Climate Change Impacts and Implications for New Zealand to 2100

Synthesis Report: RA2 Alpine Case Study

The beech forests of New Zealand

Mandy Barron[1], Roger Pech[1], Jenny Christie[2], Andrew Tait[3], Andrea Byrom[1], Graeme Elliott[2]*

[1]Landcare Research, PO Box 69040, Lincoln 7640, New Zealand
[2]Department of Conservation, New Zealand
[3]National Climate Centre, NIWA, Private Bag 14901, Wellington, New Zealand

**Corresponding author, email: barronm@landcareresearch.co.nz*

When quoting, citing or distributing the Synthesis Report or its individual sections, please provide the full reference:
Barron MC, Pech RP, Christie JE, Tait A, Byrom A, Elliot G (2016) *Climate change impacts and implications: an integrated assessment in the alpine case study*. Synthesis Report: RA2 Alpine Case Study. The beech forests of New Zealand. Climate Change Impacts and Implications for New Zealand to 2100. MBIE contract C01X1225. 19 p.

CONTENTS

HIGHLIGHTS

New Zealand's alpine and sub-alpine systems are characterised by plant communities that occasionally produce very large seed crops (masts). Masts result in irruptions of rodents and their predators, primarily stoats, with subsequent severe predation impacts on native fauna. Masts can be predicted using the difference in successive summer temperatures, i.e. the ΔT model (Kelly et al. 2013). Historic, current and projected summer temperature data were used in the ΔT model to predict the timing and extent of masts in forest dominated by beech (*Fuscospora* spp.).

- Masts are often synchronised over very large areas of beech forest, i.e. at regional scales.
- Mega-masts, i.e. masts occurring over >50% of beech-dominated forest, have occurred 11 times over the last 40 years.
- Virtual Climate Station Network (VCSN) temperature data were used to correctly forecast mega-masts in 2014 and 2016. These forecasts contributed to planning for DOC's high-profile pest control programme, 'Battle for our Birds'.
- Spatially explicit forecasts of masts will help Department of Conservation (DOC) managers identify those areas of high conservation value that coincide with a high probability of a mast and therefore are threatened by a pest irruption in any particular year.
- Climate projections up to 2100 suggest mega-masts, and hence wide-scale pest irruptions, are likely to continue to occur episodically regardless of Representative Concentration Pathway (RCP). This indicates that provision of contingency funds for managing mast-induced irruptions of pests could be based on approaches used for other natural events such as wildfires, floods and earthquakes.
- Differences between General Circulation Models (GCMs) mask any significant differences between RCPs in their predicted effects on the frequency of mega-masts during the 21st century.
- The approach of combining spatial climate projections with a climate-based model for beech masts could be used for predicting the effects of climate change on other masting ecosystems worldwide.
- Actuarial or other risk-management approaches are likely to be required in the future to better manage periodic pest irruptions.

1. INTRODUCTION

1.1. The CCII project

The "Climate Changes, Impacts and Implications" (CCII) project is a 4-year project designed to address the following question:

What are the predicted climatic conditions and assessed/ potential impacts and implications of climate variability and trends on New Zealand and its regional biophysical environment, the economy and society, at projected critical temporal steps up to 2100?

The CCII project brings together a strong research team with knowledge and modelling capabilities in climate, ecosystems, land and water use, economics, and sociocultural research to address the environment sector investment plan priority of "stronger prediction and modelling systems".

The project is based around five inter-related Research Aims (RAs) that will ultimately provide new climate change projections and advancements in understanding their impacts and implications for New Zealand's environment, economy and society. The five RAs are:

Research Aim 1: *Improved Climate Projections*

Research Aim 2: *Understanding Pressure Points, Critical Steps and Potential Responses*

Research Aim 3: *Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits*

Research Aim 4: *Enhancing Capacity and Increasing Coordination to Support Decision-making*

Research Aim 5: *Exploring Options for New Zealand in Different Changing Global Climates*

Research Aim 2 uses case study analysis of key pressures, critical time steps, and potential responses for five important environments: alpine and high elevation native forest ecosystems, high-and hill-country environments, lowland environments, coastal and estuarine systems, and marine food webs. This synthesis report presents the results of the alpine case study.

1.2. The Alpine Case Study

Climate change will influence vegetation dynamics (e.g. seedfall), species distributions (e.g. tree lines), hydrology (e.g. snow cover) and pest dynamics (e.g. ship rats *Rattus rattus* & stoats *Mustela erminea*) in novel ways that threaten the resilience of New Zealand's alpine and high elevation forested ecosystems (McGlone & Walker 2011). One of the most serious threats to the persistence of vulnerable native fauna in these areas, such as rock wren (*Xenicus gilviventris*) and mohua (*Mohoua ochrocephala*), is predation by invasive mammals, including rats, house mice (*Mus musculus*) and stoats. The risk of predation is increased significantly following high seedfall ('mast') years which fuel rodent and stoat irruptions ('the predator plague cycle': Fig. 1). Widespread, synchronous masting has been observed in many New Zealand species including southern beech trees (*Fuscospora* spp., formerly *Nothofagus* spp.) and snow tussocks (*Chionochloa* spp.) (Schauber et al. 2002).

Recently, the Department of Conservation (DOC) has taken the approach of anticipating predator irruptions following widespread beech mast events and planning a coordinated national pest control response: the 'Battle for our Birds' programme which was first conducted in 2014 and was repeated in 2016. One year's advance warning of a beech mast event is predicted by a simple climate-driven model (the ΔT model: Kelly et al. 2013) that instigates seed counting and predator monitoring to confirm a pest response and the planning of pest control operations.

Changes in climate could affect masts in two ways. First, changes in the spatial synchrony of climatic drivers could affect the extent of masts and hence the cost of large-scale control operations required to protect native species from outbreaking pest populations. Second, increasing temporal variability in climatic drivers could change the frequency of masts in particular locations. Tompkins et al. (2013) predicted substantial changes in the ability of management programmes to achieve effective control of invasive predators if the frequency of mast seedfall increases. Both spatial and temporal changes are of concern to conservation managers, thus the aim of the alpine case study was to use improved NZ climate projections to assess the potential future effects of climate change on the frequency and extent of beech forest masts and the requirements for controlling outbreaks of invasive rodents that follow these mast events.

