

**Implications of Changes in Albedo on the Benefits of Forests as
Carbon Sinks – Parameters for Assessing the Importance of
Indirect Effects**

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Summary

Project and Client

The implications of changes in albedo on the benefits of New Zealand *Pinus radiata* forests as carbon sinks were assessed by Landcare Research in collaboration with NIWA and Scion for the Ministry of Agriculture and Forestry in June 2008.

Main Findings

This report is part of a collaborative project with Dr Sam Dean of NIWA. Landcare Research's contribution to the project was the provision of relevant parameters to describe the properties of canopies of grassland and native and exotic forests. These parameters then enable Dr Dean to conduct a series of simulation runs with which the quantitative significance of indirect factors associated with land-use change can be assessed. Each of the key parameters is described in the following report, with the best values having been obtained from the available literature.

1. Introduction

Land-cover change has both direct and indirect consequences for the net energy balance of the earth and through that for global warming. Increased carbon storage resulting from afforestation of pasture lowers the atmospheric carbon dioxide concentration and thus cools the atmosphere. However, forests are usually darker than pastures which means that they absorb more incoming solar radiation. That increased radiation absorption warms the atmosphere.

In addition to these direct consequences, different vegetation types also have indirect consequences, principally related to different amounts of water vapour evaporated by different canopies, with forests usually transpiring more water than pasture canopies, which increases atmospheric humidity. Increases in atmospheric humidity trap more outgoing long-wave radiation and thus have a warming effect. On the other hand, increased humidity also increases cloud cover, and with clouds having a high albedo, they reflect a greater proportion of incoming solar radiation and have a cooling effect.

In the past, assessments of the value of using forests as a climate-change mitigation option have considered only the carbon storage benefit, but for a full assessment of the overall greenhouse mitigation benefit of planting forests, all radiatively relevant components need to be considered together. The present work is part of such a wider and more comprehensive assessment.

2. Background and Objectives

The direct consequences of planting *Pinus radiata* forests as carbon sinks in New Zealand were assessed by Landcare Research in collaboration with NIWA and Scion in a project supported by the Ministry of Agriculture and Forestry earlier in 2008. The findings have been described in a report by Whitehead et al. (2008; Landcare Research Contract Report LC0708/152). This report showed that the cooling through carbon storage can be offset by increased warming through greater surface radiation absorption by about 10–20%, averaged over the rotation period.

Indirect consequences of forest planting relate to modification of the water cycle that may change cloud formation and other atmospheric properties possibly thousands of kilometres away from the site where the difference in atmospheric composition originates. An assessment of these effects must therefore involve large-scale modelling over a scale that is large enough to capture these very distant off-site effects.

Such a model will be run by NIWA to capture, in a simplified manner, the entire land surface and atmospheric direct and indirect effects relevant to quantifying local temperature change associated with changing albedo. In this second report, we provide the appropriate parameters needed to run such a regional climate model (which will be done by Sam Dean, NIWA).

The key parameters required to run the model are:

- Classification of vegetation and land capability
- Rooting depth
- Estimates of surface albedo
- Estimate of deep snow albedo
- Surface conductance to evaporation
- Canopy height
- Vegetation roughness length
- Surface capacity to hold water
- Leaf area index
- Vegetation fractional ground cover
- Soil infiltration

3. Key Model Parameters

3.1 Classification of vegetation and land capability

The original intention was to run a regional climate model over New Zealand with four notional vegetation types to cover the whole country: native forest, exotic forest, managed pasture and unmanaged pasture. The intent was to simulate the combined effect of all atmospheric consequences in terms of the atmospheric water cycle and changes to the radiation budget of covering all of New Zealand with these different vegetation classes.

After some consideration, it was decided to exclude unmanaged pasture from the list of vegetation types because it would be unrealistic to run a scenario of unmanaged pasture for regions with good climatic conditions. Without management, vegetation in New Zealand would revert to native forest in regions with good climate and soils and to native grasslands (tussocks and grasses) in regions with poor soils or harsh climatic conditions. The current properties of native grasses, such as having a low leaf area index, are thus typical of growth in a marginal environment. If those same plants were to grow under more fertile conditions, or in a more benign climate, they would be expected to develop a higher leaf area. The properties observed in their actual habitat would thus no longer be representative of their new habitat. Without management, they would then also be replaced by native forest. So, it would be unrealistic to try and model unmanaged pasture with its currently observed properties for more productive sites across New Zealand.

The converse also applies in that forests, in particular, would not be able to grow in some of the more climatically marginal areas of New Zealand, especially at the higher elevations in the South Island.

Figure 1 classifies all of New Zealand into forest, pasture, forest/pasture mixtures or tussock grassland. Small areas also currently support orchards or horticulture and would be suitable for any land use, or, conversely, are classified as unsuitable for forest or pasture consisting of wetlands, sand dunes, heathlands or alpine and subalpine vegetation.

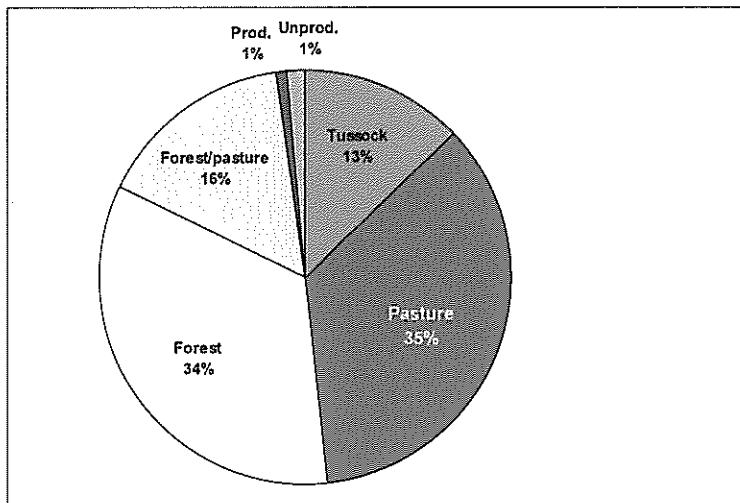


Fig. 1 Vegetation classification in New Zealand into six broad classes with respect to their suitability to support forest or pasture (after Newsome 1987).

