

Appendix 1. LandClim – model description

Detailed descriptions of the full structure of LandClim are given in Schumacher (2004) and Schumacher et al. (2004, 2006). In order to explain the effect of biotic and abiotic drivers of vegetation dynamics, the following section provides a brief overview of the stand-level processes of LandClim.

The establishment, growth and mortality of trees are the three fundamental stand-scale processes considered by LandClim. The model tracks individual trees in the aggregated form of cohorts described by their biomass. Cohorts are groups of same-aged trees within a grid-cell (25×25 m) with all individuals having the same biomass (which can be translated into diameter at breast height (dbh) using the allometric given below in section ‘Growth’) and survival probability, but with mortality occurring at the individual level.

Establishment

For the representation of establishment, tree species are filtered by propagule availability and physical properties within each cell. Establishment in a cell is possible only in years where the light available at the forest floor exceeds a species-specific threshold value, winter temperature (mean temperature of the coldest month) is higher than a species-specific minimum temperature, and the sum of growing degree-days exceeds the species-specific minimum requirement. A species-specific establishment coefficient affects the probability of actual establishment. To reduce computational effort, the number and biomass of trees in any newly established cohorts are calculated decadal.

Growth

Maximum growth rates are assigned to each species (representing the growth rate under optimum environmental conditions), which are reduced by light availability, sum of degree days and drought. Actual tree growth is determined by a combination of these reduction factors under the application of Liebig’s ‘Law of the minimum’.

For conversion of the model biomass output into dbh, an allometric relationship was derived from individual-level data for *Weinmannia racemosa* (kāmahi) and *Dacrydium cupressinum* (rimu), reported by Beets et al. (2008):

$$d = 45.598 \times b^{0.399} \quad (\text{A1})$$

where: d = dbh (cm), and b = above-ground biomass (kg; assuming that 50% of dry trunk biomass is carbon).

Mortality

Tree mortality arises from three broad factors: (1) growth-dependent stress, (2) density-dependent stress, and (3) an intrinsic, age-related component. Growth-dependent stress occurs when the annual growth rate drops below a species-specific threshold value due to unfavourable environmental conditions. Stress-related mortality probability increases after a minimum number of consecutive low-growth years accumulate. Density-dependent mortality occurs only if total stand biomass exceeds the maximum stand biomass in a given cell. Age-dependent mortality increases with tree age. The probability of an individual tree dying is given by the maximum of these three probabilities.

New Zealand’s temperate forests can attain substantial amounts of standing biomass per area (Wardle 1991), exceeding

those of central European forests. Therefore the maximum stand biomass was increased from 300 to 1000 t ha⁻¹. This increased limit to standing biomass effectively reduces the probability of density-dependent mortality.

Appendix 2. Parameterisation of tree species life-history traits

maxAge

The parameter ‘maxAge’ characterises the expected longevity of a tree species (Bugmann 1994; Schumacher et al. 2004). For the Hauhungatahi species, the maximum age was assigned based on the age estimates of oldest individuals given by the following studies: Ogden et al. (2005) for *L. bidwillii* (1000 years), Smale and Smale (2003) for *P. cunninghamii* (650 years), Lusk and Ogden (1992) for *W. racemosa* (400 years). A value of 800 years was assigned to *D. cupressinum* since a wide range of maximum ages have been reported (500 up to 1000 years; Lusk & Ogden 1992). An estimated maximum age of 150 years was assigned to the tree-fern life form.

Shade-tolerance

Species’ shade-tolerance was expressed in classes between 1 and 5, with 1 denoting the least shade-tolerance (following the classification given by Ellenberg and Strutt (2009)). These classes define species-specific minimum light requirements (see Schumacher 2004, p. 122, table B.3). Shade-tolerance classes for the tree species of Mt Hauhungatahi were determined via the pattern-oriented parameterisation approach.

R_{max}

The parameter ‘R_{max}’ determines the maximum above-ground biomass growth rate per year, and is expressed relative to the maximum biomass of a tree species. The ranges for R_{max} were determined by the pattern-oriented parameterisation approach and the refined sensitivity analysis. For comparing model results with empirical measurements, average growth rates were determined by a linear regression of the age–dbh data for both empirical and model data. The empirical sources for growth data were: Ogden et al. (2005) for *L. bidwillii* (mean annual growth rate of 0.125 cm year⁻¹), Lusk and Ogden (1992) for *W. racemosa* (0.209 cm year⁻¹) and *D. cupressinum* (0.124 cm year⁻¹), Smale and Smale (2003) for *P. cunninghamii* (0.15 cm year⁻¹).