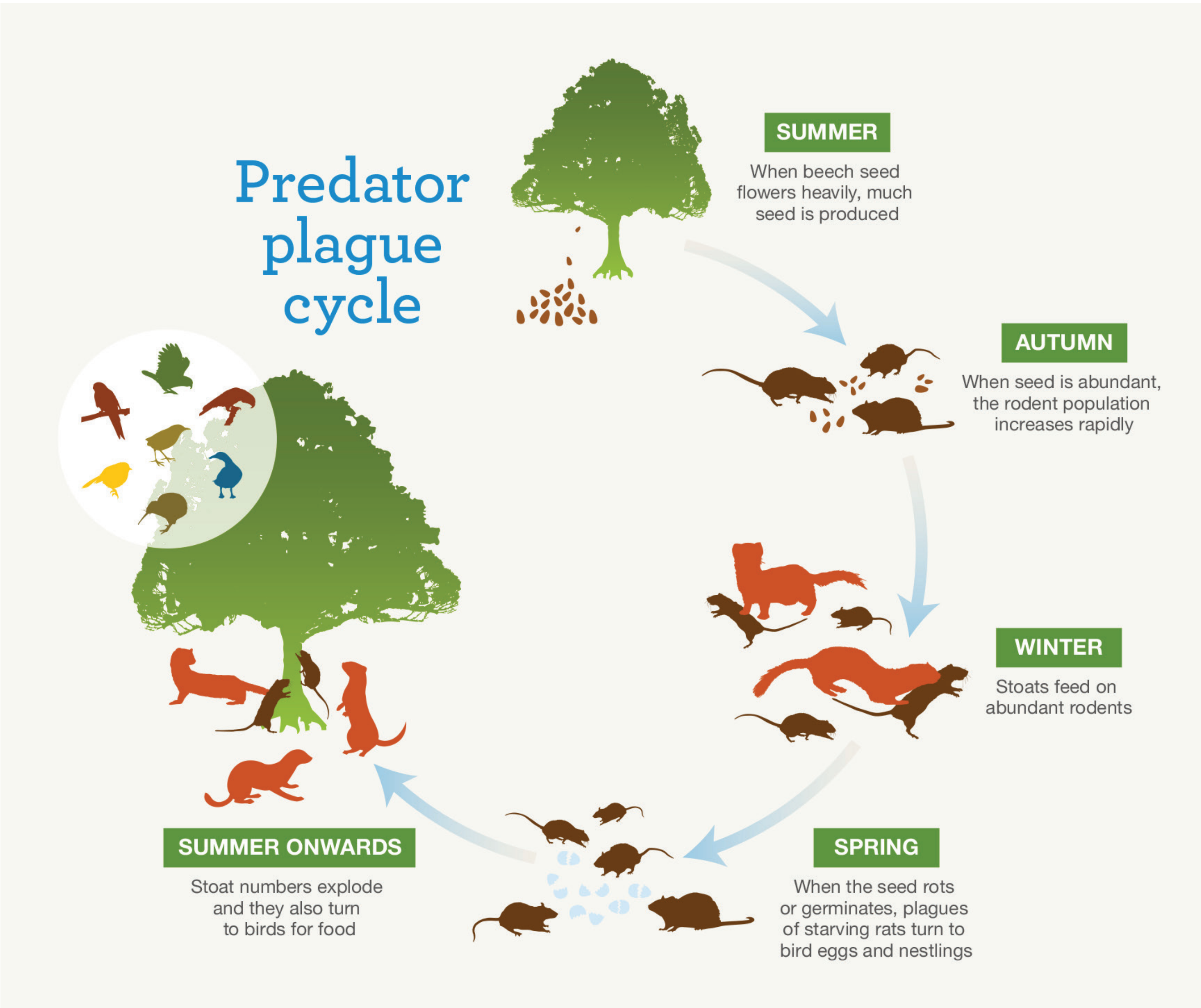

Figure 1: Predator plague cycle (Source: www.doc.govt.nz).

2. CASE STUDY SELECTION AND STAKEHOLDER ENGAGEMENT

Targeted interviews with a small number of stakeholders from DOC were conducted in lieu of a workshop for the alpine case study due to the very specific focus of the research on beech mast events and their consequences. For conservation managers, the frequency and extent of predator irruptions are key to planning effective control strategies. DOC scientists were part of the team for this case study thereby ensuring immediate application of research findings in operational management. Interviews with relevant DOC stakeholders were also incorporated into research on decision-making – including for conservation and pest management – within RA4 (Lawrence et al. 2016).

The area of interest for predicting masts was the beech (*Fuscospora* spp.) forest distribution across New Zealand. To derive this we used the Vegetative Cover of New Zealand (digitised as shapefiles; Newsome 1987) and extracted the cover classes that included a significant component of beech cover (F4, F5, F6, F7, FS3, FS4, FS5, FS7, GF5 & GF6) covering an area of approximately 4,416,067 ha (Fig. 2).

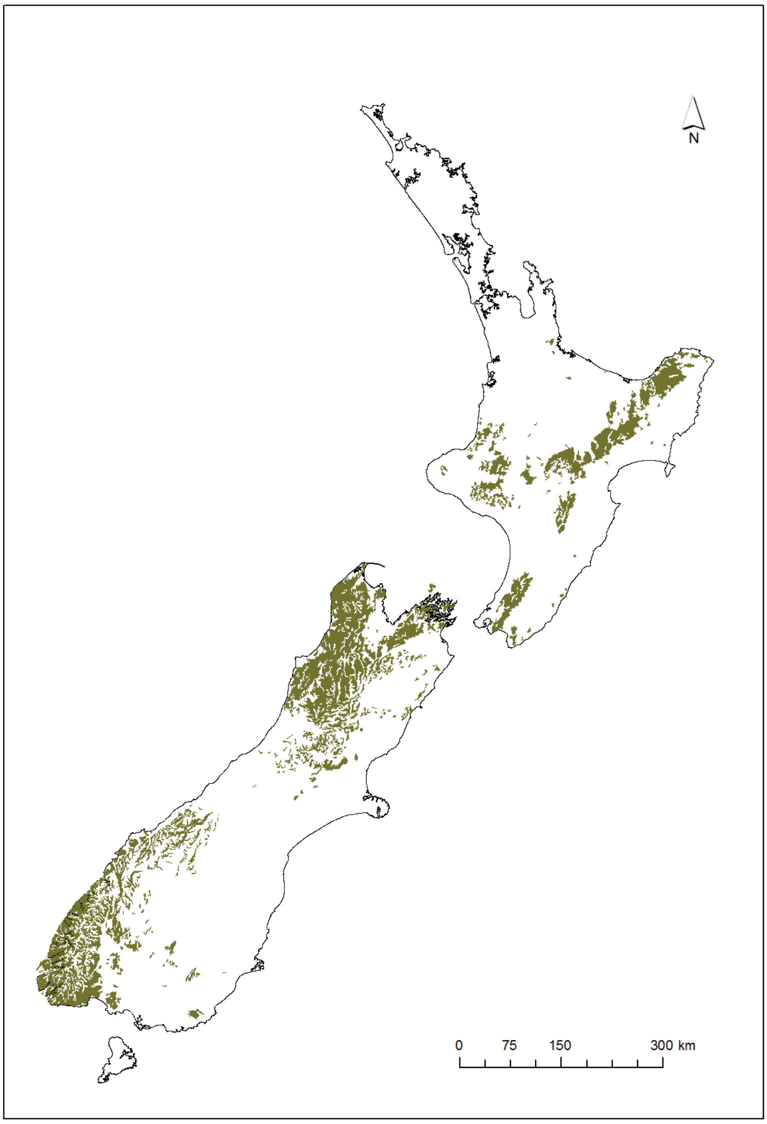

Figure 2: Map of New Zealand beech forest distribution.