Much of New Zealand currently supports a mixture of vegetation, with grasslands mixed in with some remnant or emerging trees. The designation as forest, grassland or forest/pasture thus becomes somewhat arbitrary, but the important information of Fig. 1 is that about 86% of New Zealand could potentially support either managed pasture or exotic or indigenous forest, with 14% classified as being unsuitable to support forest or managed pasture for mainly climatic reasons.

The mapping of the land classifications given in Fig. 1 is shown in Fig. 2. This classification allows land-use changes to be applied only to the 86% of the country where such a change would be biophysically realistic.

3.2 Rooting depth

Actual rooting depth is a function of both vegetation type and the depth of the soil to bedrock or to an otherwise inaccessible layer. Pasture could be considered to have maximum effective roots depths of 0.6 m (Breuer et al. 2003), while trees, both native trees and *Pinus radiata*, can have root systems extending to several metres depth (Breuer et al. 2003). In practice, these depths are often curtailed by the shallowness of many soils that do not allow this biological potential of trees to be fully expressed.

For the data used here, soil depths have been taken from the National Soils Database. For trees, rooting depth was taken to be equivalent to soil depth. For pastures, rooting depth was calculated as the lesser of the soil depth and an assumed maximum depth of 0.6 m.

In using these values, it needs to be recognised, however, that the data contained within the National Soils Database are limited to a maximum depth of 1.2–1.5 m because there is insufficient information for constructing national surfaces for depths deeper than 1.5 m. It is well recognised, however, that there are many soils that extend to greater depths, but the paucity of actual measurements has prevented the construction of more detailed soils maps that would express that. It is, therefore, important to recognise that the 1.2–1.5 m depth actually means a depth > 1.2 m.

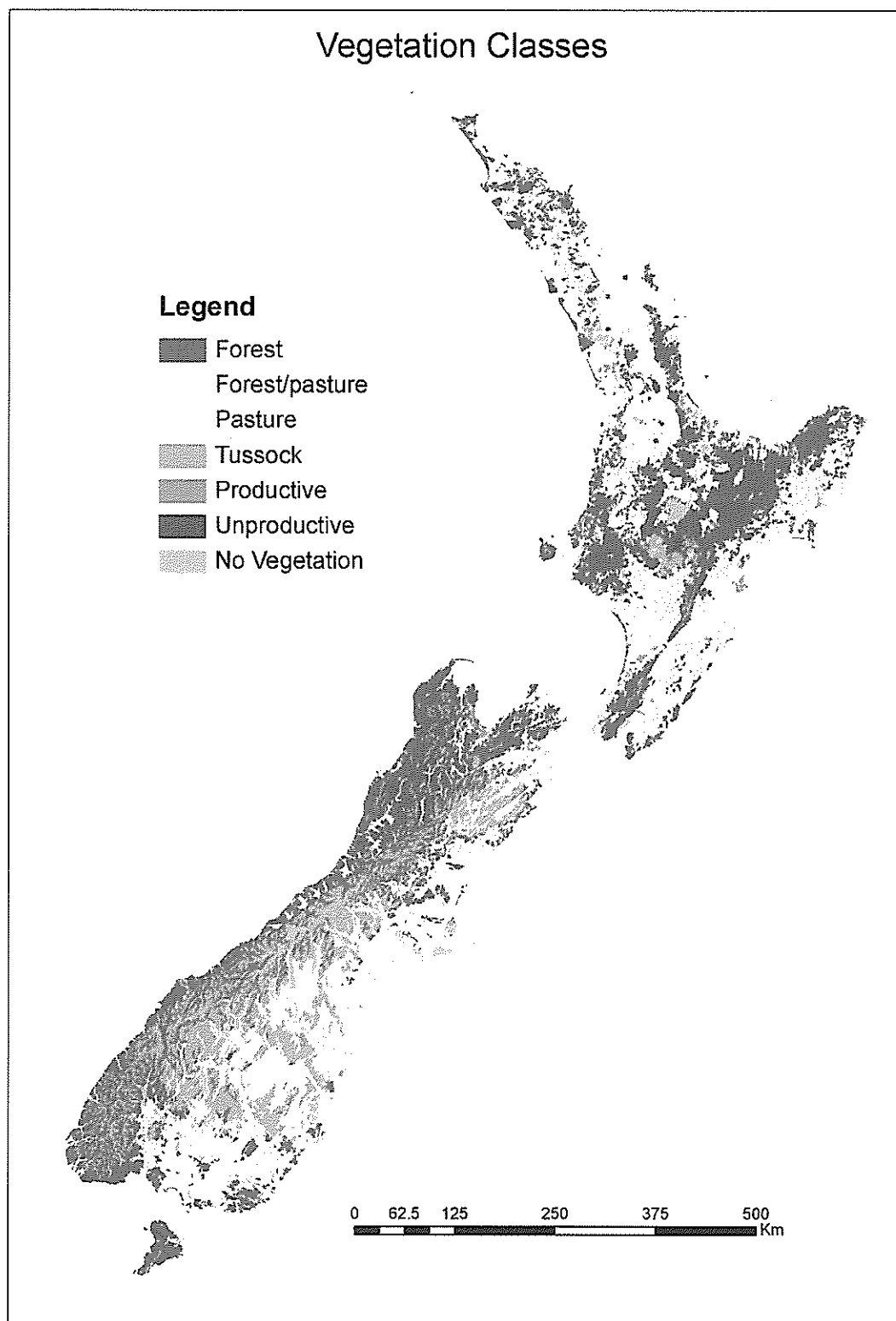


Fig. 2 Map of vegetation classification in New Zealand into six broad classes with respect to their suitability to support forest or pasture (after Newsome 1987). Data classes are the same as summarised in Fig. 1.

