorological station, and monthly totals of incoming radiation would be modified by terms which represented the likely ability of the crop to use the radiation given climatic conditions that occurred within the month. The idea was first successfully applied in yield form to represent tree measurements in a complicated weed competition experiment (Mason et al. 2007), and allowed highly divergent and intercrossing yield trajectories to be represented by just one equation. Sub-models employed in 3-PG were used to calculate radiation sum modifiers, and so it is important to understand how these modifiers represent impacts of climate.

Photosynthesis resulting from a given amount of intercepted radiation is affected by temperature. For each species there is a minimum temperature below which no photosynthesis occurs, and optimum temperature at which photosynthesis is maximised, and a maximum temperature above which no photosynthesis occurs. The 3-PG model uses the mean temperature during a month to calculate a number between 0 and 1 to represent the proportion of maximum photosynthetic activity that would occur for any given amount of radiation. This modifier is multiplied by the radiation total for each month in order to provide an estimate of “useable” radiation. During the study described here and in some previous studies, an estimate of mean temperature during daylight hours was found to provide better fits to PSP data.

Plants exchange gases and water with the atmosphere through apertures in leaves known as stomata (Figure 3). It is essential for a plant to get CO₂ from the atmosphere
into solution, and so water absorbed by roots is exposed to the atmosphere within stomata, resulting in large losses of water through transpiration. If a tree is stressed by low water supplies, then there is a danger that the water column within its stem will break, or “cavitate”, and if enough cavitation occurs then the top of the tree can die. Trees can close stomata to avoid excessive water loss, thereby also reducing photosynthetic activity by restricting CO$_2$ intake. Two environmental conditions promote stomatal closure: high vapour pressure deficits$^1$; and low levels of soil water. The 3-PG model has sub-models that represent both these influences, and each produces a radiation sum modifier between 0 and 1. Because they both act on stomata, only the smallest of the two modifiers is applied to any given monthly radiation sum.

The soil water modifier requires an estimate of the soil water deficit in any month, and a “soil water balance” sub-model is used to provide this estimate. Briefly, a proportion of the rainfall in a month is intercepted and evaporates from leaves, some evaporates from the soil surface, some enters the soil and is taken up and then transpired by plants, and any excess above soil field capacity drains away from the root zone. Soil water balance models need estimates of leaf area per unit area of ground, or “leaf area index” (LAI), and so at least a rough model of leaf area index development is required in order to run the water balance model. For the model described here, a simple relationship between leaf area index and time, approaching an asymptote of 6.5 at around age 15, was used.

The leaf area index model was not considered accurate enough to estimate radiation interception, and so radiation sums represented light that would potentially have been used had it been intercepted. Sigmoid equations used in mensurational models implicitly represent both patterns of light interception in stands and also carbon allocation (Mason 1992), and so these processes were not explicitly represented in the model.

Radiation measured at Rotorua airport was multiplied by localised, monthly estimates of soil water, temperature, and vapour pressure deficit modifiers in order to arrive at modified radiation sums for each PSP. Substituting modified radiation sum since time of planting for time in Methol’s mean top height and basal area per hectare equations (Methol 2001), resulted in improvements in precision when the models were fitted to PSP data (Mason et al. 2008), and radiation sum models were also more precise when fitted to independent datasets.

Figure 3 - Stomata on the surface of a pine needle. Credit: Mr. Karl Hagglund, Northern Kentucky University.

Estimates of impacts of climate change on forest productivity

A prevailing view among scientists has been that climate change will prove beneficial to forests, at least in the short term. The argument is straightforward; plants need CO$_2$ to undergo photosynthesis so as to produce food and O$_2$. But with factories and cars emitting evermore carbon dioxide into the atmosphere, this will cause crops and trees to grow bigger and faster. However, this scenario is challenged by results from large-scale field experiments at Duke (Duke University 2004) and Stanford (Stanford University 2002) Universities. At Duke University, after exposing loblolly pine to enhanced levels of carbon dioxide for seven years, a complex pattern of results has emerged. While annual growth rates have increased by 10-25%, most of these have occurred only in dry years. Given normal or wet years, responses have been a lot less and may be the effect of inadequate nutrition. Studies of impacts of elevated CO$_2$ on growth of radiata pine have been conducted in large open-topped containers at Bromley on the outskirts of Christchurch (Griffin et al. 2000). Growth with CO$_2$ at 650 ppm was elevated during the first two years of the experiment compared to growth with CO$_2$ at 360 ppm, but then trees gradually ‘acclimated’, reducing stomatal conductance and thereby increasing water use efficiency. This increase in water use efficiency may explain the results at Duke University. We can conclude that responses of forests to elevated CO$_2$ are expected to be positive, but that uncertainty is high. Models presented in this paper do not attempt to include the effects of CO$_2$ on tree growth.