3. METHODOLOGY

3.1. Climate inputs

The Intergovernmental Panel on Climate Change Fifth Assessment Report adopted four greenhouse gas (GHG) concentration trajectories, referred to as Representative Concentration Pathways (RCPs), to facilitate comparable global assessments of the effects of climate change. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5) (IPCC AR5). The effect of these RCPs on projected climate was modelled via the Coupled Model Inter-comparison Project (CMIP5) through multiple Earth System Models or General Circulation Models (GCMs). Outputs from six GCMs (BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and NorESM1-M) using the four RCP scenarios were downscaled to give regional-scale climate projections across a 0.05° latitude/longitude grid covering the whole of New Zealand (Tait et al. 2016). This grid has the same extent and resolution as that used for the Virtual Climate Station Network (VCSN), which is a spatial interpolation of climate data recorded from climate stations. For the alpine case study we used maximum and minimum air temperature projections summarised monthly over the years 1971–2100 as input to the model for predicting masts.

3.2. Mast model

The model used to predict masts was based on the ΔT model in which the inter-annual difference (Δ) in mean summer air temperature (T) is positively correlated with the amount of seedfall (Kelly et al. 2013). For each grid cell we calculated mean monthly air temperature as the average of the minimum and maximum air temperature, then summer air temperature as the mean of the January, February, and March monthly means. The ΔT value for year n was calculated as the difference in the preceding summer temperatures, i.e. $\Delta T_n = T_{n-1} - T_{n-2}$.

The amount of seedfall during a beech mast is highly variable (Kelly et al. 2013) but for the purposes of this report we are interested in seedfall that is sufficient to result in an irruption of rodents. We assumed that a threshold value of $\Delta T \geq 1$ resulted in a rodent outbreak based on the analysis of Holland et al. (2015), which showed large increases in both overall mouse (*Mus musculus*) abundance and the rate of change in mouse abundance once this threshold value was exceeded.

ΔT threshold value derived from climate station data and VCSN data

Both Kelly et al. (2013) and Holland et al. (2015) calculated ΔT from temperature data recorded at the nearest climate station. However, nationwide climate summaries are based on the spatial interpolation of base climate station data across the VCSN grid at a 0.05°latitude/longitude ≈ 5 km grid resolution (Tait 2008). This interpolation method involves smoothing the climate variables (in this case air temperature) between locations which, by definition, reduces the variation. To account for this, we estimated the relationship between the ΔT values calculated by Kelly at al. (2013) based on the climate station data (ΔT_{CS}) and those calculated from the corresponding VCSN grid cells (ΔT_{VCSN}). We compared these for the four beech forest locations used in Kelly et al. (2013) and for the years 1974–2011. The fitted relationship showed that ΔT_{VCSN} values were consistently 0.84 of the ΔT_{CS} values (R^2=0.65, P<0.0001). Thus we assumed a threshold value of ΔT_{VCSN} = 0.84 initiated a rodent outbreak.

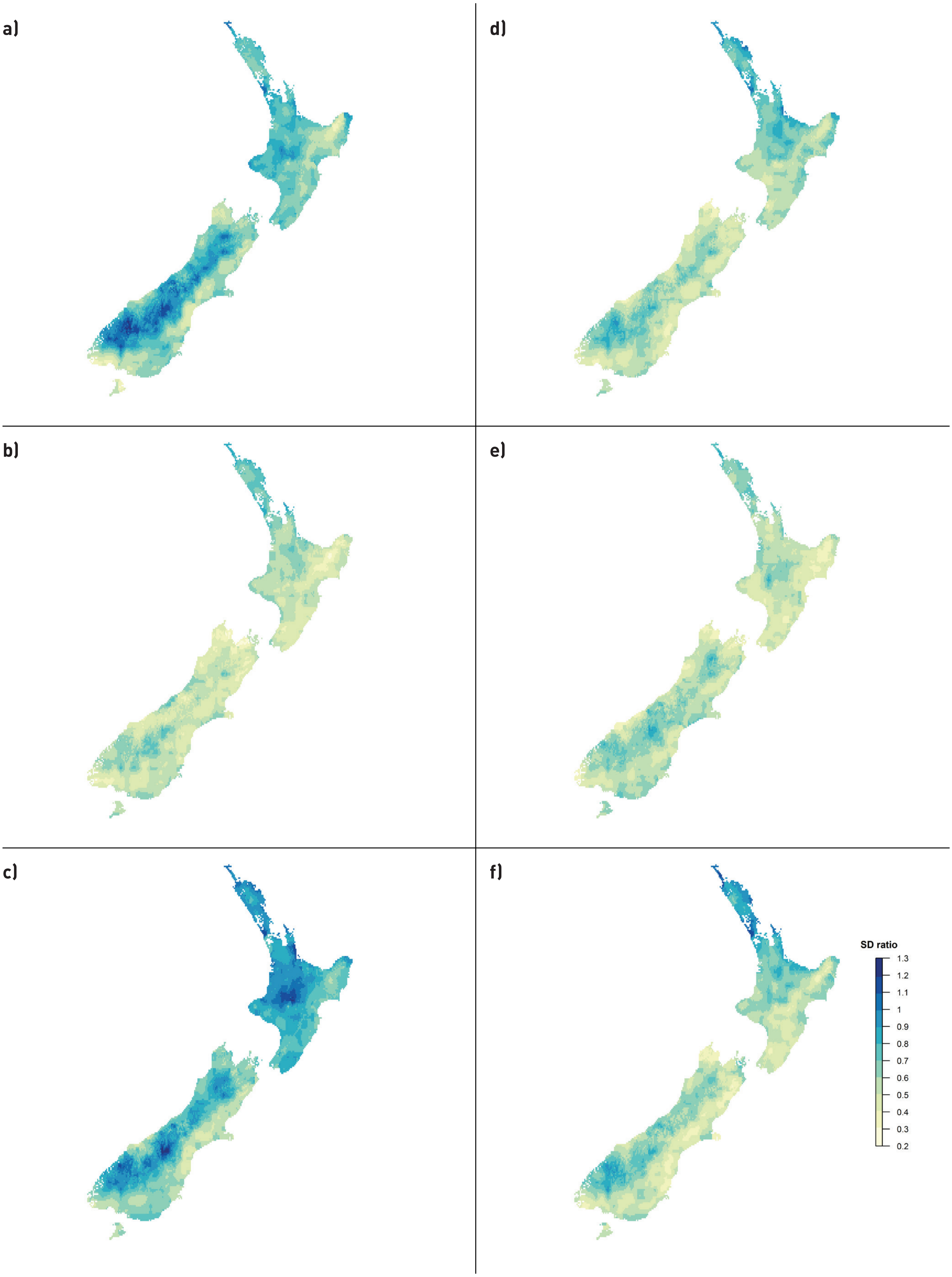

Figure 3: Ratio of standard deviations of ΔT values calculated from projected versus observed temperature data for a) BCC-CSM1.1, b) CESM1-CAM5, c) GFDL-CM3, d) GISS-E2-R, e) HadGEM2-ES, and f) NorESM1-M GCMs over the period 1974–2006. Ratios less than one (green tones) indicate projected ΔT values are less variable than those observed, ratios greater than one (blue tones) indicate they are more variable.