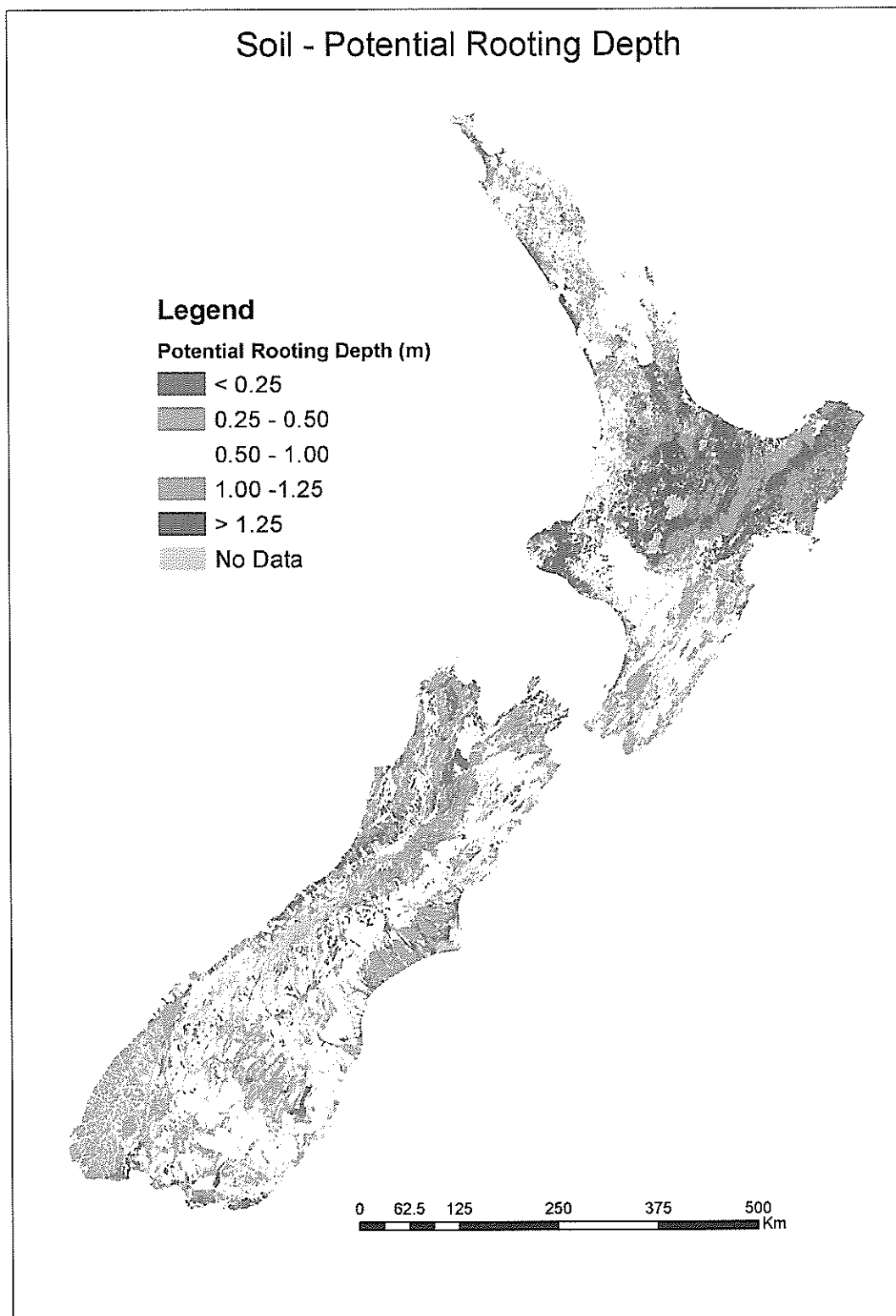


Fig. 3 Potential rooting depth derived from fundamental soils layers from the National Soils Database.

3.3 Estimates of surface albedo

Surface albedo was obtained from satellite-based measurements for homogenous units of the respective vegetation types throughout New Zealand. Data vary with time of year, location and due to additional random factors. The albedo data in this section are calculated for solar noon, but there is also variation throughout the day (Fig. 4).

Albedo tends to be higher earlier and later in the day when solar elevations are low. There is a fairly broad flat area of relatively low values for albedo around solar noon, and they increase towards fairly high values near sunrise and sunset. Since most radiation is received over the few hours either side of noon, radiation-weighted daily average values of albedo are only approximately 5% higher than noon values. An exact quantification of the ratio of noon to all-day values of albedo is given in Table 1.

Figure 5 shows satellite-derived estimates of direct-beam surface albedo for managed pasture, native forest and exotic forest. Data have been summed over polygons in New Zealand that have been identified as consisting of the same vegetation type throughout the identified area. The data are thus aiming to provide a New Zealand-wide estimate of albedo of the respective vegetation types.

Raw data obtained from MODIS provided observed reflectance at known sun and satellite angles. These data were processed with a BRDF (Bidirectional Reflectance Distribution Function) to estimate albedo at the known sun angle throughout the year and with reflectance over the integral of all outgoing angles (Dymond et al. 2001). The BRDF was also used to estimate the albedo of diffuse radiation (see below).