K_{max}

Maximum biomass of an individual tree (K_{max}) was estimated from an allometric relationship given in Hall et al. (2001), relating dbh and height to biomass. Unless otherwise noted, values of mean maximum tree height were taken from the ecological traits database (Landcare Research 1996–2005); maximum dbh values were taken from the electronic version of the *Flora of New Zealand* (Landcare Research no date). For *P. cunninghamii*, the dbh value reported in Russo et al.’s (2007) table S1 was used. For *D. cupressinum*, both dbh and height values were derived from the *Flora of New Zealand* (Landcare Research no date). Since several maximum heights were reported, the standard maximum height listed in the ecological traits database was assumed and the resulting K_{max} value rounded to the nearest whole number. For *L. bidwillii*, the dbh and height values given in the Flora and ecological trait

databases (Landcare Research 1996–2005, no date) resulted in a K_{\max} value of 3.92. Since *L. bidwillii* did not occur in the carbon stock assessment report of Beets et al. (2008), we used the maximum dbh values given by Ogden et al. (2005) as calibration targets and found that with $K_{\max} = 3.92$ LandClim significantly underpredicted dbh (with a maximum around 60 cm, compared with the 100+ cm observed by Ogden et al. (2005)). Therefore, K_{\max} was increased to 8, which resulted in a more reasonable maximum dbh of 90–100 cm. Preliminary test scenarios using a wide range of K_{\max} values for *L. bidwillii* showed that the model was reasonably robust to changes in this parameter's value.

Leaf habit

The 'LeafHabit' distinguishes between 'evergreen', 'broadleaved evergreen' and 'deciduous' species (Schumacher 2004). Classes were assigned according to leaf morphology information given in the ecological traits database (Landcare Research 1996–2005).

Foliage type

Foliage type is a parameter ranked in five classes that determines the shading potential of a tree species. An allometric function is applied that scales from foliage characteristics to the shade cast by a tree individual (via tree size expressed as dbh). We estimated the foliage type based on information about leaf morphology given in the ecological traits database (Landcare Research 1996–2005) and from expert opinion about the species' canopy structure and shading potential.

Min temperature

This parameter determines the minimum temperature (°C) for species establishment (Bugmann 1994). We used the freezing resistance reported by Sakai and Wardle (1978) to assign this trait to *L. bidwillii*, *D. cupressinum*, *P. cunninghamii* and *W. racemosa*. For the tree-fern life form the same minimum temperature as *W. racemosa* (−7°C) was assumed.

minDD

The minimum annual degree day sum ('minDD') parameter expresses a species' temperature requirements for growth (see also Bugmann (1994) for further explanations of the degree day concept). It was assumed that upper limits of tree species of Mt Hauhungatahi were determined by temperature. Therefore the parameter 'minDD' was calibrated in order to fit the observation of upper species elevational limits by Druitt et al. (1990). For this purpose, each species was simulated under monocultural conditions with a range of possible minimum degree day values (between 1060 and 2200, as suggested by Hall and McGlone (2006)). For comparability with measurements of Druitt et al. (1990), only individuals with a dbh > 10 cm were considered.

Appendix 3. Parameterisation of the tree-fern life form

Demographic and allometric data for tree-fern species are very scarce. Because tree-ferns are monocots they do not show secondary thickening, making the development of the allometric relationships that underpin forest gap models difficult. This, in turn, can have substantial effects on the simulated competition for light resources. To overcome these

restrictions, tree-ferns were not simulated as a specific species but as a more general life form drawing on information provided by Beets et al. (2008), Ogden et al. (1997) and Bystriakova et al. (2011).

At Mt Hauhungatahi, the dominant tree-fern species is *Cyathea smithii* (Druitt et al. 1990). Therefore the life-history traits of the tree-fern life form were modelled on the ecology of *Cyathea smithii*. Bystriakova et al. (2011) investigated the ecological differences between tree-fern species in terms of shade-tolerance and growth rates and found that *Cyathea smithii* and *C. dealbata* were the slowest growing and most shade-tolerant species. Therefore the tree-fern life form was implemented as a slow-growing, shade-tolerant species.