ΔT threshold value based on historic climate data compared with projected climate data

For the 'historic' period of 1971–2005 the GCMs used observed greenhouse gas concentrations to model climate. We compared historic ΔT values calculated from GCM-generated temperature data against those calculated from observed temperature data over the 25-year period 1974–2006[1] for calibration purposes. Comparison of the distribution of ΔT values showed that those based on observed temperatures had more variation than those calculated from model projections for all of the six GCMs suggesting that the GCM-projected climate did not capture all the observed inter-annual variation in temperature. The differences in observed to modelled ΔT variance differed between GCMs but also varied with space when calculated on a (VCSN) grid cell basis (Fig. 3). We used the ratio of the standard deviation of ΔT values calculated from GCM projections to those calculated from observed temperatures as a correction factor for the ΔT threshold value, i.e. we performed a linear transform of the modelled ΔT (Gaussian) distribution to the actual/observed ΔT (Gaussian) distribution. The ΔT threshold value was thus different for each grid cell and was calculated as 0.84 multiplied by the standard deviation ratio.

Definition of a 'mega-mast'

If the grid cell ΔT value is greater than the threshold value we classify that as a mast and can tally the number of cells to derive the area of beech forest masting on a given year. The historic observed ΔT values calculated from the VCSN grid show a U-shaped distribution of beech mast extent with a breakpoint at 40–50% of the beech forest area (Fig. 4). We therefore defined a year with synchronous widespread masting and associated rodent outbreaks, termed a 'mega-mast', as one where >50% beech forest area is masting. In addition, this definition meets an operational need. Mega-masts are of particular concern for conservation managers because (a) the impacts of widespread predator irruptions can reduce severely the connectivity between remnant populations of vulnerable native species, and (b) the cost of pest control to mitigate these impacts is proportionate to the spatial extent of the mast.

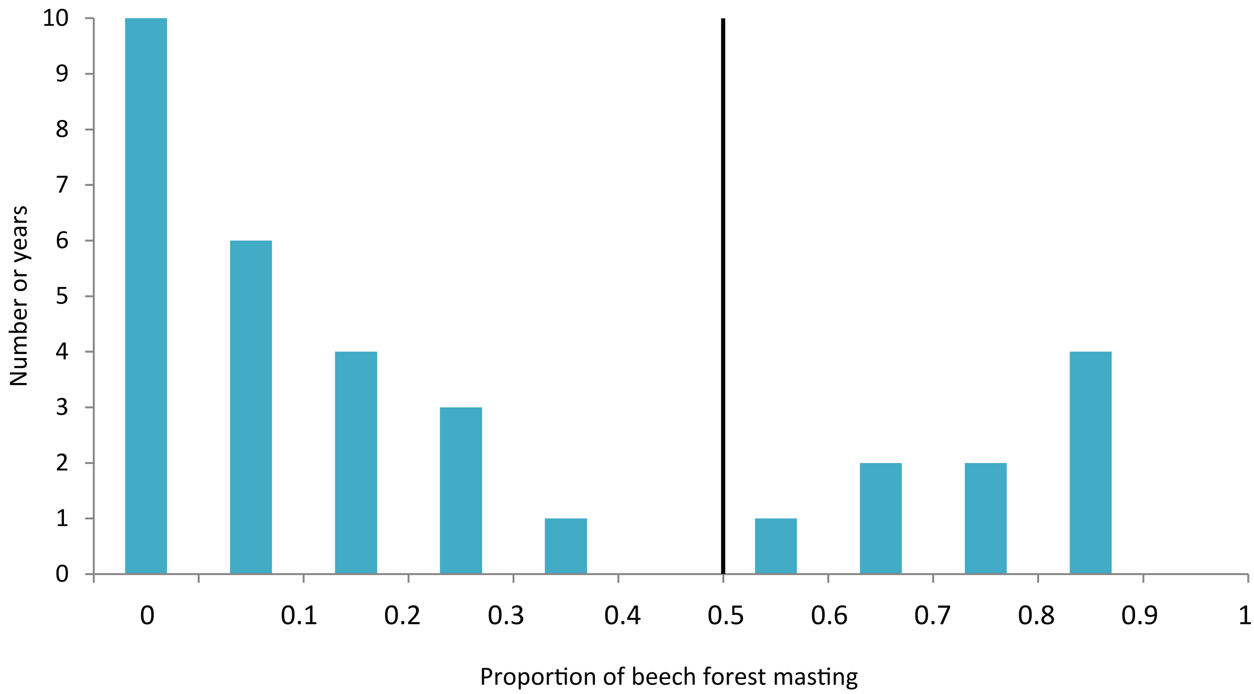

Figure 4: Proportion of beech forest area predicted to experience a mast (defined as ΔT values greater than 0.84) over the historic period of 1974–2006. ΔT values were calculated from observed air temperatures for the VCSN grid. A mega-mast was defined as year in which over 50% of the beech forest was masting (solid line).

[1]Observed VCSN data were only available from 1972 onwards giving ΔT predictions for 1974 onwards. The prediction for 2006 is based on 2005 and 2004 summer air temperatures.

3.3. Analysis of projected mega-mast frequency

The alternative RCPs could generate differences in the mean frequency of mega-masts and/or in the variability in time intervals between successive mega-masts. To determine if there were any differences between the four RCP scenarios we fitted a marginal means/rates model for recurrent events using the 'survival' package in R. The analysis takes the interval between successive mega-masts (in years) as the response with RCP as a covariate and model simulation (GCM*RCP combination) as a random effect to account for the potential correlation between mega-masts within a model simulation. We fitted this model to the inter-mega-mast intervals tallied over the 2006–2100 time period. The fitted coefficients for RCPs 4.5, 6.0 and 8.5 can be exponentiated to give hazard ratios which are interpretable as multiplicative effects on the baseline (RCP2.6) hazard rate where an estimate of 1.1 would indicate a 10% increase in the rate of occurrence and 0.9 a 10% reduction in the rate.

3.4. Costs of pest control

Aerially delivered 1080 baits are the only feasible method of pest control over large areas of relatively inaccessible forest. We obtained data from DOC on the nationwide costs of aerially delivered pest control and the area controlled each year for the period 2003–2013. We fitted a simple linear relationship to the cost versus area controlled and used this estimate to extrapolate costs over larger areas and into the future. We also compared the area controlled with the area predicted to mast using the ΔT model and observed VCSN temperature data.

4. RESULTS

4.1. Frequency of local masts over the historic period 1974–2006

The mean inter-mast interval calculated for each VCSN grid cell from the observed VCSN air temperature data (assessed over the historic period 1974–2006) was 4 years, while calibrated predictions from modelled climate using the six GCMs ranged from 4 to 4.6 years between masts. The spatial variation in mast frequency, i.e. some locations masting more often than others, was captured reasonably well, with the NorESM1-M projections showing the most similarity to the observed patterns (Fig. 5). Note that this is an estimate of frequency per grid cell and not a measure of the synchrony in mast events, which is described in the following section.