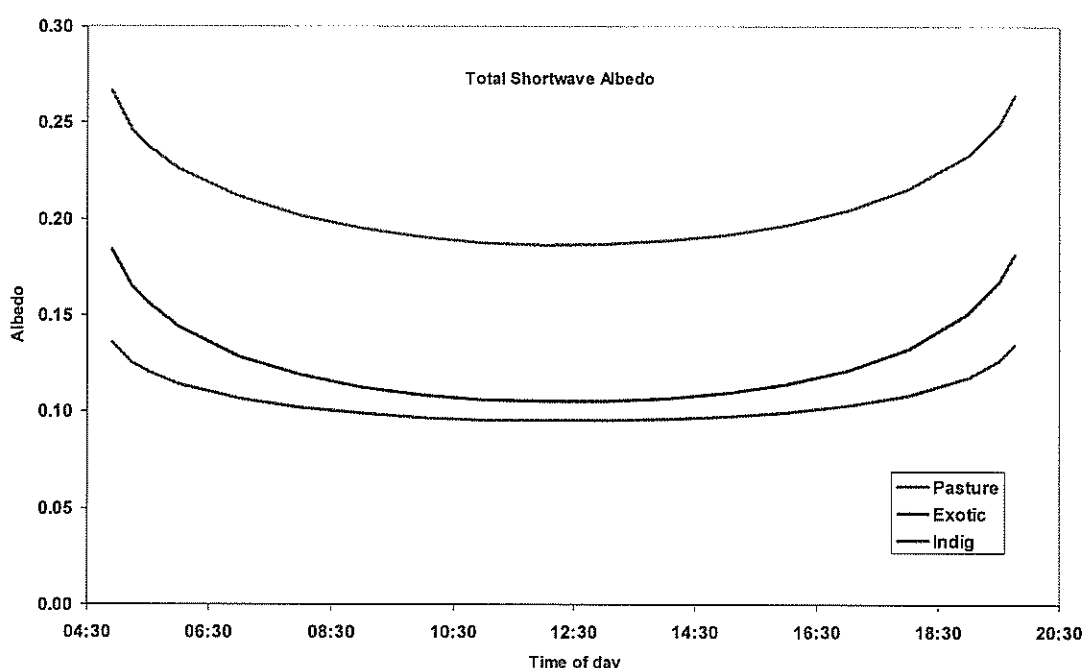


Fig. 4 Daily variation in short-wave albedo for managed pasture, native and exotic forests derived from MODIS satellite observations. Modelled curves are for data on 1 January.

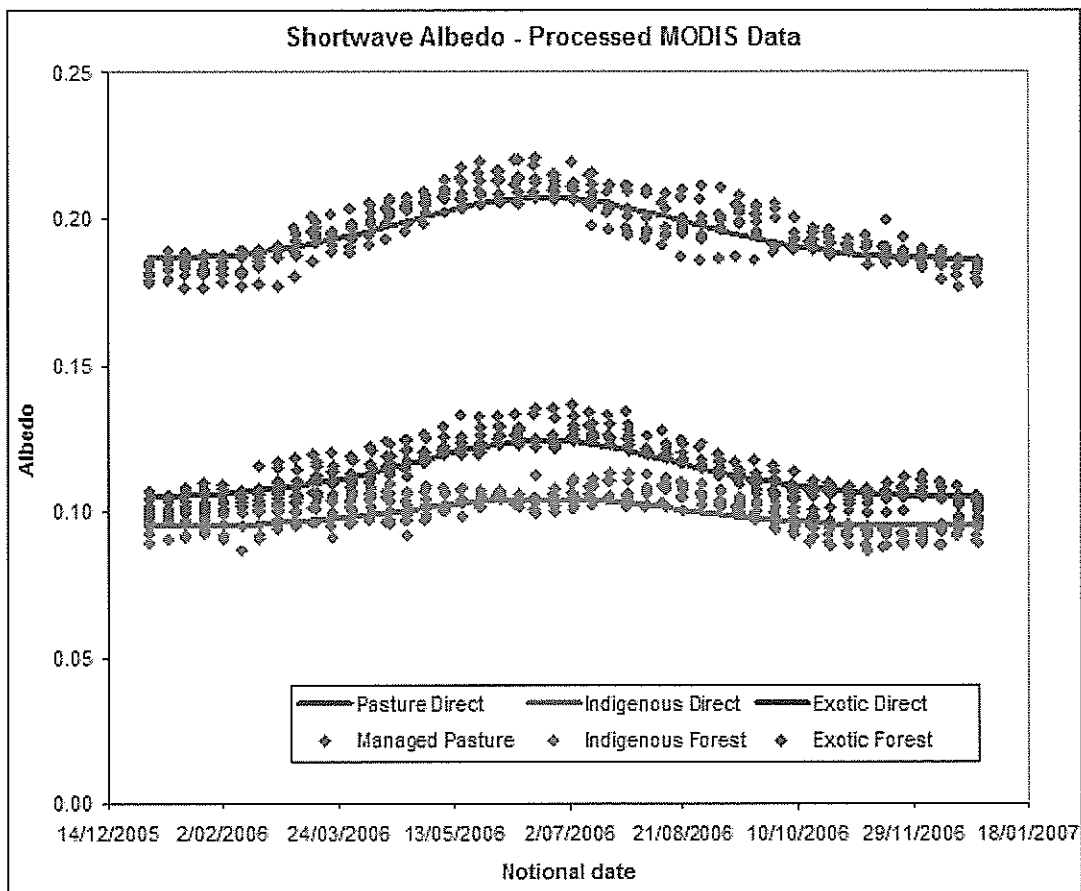


Fig. 5 Direct-beam short-wave albedo for managed pasture, native and exotic forests derived from MODIS satellite observations. Data were obtained over 8 years, but are all plotted here for the same (notional) year for ease of separating out the seasonal changes. Solid lines show curves fitted to the data, with parameters given in Table 1.

Data were collected from 2000 to 2008 and generally obtained every 8 days. The scatter apparent in Fig. 5 is due to year-to-year variations in measured values because of random variations and some slight changes in physiological conditions of plant canopies. The parameters of the BRDF are not changed throughout the year so that it describes only the dependence of reflectance on the changing angle of the sun and differing outgoing angles, but is not responsive to physiological changes throughout the year.

Visual checking of the data ensured that the full extent of each polygon remained within the specified vegetation class over the whole observation period. That was particularly important for exotic forest, which is typically harvested at the end of a rotation period of 25–30 years. During harvesting and the subsequent growth of a new stand, albedo tends to change significantly, with a general darkening as canopies close during the first few years after planting and as stands continue to grow towards maturity. The data shown here thus correspond to an average over the growth of stands but exclude periods during harvesting and over any possible fallow period between rotations.

The data, especially for pasture, and to a somewhat lesser extent for exotic forest, show some seasonality, with highest values over the winter months. That pattern is due to the changing

angle of incoming solar radiation and is well described by the fitted model. Part of the seasonal variation is due to phenological factors (such as new shoot growth) and irregular seasonal patterns, such as drying in late summer in some years. These patterns are more apparent in data where visible and near-infrared (NIR) radiation are separated (Figs 6 and 7).

Reflectance of visible radiation shows greater relative variability than total short-wave radiation. As the absorption and reflectance of visible light is primarily dependent on the presence of chlorophyll, it is strongly affected by changes in the physiological condition of leaves. The highest summer values for pasture, for example, were obtained in February 2008, and correspond to the drought experienced over much of New Zealand in that year.