Growth estimates given by Ogden et al. (1997) were used to determine growth rates of the tree-fern life form. Ogden et al. (1997) report average height increments for the slowest growing tree-fern (*Cyathea dealbata*) of approximately 5 cm per year, which was used as a target for parameterisation of R_{\max} . In order to convert Ogden et al.'s height-growth estimates into biomass growth, a highly simplified allometric relationship was derived from the data given by Beets et al. (2008) (Eq. A3):

$$b = \frac{h}{0.289} \quad (\text{A3})$$

where: b = total above-ground biomass (kg) and h = height (m).

For the conversion function (Eq. A3), it was assumed that tree-ferns maintain a constant diameter during their lifespan and as a result above-ground-biomass acquisition can be translated into height growth via a linear relationship.

References

- Beets PN, Oliver GR, Kimberly MO, Pearce SH 2008. Allometric functions for estimating above ground carbon in native forest trees, shrubs and tree ferns. Scion Client Report No. 12679. 63 p.
- Bugmann H 1994. On the ecology of mountainous forests in a changing climate: a simulation study. PhD thesis no. 10638, Swiss Federal Institute of Technology, Zurich, Switzerland. 252 p.
- Bystriakova N, Bader M, Coomes DA 2011. Long-term tree fern dynamics linked to disturbance and shade tolerance. *Journal of Vegetation Science* 22: 72–84.
- Druitt DG, Enright NJ, Ogden J 1990. Altitudinal zonation in the mountain forest of Mt Hauhungatahi, North Island, New Zealand. *Journal of Biogeography* 17: 205–220.
- Ellenberg H, Strutt GK 2009. *Vegetation ecology of Central Europe*. 4th edn. Cambridge University Press. 756 p.
- Hall GMJ, McGlone MS 2006. Potential forest cover of New Zealand as determined by an ecosystem process model. *New Zealand Journal of Botany* 44: 211–232.
- Hall GMJ, Wiser SK, Allen RB, Beets PN, Goulding CJ 2001. Strategies to estimate national forest carbon stocks from inventory data: the 1990 New Zealand baseline. *Global Change Biology* 7: 389–403.
- Landcare Research 1996–2005. *Ecological Traits of New Zealand Flora database*. Available at: <http://ecotraits.landcareresearch.co.nz/>
- Landcare Research No date. *Flora of New Zealand Series* [online]. Available at: <http://floraseries.landcareresearch.co.nz/pages/index.aspx> (accessed 2011).

- Lusk CH, Ogden J 1992. Age structure and dynamics of a podocarp-broadleaf forest in Tongariro National Park, New Zealand. *Journal of Ecology* 80: 378–393.
- Ogden J, Braggins J, Stretton K, Anderson SH 1997. Plant species richness under *Pinus radiata* stands on the Central North Island volcanic plateau, New Zealand. *New Zealand Journal of Ecology* 21: 17–29.
- Ogden J, Fordham RA, Horrocks M, Pilkington S, Serra RG 2005. Long-term dynamics of the long-lived conifer *Libocedrus bidwillii* after a volcanic eruption 2000 years ago. *Journal of Vegetation Science* 16: 321–330.
- Russo SE, Wisser SK, Coomes DA 2007. Growth-size scaling relationships of woody plant species differ from predictions of the Metabolic Ecology Model. *Ecology Letters* 10: 889–901.
- Sakai A, Wardle P 1978. Freezing resistance of New Zealand trees and shrubs. *New Zealand Journal of Ecology* 1: 51–61.
- Schumacher S 2004. The role of large-scale disturbances and climate for the dynamics of forested landscapes in the European Alps. PhD thesis no. 15573, Swiss Federal Institute of Technology. Zurich, Switzerland. 141 p.
- Schumacher S, Bugmann H, Mladenoff DJ 2004. Improving the formulation of tree growth and succession in a spatially explicit landscape model. *Ecological Modelling* 180: 175–194.
- Schumacher S, Reineking B, Sibold J, Bugmann H 2006. Modeling the impact of climate and vegetation on fire regimes in mountain landscapes. *Landscape Ecology* 21: 539–554.
- Smale MC, Smale PN 2003. Dynamics of upland conifer/broadleaved forest at Waihaha, central North Island, New Zealand. *Journal of the Royal Society of New Zealand* 33: 509–528.
- Wardle P 1991. *Vegetation of New Zealand*. Cambridge University Press. 672 p.