Implications – According to the ΔT model, increased temporal variability in summer temperature should increase the frequency of masts. Forest ecologists have questioned whether it is physiologically possible for trees to produce heavy seed crops much more frequently than the typical 4-year interval. Based on the VCSN climate data for the 25-year period 1974–2006, there is substantial local variation in the mean inter-mast period for beech forest, and some locations, for example on the West Coast of the South Island, are predicted to experience masts every 2 years on average (Fig. 5). On-ground monitoring at these sites should answer the question about the physiological capacity of beech trees for frequent masts and therefore determine whether or not climate change could alter masting frequency, pest irruptions, and the need for pest control.

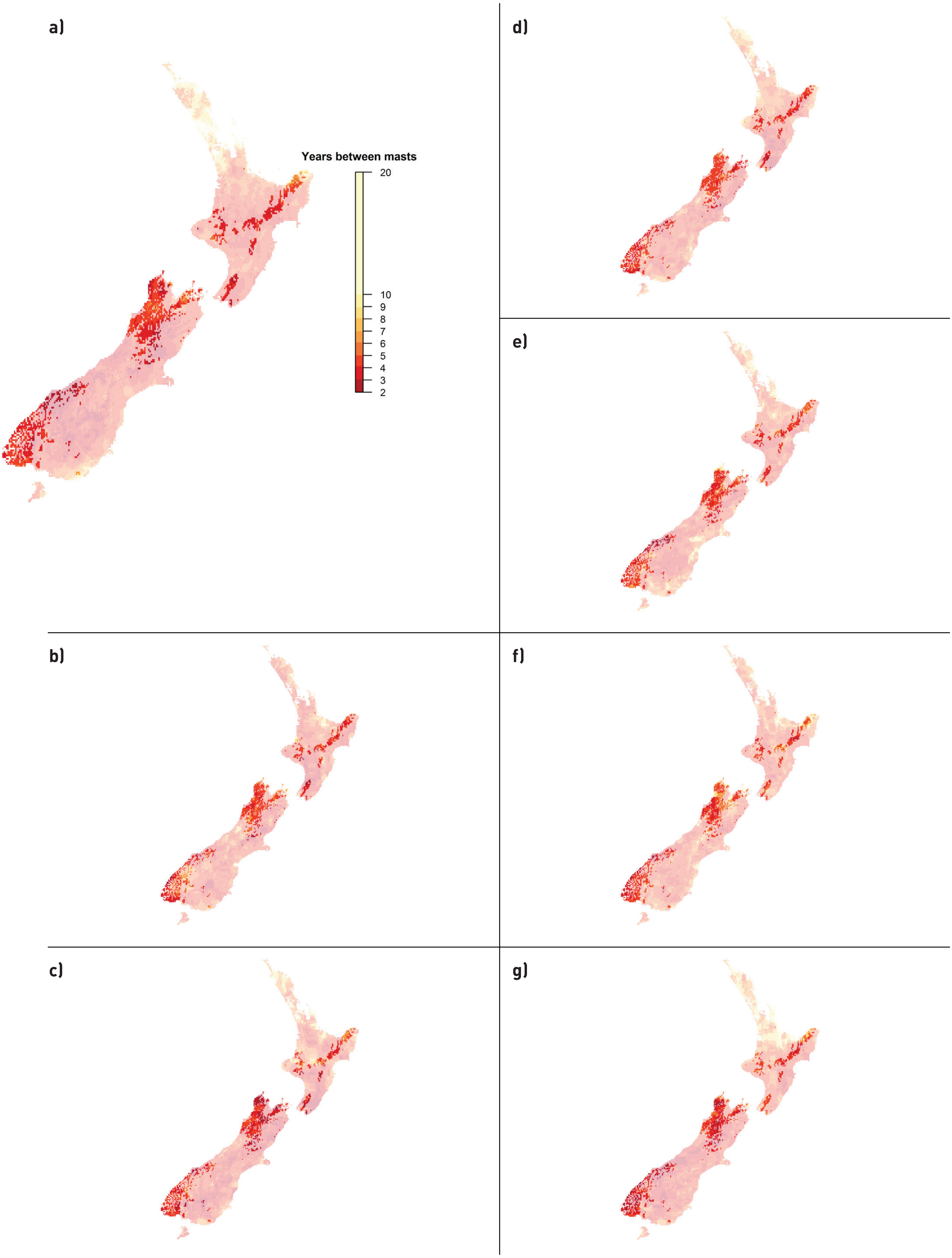

Figure 5: Mean inter-mast interval per VCSN grid cell using ΔT values calculated from a) observed and projected b) BCC-CSM1.1, c) CESM1-CAM5, d) GFDL-CM3, e) GISS-E2-R, f) HadGEM2-ES, and g) NorESM1-M GCMs air temperatures over the historic period 1974–2006. Solid colours show the beech forest area.

4.2. Synchrony in mast events

The predicted synchrony in masting from observed temperature data 1974–2006, assessed as the proportion of beech forest masting within a year, showed a bi-modal distribution (where either little or most of the beech forest masted), but no occasions where greater than 90% of the forest masted (Figs 4, 6a). In contrast, the predictions from modelled climate showed uni-modal distributions. Predictions span the entire range (0–100%), with a peak in the 0–10% category and fewer occasions where none of the beech forest masted compared to predictions based on observed temperatures (Fig. 6a). The difference in distributions meant that 27% of the years predicted from observed temperature data would be classified as mega-masts but only 18–21% of those predicted from GCM modelled data would be in this category although the difference was not statistically significant. Projecting into the future, the distribution of the extent of beech forest masting did not change under the different RCP scenarios or between GCMs for each RCP (Fig. 6b–e).

Implications – The temperature-based predictions for the period 1974–2006 suggested a clear distinction between years with very widespread mega-masts and years with only localised masts or no masts (Fig. 4). This dichotomy was reinforced by the predicted, and observed, mega-masts in 2014 and 2016 that resulted in the widespread pest control used for DOC's 'Battle for our Birds' programme. However, predictions based on summer temperatures generated by GCMs suggest masts are likely across the entire size range (Fig. 6). If the GCM-based predictions for future patterns of mast size are correct, managers might require a more nuanced approach to pest management. By providing spatially explicit forecasts, the ΔT model should enable DOC managers to focus on those areas of high conservation value that coincide with a high probability of a mast and therefore are threatened by a pest irruption in any particular year.