Reflectance of near-infrared radiation is much higher than that of visible light, with 35% of NIR radiation (Fig. 7) reflected by pasture canopies compared with only 5% of visible radiation (Fig. 6). Since there are about equal proportions of visible and NIR radiation in incoming sunlight, the albedo of total short-wave radiation is approximately the average of the NIR and visible values for albedo, or about 20% for pasture (Fig. 5). The calculated short-wave-radiation values given here have been calculated with the algorithm of Liang (2001) that is based on an exact quantification of the contribution of each wavelength band to total incoming solar radiation.

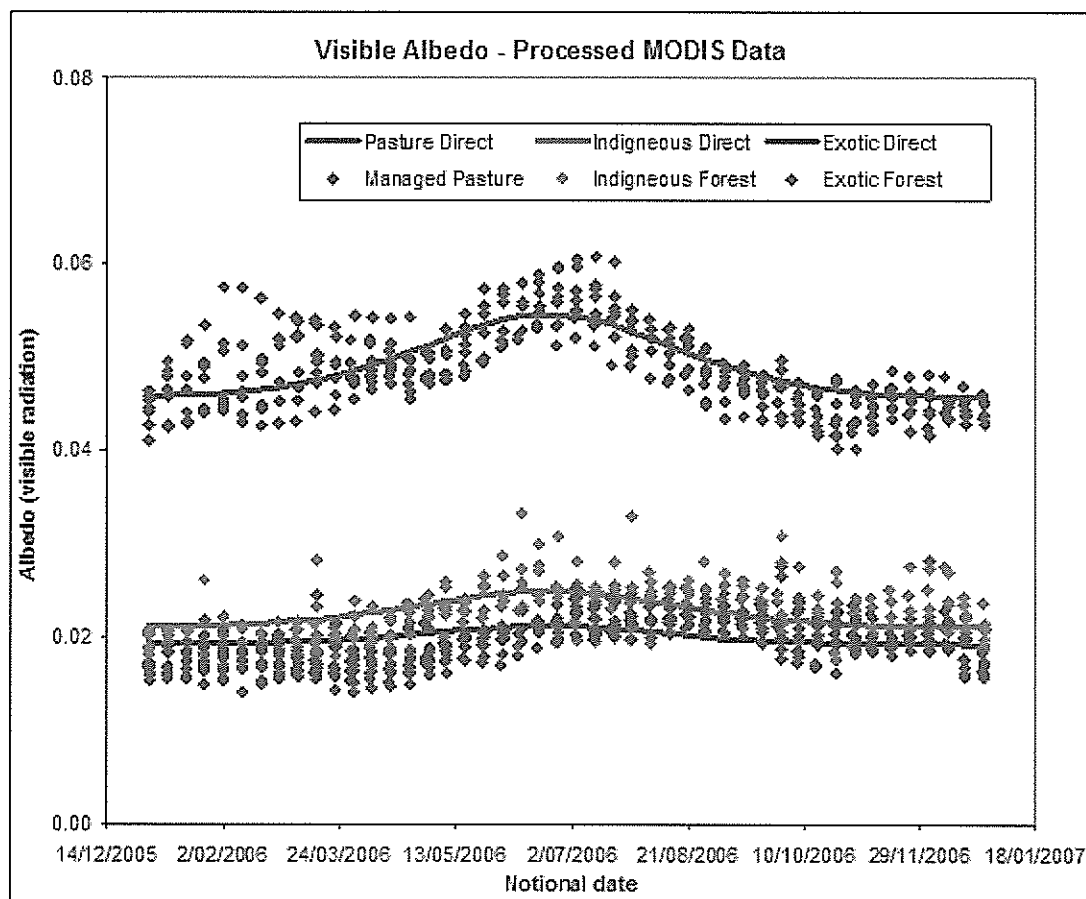


Fig. 6 Direct-beam visible radiation albedo for grasslands, native and exotic forests derived from MODIS satellite observations. Note the different scale from Fig. 5. Solid lines show curves fitted to the data, given here for better visualisation of seasonal trends.