In order to simulate likely crop responses to changing climate in the Central North Island region, two contrasting sites were selected. Productivity is strongly influenced by altitude in this region (Mason 1992; Mountfort 1979), and so sites at altitudes of 400 and 700 m a.s.l. were chosen. The initial growth model (Mason 2001) was used to derive

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$^1$ Vapour pressure deficit is the difference between the amount of water the atmosphere could hold at any given temperature and the amount of water it actually holds.
starting values for these sites, as it is sensitive to altitude, and has been shown to join smoothly with existing growth and yield models for the Kaingaroa vicinity (Mason 1996). For 2040 the same starting values were employed.

Using the same starting values for each year of simulation might provide conservative estimates of change, but two major caveats suggest a conservative approach:

1) The models do not yet take into account any deleterious effects of wind.
2) Changes in regional temperature may not be uniformly allocated across altitudes (that is, at higher altitudes, predicted increases in temperature may be less than a general average figure). NIWA advice is that detailed studies have been limited to surface fields. (Dr. Andrew Tait, pers. comm.)

The sites and starting values are shown in Table 1.

Table 1: Site characteristics and starting values for simulations

<table>
<thead>
<tr>
<th>Elevation (m.a.s.l.)</th>
<th>Mean ht (m)</th>
<th>Basal area (m²/ha)</th>
<th>Stocking stems/ha</th>
<th>MTH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>6.72</td>
<td>9.11</td>
<td>814</td>
<td>8</td>
</tr>
<tr>
<td>700</td>
<td>4.1</td>
<td>3.92</td>
<td>720</td>
<td>4.9</td>
</tr>
</tbody>
</table>

For each site a daytime temperature modified light sum was calculated for the years 1985 to 1995, and for the same years but adding 1 degree C to summer and autumn temperatures, 0.9 degrees C to winter temperatures, and 0.8 degrees C to spring temperatures, as specified in the NIWA climate projections (Ministry for the Environment, 2008) for the Bay of Plenty region.

These modified light sums were then replicated to reach age 30 for the simulation at each site. The regimes specified for each site was planting 1000 stems/ha and then thinning down to 300 stems/ha at a mean top height 10 m.

Estimated gains in productivity are shown in Figures 4, 5 and 6. It should be noted that these estimates are for the Central North Island region only, and also that they are modelled estimates and they should therefore be treated with caution.

The wavy plots depict the influences of monthly radiation and climatic variation on growth within each year.

The impact of projected changes in temperature on the simulation was greater for the higher elevation site, because at lower elevations the optimum temperature for photosynthesis of radiata pine is sometimes exceeded.
and therefore higher temperatures during summer occasionally reduced the potential for light to be used for photosynthesis.

Estimates of enhanced growth through climate change in the order of 70-100 m³/ha in a 30 year rotation are shown, but these must be considered in relation to the caveats listed above. Note that the estimated change in productivity is similar to that assumed for the previously described analysis of traditional growth and yield modelling during periods when site productivity changes.

What are the implications for forest managers?

Opportunities

Forest managers should be aware that if they employ traditional mensurational growth and yield models when productivity is changing during rotations then they will very likely obtain biased estimates of future yields.

The methodology described here offers an opportunity to not only secure less biased estimates of future yields when productivity changes, but also more precise estimates even if climate change does not materialise.

In addition to improved estimates of future yields, the new methodology offers a smoother integration of impacts of site management and also wood property maps into a growth and yield modelling system. Site management practices such as weed control impact primarily on light use, and the precise representation of seasons within these models offers the potential to represent earlywood/latewood ratios within growth rings.

Risks

While the new modelling methodology offers some gains for forest managers, at least two aspects of it need attention before it is applied widely:

1. Estimates of rooting depth are critical for soil water balance modelling, and investigations in Canterbury suggests that while national database estimates of rooting depth may be fine for agronomy, they are often very much underestimates for forest crops. Using a water balance modifier based on unrealistic rooting depths in regions subject to high moisture deficits will result in poor fits to PSP data.
2. Site quality generally influences LAI development within stands (Allen et al. 2002), and so the models could be improved if managers were willing to estimate LAI in PSPs and in inventory plots. Using growth prior to the interval being simulated as an independent variable in these models reduces the significance of not including a fertility modifier, but a robust modifier representing soil fertility would be a valuable addition.

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References


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