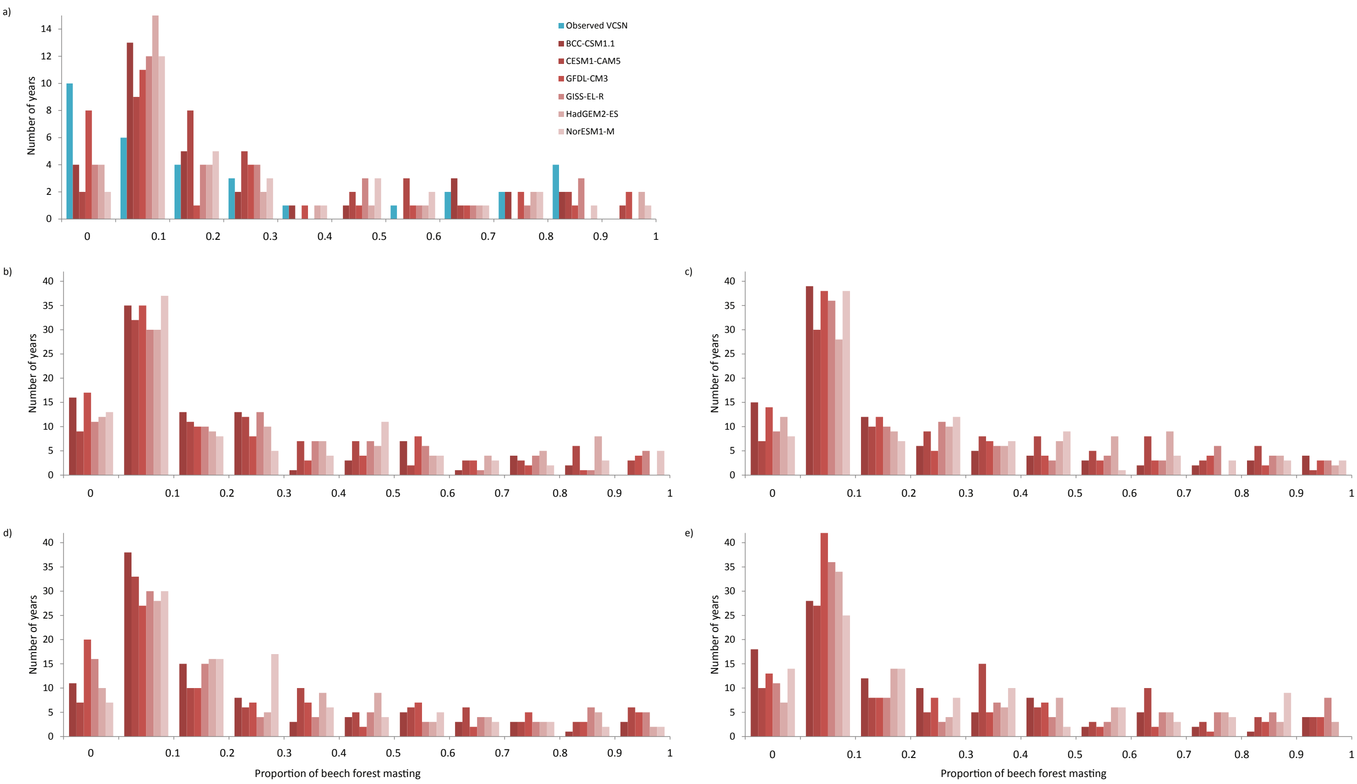

Figure 6: Synchrony in beech forest masting – proportion of the beech forest area predicted to be in mast in the same year. Panel a) are the predictions for the period 1974–2006 where the blue bars show predictions from observed temperature data and the red bars show predictions from GCM-modelled climate. The rest of the panels show predictions for the period 2007–2100 using GCM climate projections under scenarios b) RCP2.6, c) RCP4.5, d) RCP6.0, and e) RCP8.5.

4.3. Frequency of mega-masts under modelled RCPs

The marginal rates model showed a slight increase in the frequency of mega-masts across the sequence of RCPs from 2.6 to 8.5 but this difference was not statistically significant as the confidence intervals for the hazard ratios all included one. The hazard ratios (RR) for mega-mast frequency for the RCPs (all relative to the reference scenario RCP2.6 with 95% confidence intervals in brackets) were: $RR_{4.5}$ = 1.05 (0.86–1.28); $RR_{6.0}$ = 1.10 (0.92–1.31); and $RR_{8.5}$ = 1.15 (0.92–1.45). A Poisson regression model was used to provide fitted estimates for the mean mega-mast frequency (since the marginal model does not fit the baseline hazard) under the different RCPs. The mean mega-mast intervals (I) for the RCPs (estimated as 1/ frequency with 95% confidence intervals in brackets) were: $I_{2.6}$ = 5.51 (4.48–6.88) years; $I_{4.5}$ = 5.26 (3.26–8.59) years; $I_{6.0}$ = 5.03 (3.13–8.18) years; and $I_{8.5}$ = 4.77 (2.98–7.75) years. The predicted intervals between mega-masts were just as variable between models (GCMs) as they were between RCPs. Also, the time between mega-masts was often predicted to be very long, up to 23 years, which is substantially different to the maximum interval of 6 years between the mega-masts predicted from observed temperatures for the 32-year period from 1974–2016.

Implications – Based on climate projections up to 2100, very widespread masts are likely to occur episodically regardless of which RCP most closely represents realised greenhouse gas concentrations (Fig. 7). This implies DOC needs to assume a continued requirement for episodic high-cost pest control programmes. Short intervals between mega-masts stretch the capacity to fund large-scale pest control programmes and, conversely, the potential for very long intervals between successive mega-masts may be difficult to manage across timeframes normally used for financial planning. Provision of contingency funds for managing mast-induced irruptions of pests could be based on approaches used for other natural events such as wildfires, floods, and earthquakes.