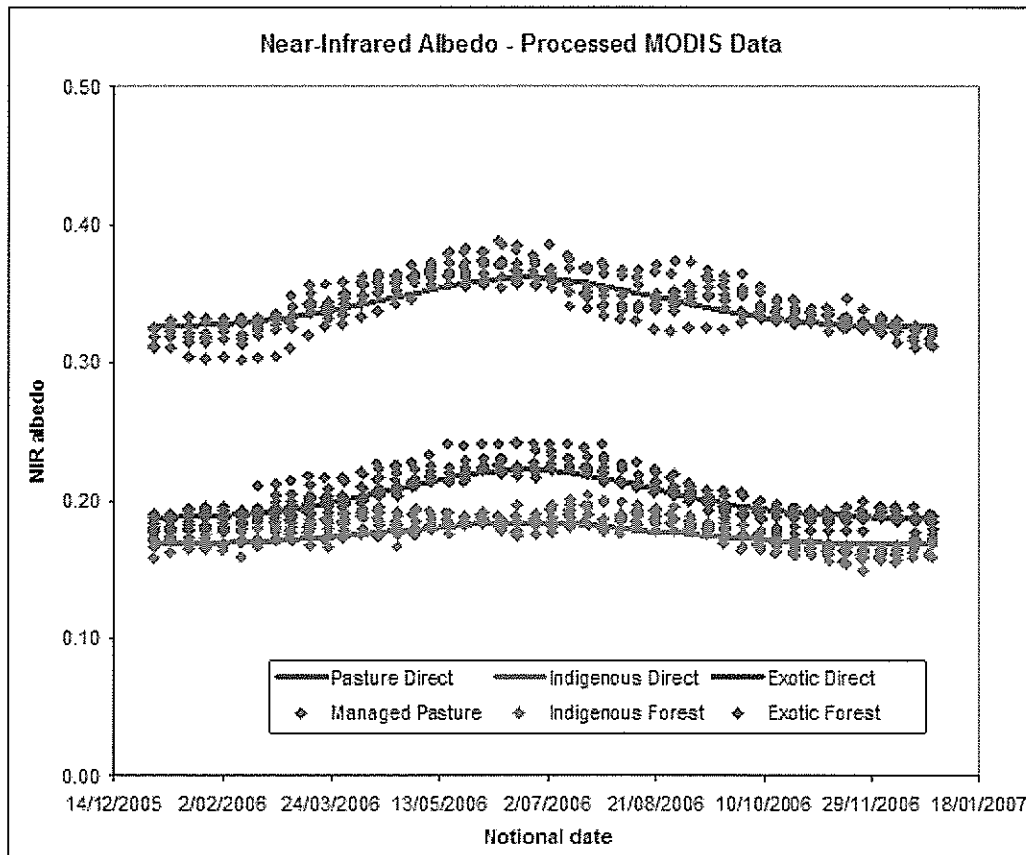


Fig. 7 Direct-beam near-infrared (NIR) radiation albedo for grasslands, native and exotic forests derived from MODIS satellite observations. Solid lines show curves fitted to the data, given here for better visualisation of seasonal trends. Note the different scale from Figs 5 and 6.

Satellites can observe radiation reflectance from the ground only under cloud-free conditions. Otherwise, the measured reflectance would be determined by the reflectance of clouds rather than the properties of the ground surface. To complete the reflectance under all conditions, it is therefore necessary to calculate reflectance under cloudy, or diffuse-radiation, conditions as well. The same BRDF model can be used as before, but in this case, an integration is performed not only over the range of angles at which radiation can be reflected, but also over all possible angles over which radiation can be received (Fig. 8).

While the albedo of direct-beam radiation varies with the angle of the sun, the albedo of diffuse radiation is constant throughout the year and numerically quite similar to the average of the seasonally varying albedo of direct beam radiation. Average values of albedo for the three vegetation types are given in Table 1.

The seasonal pattern in direct-beam short-wave albedo, α , for the three vegetation types can be described as:

$$\alpha_{in} = 0.09865 + 0.0046 [\sin(2 \pi d/365 + 4.88)] - 0.0009 [\sin(4 \pi d/365 + 5.06)] \quad (1)$$

$$\alpha_{ex} = 0.1127 + 0.0092 [\sin(2 \pi d/365 + 4.88)] - 0.00194 [\sin(4 \pi d/365 - 1.22)] \quad (2)$$

$$\alpha_{mp} = 0.1949 + 0.01032 [\sin(2 \pi d/365 - 1.405)] - 0.0019 [\sin(4 \pi d/365 - 1.22)] \quad (3)$$

where d is the day of the year.

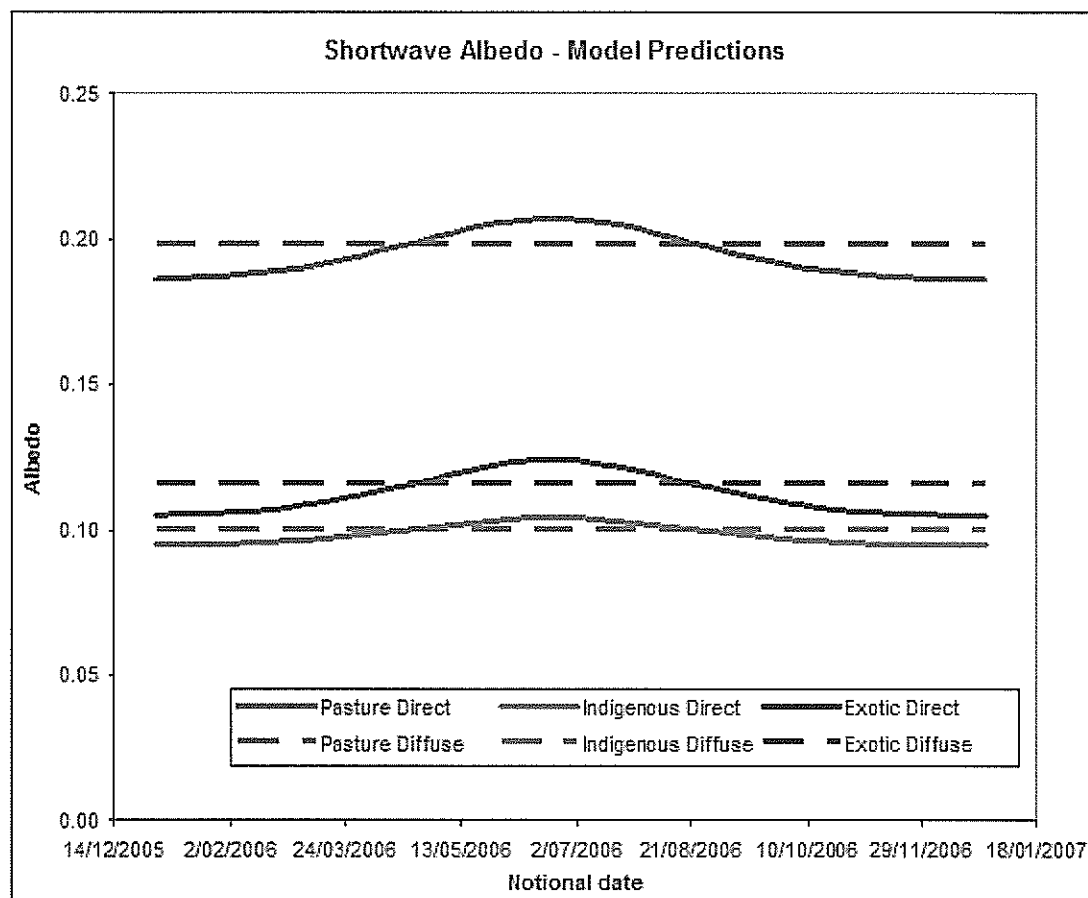


Fig. 8 Direct-beam and diffuse-radiation values of albedo for grasslands, native and exotic forests derived from MODIS satellite observations.

Table 1 Annually averaged direct-beam and diffuse radiation values of albedo in the visible, near-infrared (NIR) and combined short-wave bands for grasslands, native and exotic forests derived from MODIS satellite observations. The ratio of daily to noon albedo was calculated for 1 January by weighting each hourly albedo (Fig. 4) by an estimate of incoming solar radiation at that time. All-day albedo is calculated by multiplying the noon direct-beam albedo by the ratio of daily to noon albedo.

	Indigenous forest			Exotic forest			Managed pasture		
	Visible	NIR	Short	Visible	NIR	Short	Visible	NIR	Short
Direct beam	0.023	0.175	0.099	0.020	0.202	0.113	0.049	0.341	0.195
Daily : noon albedo	1.078	1.038	1.042	1.043	1.077	1.075	1.082	1.045	1.047
All day albedo	0.025	0.182	0.103	0.021	0.218	0.121	0.053	0.356	0.204
Diffuse radiation	0.023	0.178	0.101	0.020	0.208	0.116	0.051	0.346	0.198

3.4 Estimate of deep snow albedo

There are no values for snow albedo specific for New Zealand. It is therefore suggested to use an established relationship from the literature. Betts (2000) calculated albedo, α , as:

$$\alpha = \alpha_0 + (\alpha_D - \alpha_0) (1 - e^{-0.2S}) \quad (4)$$

where α_0 is snow-free albedo as given above, α_D is a temperature-dependent snow albedo, and S is snow mass in millimetres rain equivalent or kg m^{-2} .

The temperature-dependent snow albedo is calculated as:

$$\alpha_D = \alpha_s \text{ if } T_s < -\Delta T \quad (5)$$

$$\alpha_D = \alpha_s + 0.3 (\alpha_0 - \alpha_s)(T_s + \Delta T) / \Delta T \text{ if } -\Delta T < T_s < 0 \quad (5a)$$

where α_s is the deep-snow albedo for different vegetation types, T_s is surface temperature in $^{\circ}\text{C}$, and ΔT is temperature range over which snow albedo changes due to partial melting. Betts (2000) used a temperature of 2°C for ΔT and values for deep-snow albedo for cropland and ‘dense coniferous forest’ of 0.78 and 0.26, respectively.

We suggest that a value of 0.78 is equally applicable for snow-covered pastures, that ‘dense coniferous forest’ adequately describes New Zealand exotic forests, and that the same value can also be used for New Zealand’s evergreen native forests.

3.5 Surface conductance to evaporation

Surface conductance is defined as the mean stomatal conductance integrated over the whole plant canopy. Conductance is the preferred term and numeric expression typically used in plant physiological work. Resistance is simply the inverse of conductance. The specific parameter required for the model is surface resistance. The review paper of Breuer et al. (2003) presented a large range of values of stomatal conductance for grasses, pines and broadleaved trees. These values, excluding data for acacias and eucalypts from the data set for broadleaved trees, are summarised in Table 2. A number of specific observations for pines from New Zealand and Australia have further been added to these summarised values.

Breuer et al. (2003) summarised stomatal conductance, g_s , for a range of species from which values for grasses, pines and broadleaved trees other than acacias and eucalypts could be extracted. Some specific observations for *Pinus radiata* observed in New Zealand and Australia were added to the list. Conductance values for *P. radiata* were somewhat lower than for most other pine species. The numbers summarised by Breuer et al. (2003) varied widely, reflecting differences in species within the groups but also differences in growth stage, nutrition or other unspecified plant physiological factors. Because of these widely differing values, results are given for both the mean and the median of observations (Table 2).

Resistance is the inverse of conductance so that leaf resistance can be readily calculated from the reported leaf conductances. A rounded value between the calculated resistances based on mean and median values is then suggested as an appropriate value for modelling purposes. Total canopy conductance is calculated by dividing individual leaf resistances by leaf area

index. The derivation of leaf area index is discussed in Section 3.9 dealing with leaf area index (see below).

Canopy conductance for grasslands is the same as has been used in the default model runs ('Vegetation_ancillary.pdf') but resistance for exotic forests (at 150 s m^{-1}) is considerably higher than the default value (85 s m^{-1}) for conifers. That probably reflects the lower conductances for *P. radiata* than for most other pines as expressed in the compilation of Breuer et al. (2003). The value for broadleaved (native) forest, on the other hand, is substantially lower (at 75 s m^{-1}) than the default value (130 s m^{-1}) for evergreen broadleaved trees. There are no readily apparent reasons for those differences.

Table 2 Average stomatal conductance, g_s , summarised by Breuer et al. (2003), plus selected additional values for *Pinus radiata* by Whitehead & Kelliher (1991), Thompson & Wheeler (1992) and Whitehead et al. (1994) and derived stomatal, r_s , and canopy resistance, r_c , from $r_c = r_s/L$ where L is canopy leaf area index. n is the number of representative species included by Breuer et al. (2003).

	g_s mm s^{-1}			r_s s m^{-1}			L	r_c s m^{-1}
	Mean	Median	n	Mean	Median	Approx. value		
Grasses	5.2	6.7	9	192	149	180	3	60
Pines	2.4	2.0	33	417	500	450	3	150
Broadleaved (excl. eucalypts)	3.7	2.9	73	270	345	300	4	75

3.6 Canopy height

The height of forest stands varies markedly with the age of stands. This is particularly important for pine stands that are typically felled at age 25–30 years. So, the total national pine estate consists of a mixture of stands of different ages and thus different heights. Height also varies with site class, with trees on higher-fertility sites growing taller. This latter effect is partly negated by those stands likely to be harvested sooner, or at a size that is more similar to the size at which stands on low-productivity sites will be harvested.

Using the graph in Fig. 9, integrating it over 25 or 30 years (to cover an upper and lower limit of rotation lengths) and including an additional fallow year between plantations, this translates into average heights of 15.5 m (for rotation lengths of 25 years) or 18.6 m (for rotation length of 30 years). It is suggested to use an average height of 17 m between these calculated upper and lower ranges.

For pasture, canopy height depends critically on grazing intensity and frequency. For the present purpose, it would be appropriate to assume that pastures are frequently grazed, and that average height is therefore a low 20 cm.