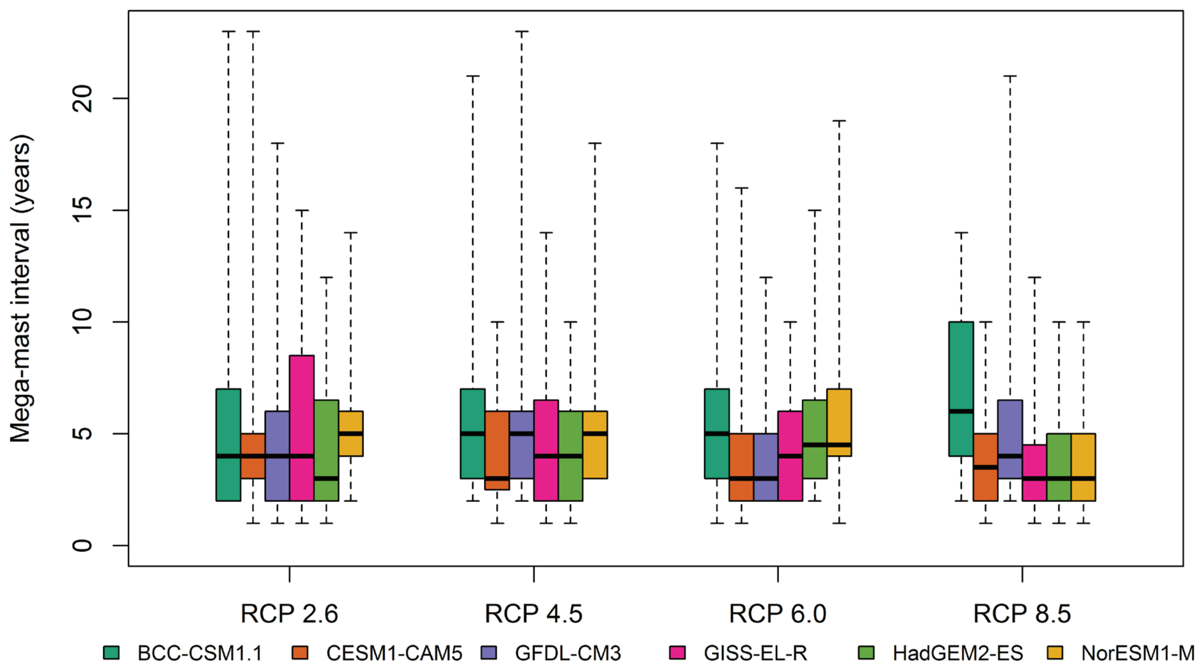

Figure 7: Predicted years between mega-masts under different RCPs (x-axis) and using different model climates (GCMs: coloured bars) for the projected period 2006–2100. Box plots show the median (solid horizontal bar), interquartile range (box) and the range (whiskers) of the mega-mast intervals.

4.4. Planning for pest control after mega-masts

There was a linear relationship between the costs of aerial 1080 control and the area covered, with a slope estimated at $17.50 per hectare (Fig. 8). These costs are only for operational expenses: additional costs of consultation and consenting can double costs to around $34 per hectare (S. Timmins, DOC, pers. comm.).

Over the period 2003–2013, which was before the availability of forecasts using the ΔT model, there was no significant relationship between the area predicted to mast and the area controlled by DOC using aerial 1080 baiting (Fig. 9). However, the forecast of a mega-mast year in 2014 contributed to a major change in DOC policy, which resulted in very widespread pest control to mitigate the impacts of rodents and stoats on native fauna ('Battle for our Birds').

Implications – DOC allocated additional resources for pest control following the mega-masts of 2014 and 2016. For example, 'Battle for our Birds 2016' received $20.7 million in new operating funding (press release from Office of the Minister of Conservation, 7 May 2016). However, the costs would be substantially higher if control was applied across the entire area of beech-dominated forest where a mast was predicted. Assuming $17.50 per hectare, pest control across the entire area of mega-masts over the last 40 years would have cost $42M–$68M per event. The temperature-based estimates of the spatial extent of masts highlight the potential costs of control in pest-affected forest.

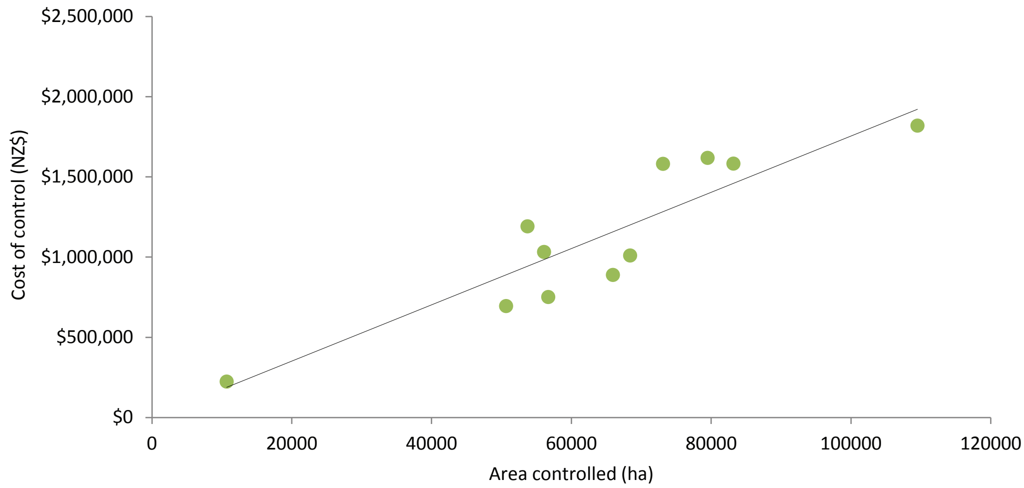

Figure 8: The annual cost of DOC pest control programs using aerially-delivered 1080 toxin (NZ$) versus the area subject to control for the years 2003–2013.

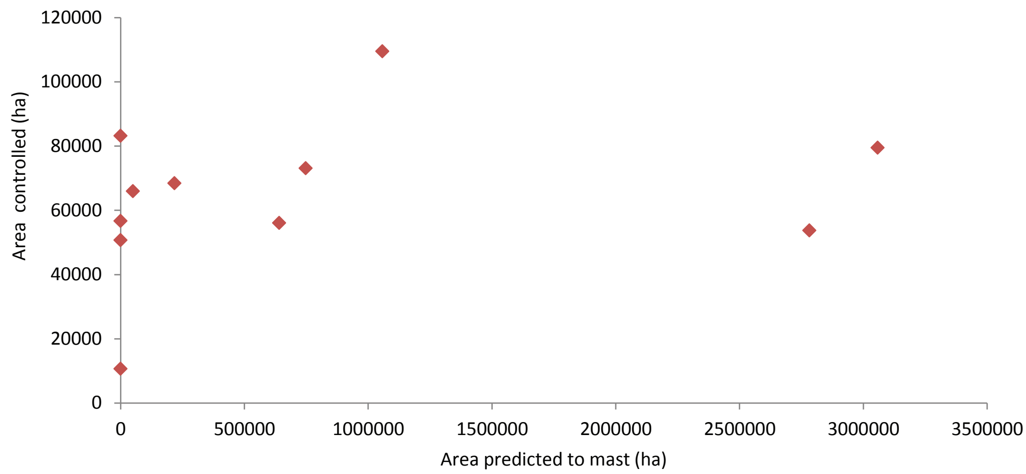

Figure 9: The area of the DOC estate subject to pest control using aerially-delivered 1080 toxin versus the area of beech forest predicted to mast using the ΔT model and VCSN air temperature data for the years 2003–2013.

5. DISCUSSION

The ΔT model has proved useful for short-term (1 year in advance) prediction of widespread masts and planning of pre-emptive pest control operations to mitigate predator irruptions. In the long-term (to 2100) the frequency of mega-masts is not predicted to increase significantly under any RCP scenario. However, even if mega-masts still occur at the same frequency, their episodic nature is challenging to manage within a financial system based on fixed annual budgets. We suggest that enough is known now about the risk and uncertainty of masting (i.e. one in every 4–5 years' chance of mast, with a one in every 50 years' chance of a double mast) to take an actuarial approach to the funding of managing mast-induced irruptions of pests similar to that used for other natural events such as wildfires and floods.

The successful application of the ΔT model for predicting masting in the short and long term is partly due to its simplicity – it requires few data inputs (summer air temperature) and those data are readily available over large spatial scales. The results presented in this report have focussed on forest ecosystems. The ΔT model is applicable to tussock grasslands where masts can generate irruptions of house mice and their predators. Further, there is evidence that the ΔT model is applicable to other masting systems in different countries. Examples include cone production by white spruce (*Picea glauca*) in boreal forests in Canada (Krebs et al. 2016) and pollen cone and seed production in Japanese cedar *Cryptomeria japonica* (Kon & Saito 2015). Long-term climate projections could be used to assess the implications of climate change for these areas.

Predictions of masting frequency depend on the assumed model structure and the GCM-derived climate inputs. Because ΔT is a difference model it removes any effect of trend in air temperature and is thus insensitive to the projected increase in mean summer temperature with increasing greenhouse gas concentrations. A trend of increasing seed production over the past 45 years has been detected at some mountain beech sites (Allen et al. 2014) and there is a perception that widespread (mega-) masts are becoming more frequent over time, with three occurring in the last decade. Refinements of the ΔT model have included a time trend or the addition of absolute summer temperature to capture this trend (G. Elliot & J. Griffiths, DOC, pers. comms). Other potential improvements to the ΔT model could include additional climate parameters such as rainfall which is thought to influence seedfall through increased resource availability (nitrogen for plant reproduction) with increasing soil moisture (Smaill et al. 2011). Adding climate covariates that show a trend with global climate change to the ΔT model will produce a trend in mega-mast frequency. Thus the predictions made in this report of no change in frequency with climate change may be optimistic at best.

Comparison of GCM-derived annual summer temperatures with those observed over the historic period (1973–2005) showed that the inter-annual variance in projected summer temperatures was not as great as that observed which necessitated a calibration of the estimated ΔT values to reproduce the observed frequency and extent of mega-masts. The El Niño-Southern Oscillation (ENSO) phenomenon is the dominant mode of climate variability on inter-annual time scales (Christensen et al. 2013) and limitations of the GCM models in modelling ENSO dynamics is the likely cause of this lack of variation in inter-annual summer temperatures. Further, there is large uncertainty about how ENSO dynamics will evolve under global climate change hampering predictive ability (Christensen et al. 2013). While all the GCM models predicted an increase in the variation in inter-annual summer temperature for the worst case scenario (RCP8.5), this was not enough to produce a statistical difference in predicted mega-mast frequency. If climate change reinforces ENSO dynamics there is potential for even greater inter-annual variation in summer temperatures and thus increased mast frequency.

Because of computational limitations, for each RCP downscaled climate projections were available from six simulations only (from each of 6 GCMs), limiting inference and the ability to make probabilistic assessments of the change in masting frequency. Ideally we would use an emulator such as the EPIC method (Ensemble Projections Incorporating Climate model uncertainty; Tait et al. 2016) to capture the full range of uncertainty in the climate model structure and parameter values and generate a probability density function for our ΔT predictions. However, these methods have not been sufficiently developed to handle spatial dependencies (each VCSN grid cell is treated independently) so cannot emulate the large-scale spatial synchrony typical of mast seedfall.

6. CONCLUSIONS

There was some indication of an increased frequency of masting with the highest greenhouse gas concentration pathway (RCP 8.5) however this increase was not statistically significant. The ΔT model, was useful for making short-term predictions of masting events based on observed air temperature. Its use for making long-term predictions based on climate projections was limited because it uses inter-annual temperature differences and the GCMs do not adequately capture ENSO dynamics which is the dominant driver of inter-annual variation in climate. For conservation managers, the prediction that masts (and associated pest irruptions) will continue to occur periodically at the same or greater rate, means that budgeting for pest control operations should take an actuarial approach.

7. REFERENCES

Allen, R. B., Hurst, J. M., Portier, J., & Richardson, S. J. (2014) Elevation-dependent responses of tree mast seeding to climate change over 45 years. Ecology and Evolution 4(18): 3525–3537. http://doi.org/10.1002/ece3.1210

Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie and T. Zhou (2013) Climate phenomena and their relevance for future regional climate change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1217–1308, doi: 10.1017/CBO9781107415324.028.

Holland, E.P., James, A., Ruscoe, W.A., Pech, R.P. and Byrom, A.E. (2015) Climate-based models for pulsed resources improve predictability of consumer population dynamics: outbreaks of house mice in forest ecosystems. PLoS ONE 10(3): e0119139.

Kelly, D., Geldenhuis, A., James, A., Penelope Holland, E., Plank, M.J., Brockie, R.E., Cowan, P.E., Harper, G.A., Lee, W.G., Maitland, M.J., Mark, A.F., Mills, J.A., Wilson, P.R., and Byrom, A.E. (2013) Of mast and mean: differential-temperature cue makes mast seeding insensitive to climate change. Ecology Letters 16(1): 90–98. doi:10.1111/ele.12020

Kon, H. and Saito, H. (2015) Test of the temperature difference model predicting masting behaviour. Canadian Journal of Forest Research 45: 1835–1844 dx.doi.org/10.1139/cjfr-2015-0118

Krebs, C.J., O'Donoghue, M., Taylor, S., Kenney, A.J., Hofer, E.J. and Boutin, S. (2016) Predicting white spruce cone crops in the boreal forests of the southern and central Yukon. Canadian Journal of Forest Research (in press).

Lawrence, J., Blackett, P., Cradock-Henry, N., Flood, S., Greenaway, A. and Dunningham, A. (2016) Synthesis Report RA4: Enhancing capacity and increasing coordination to support decision making. Climate Change Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 74 p.

McGlone, M., Walker, S. (2011) Potential effects of climate change on New Zealand's terrestrial biodiversity and policy recommendations for mitigation, adaptation and research. Science for Conservation 312. Department of Conservation, Wellington. 77 p.

Newsome, P. F. J. (1987) The vegetative cover of New Zealand. Published for the National Water and Soil Conservation Authority by the Water and Soil Directorate, Ministry of Works and Development, Wellington, N.Z.

Schauber, E. M., Kelly, D., Turchin, P., Simon, C., Lee, W. G., Allen, R. B., Payton, I. J., Wilson, P. R., Cowan, P. E. and Brockie, R. E. (2002) Masting by eighteen New Zealand plant species: the role of temperature as a synchronizing cue. Ecology 83: 1214–1225. doi:10.1890/0012-9658(2002)083[1214:MBENZP]2.0.CO;2

Smaill, S.J., Clinton, P.W., Allen, R.B., and Davis, M.R. (2011) Climate cues and resources interact to determine seed production by a masting species. Journal of Ecology 99: 870–877. doi:10.1111/j.1365-2745.2011.01803.x

Tait, A. (2008) Future projections of growing degree days and frost in New Zealand and some implications for grape growing. Weather and Climate, 28: 17–36.

Tait, A., Sood, A., Mullan, B., Stuart, S., Bodeker, G., Kremser S, and Lewis, J. (2016) Updated climate change projections for New Zealand for use in impact studies: Synthesis Report RA1. Climate Changes, Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. 18 p.

Tompkins, D. M., Byrom, A. E. and Pech, R. P. (2013) Predicted responses of invasive mammal communities to climate-related changes in mast frequency in forest ecosystems. Ecological Applications 23: 1075–1085. doi:10.1890/12-0915.1