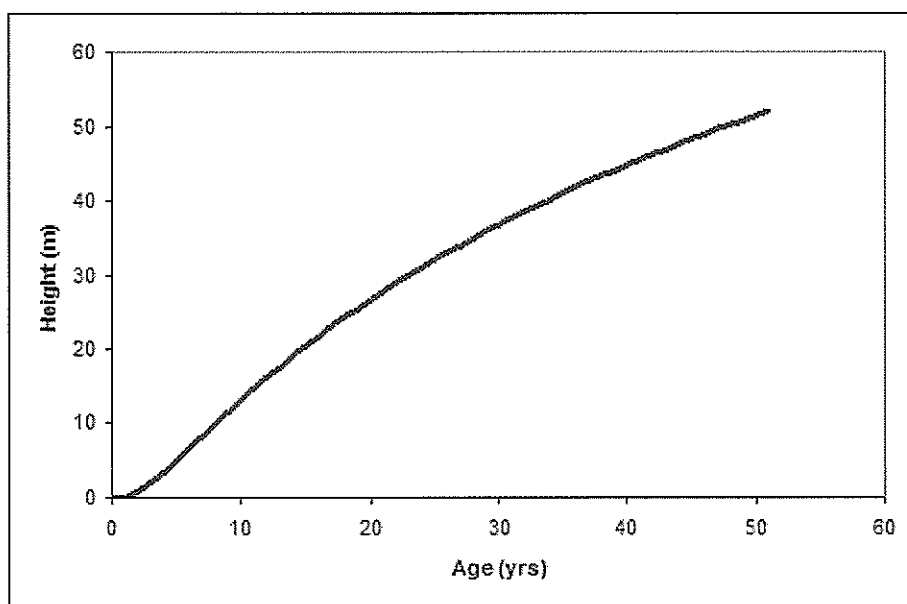


Fig. 9 Average tree heights for pine stands from across New Zealand plotted as a function of tree age. The fitted equation shown here is based on data in Dzierzon & Mason (2006).

Table 3: Typical tree heights for a few key forest species of native-forest stands in New Zealand. Based on Wardle (2002).

		Height (m)
Low altitude mixed forest		
Kauri	<i>Nothofagus truncata</i>	25–30
Rimu	<i>Dacrydium cupressinum</i>	30–40
Higher altitude mixed forest		
Southern rātā	<i>Metrosideros umbellata</i>	10–15
Early succession		
mānuka/kānuka	<i>Kunzea ericoides</i> / <i>Leptospermum scoparium</i>	5–20

The category of ‘native forests’ comprises a range of different actual forest types, which mainly reflect differences in soil and climatic conditions. Wardle (2002) lists 48 different species of tall and medium-sized trees in New Zealand. Differences also include an element of the successional position, with early-succession forests, such as mānuka/ kānuka, typically of shorter stature than the late-successional species that eventually overtop and replace them. In modelling ‘native forest’ one must thus recognise that it will consist of a multitude of stands with different properties that may be most marked with respect to height.

A range or representative heights for different species are given in Table 3. It is suggested to use an average height of 20 m to give a representative value.

3.7 Roughness length

Based on information supplied by Sam Dean (pers. comm), roughness length, z_0 , is calculated from canopy height, h , as:

$$z_0 = h/20 \text{ for trees} \quad (6a)$$

$$z_0 = h/10 \text{ for pasture.} \quad (6b)$$

This translates into

$$z_0 = 0.85 \text{ for pine forest} \quad (7a)$$

$$z_0 = 1.0 \text{ for native forest} \quad (7b)$$

$$z_0 = 0.02 \text{ for pasture} \quad (7c)$$

3.8 Surface capacity

This has also been called canopy water capacity, and is the canopy's capacity to hold water, which then evaporates from the canopy instead of reaching the ground and the soil from where it would be available for plant uptake and loss by transpiration or runoff through rivers to the ocean. Rainfall interception varies as a function of the size of rainfall events. During light rainfall events, the number of canopy gaps determines the fraction of rain that bypasses foliage and can reach the ground, and for heavy rainfall events, the size of the canopy determines the amount of rain that can be held before any further excess reaches the ground.

Myers and Talsma (1992) also reported that the percentage of intercepted rain, I_p , could be described as:

$$I_p = -3.61 + 2.01 F \quad (8)$$

where F is foliage mass (in tDW ha⁻¹). For typical foliage mass of 10–15 tDW ha⁻¹, this translates into interception losses of 16.5–26.5%. Similar values have been reported by Watt et al. (2008).

Rowe et al. (2002) and Breuer et al. (2003) summarised values for maximum canopy storage from a range of studies. The values from Rowe et al. (2002) are particularly pertinent as they specifically summarised data for the relevant species in New Zealand. For *P. radiata*, they report a range of values from 0.4 to 2.5 mm, with the lowest value reported for a very young stand (7 years) and the highest value for the oldest stand (at 31 years) for which a value was reported.

For Douglas-fir, the report generally listed higher values, ranging from 1.2 to 3.9 mm. The mean of all values reported by Rowe et al. (2002) for pines and Douglas-fir (*Pseudotsuga menziesii*) was 2.1 mm. Since pines had lower values than Douglas-fir, and since the plantation estate in New Zealand predominantly consists of pines, it is suggested that 2.0 mm might be an appropriate average value for exotic forests.

Rutter (1975) reported values of 0.5–1.0 mm for a range of herbs and grasses other than a very tall ryegrass (*Lolium perenne*) pasture that was reported to hold 2.8 mm. This is likely to reflect the fact that canopy water storage will be strongly dependent on leaf area, and if a pasture can grow into a tall plant without being grazed, it will exhibit very different

properties from that of a grazed and much shorter canopy. Breuer et al. (2003), in their summary of literature values, reported somewhat higher values than those given by Rutter (1975). It is suggested that a value of 1.5 mm is appropriate for pastures.

Rutter (1975) also reported values of 1.0 mm for two broadleaved forests, and van der Salm et al. (2007) reported values of 1.4 mm for oak and 1.7 mm for beech forests in Europe. Sraj et al. (2008) gave a storage value of 1.2–1.3 mm for two Mediterranean forests. Wallace and McJannet (2008) reported a value of 2.7 mm for rainforests in northern Queensland, and Breuer et al. (2003) report a range of values, with lowest values for eucalypts and highest values of 2.6 mm for *Fagus sylvatica* and 2.7 mm for a mixed forest.

Rowe et al. (2002) specifically summarised data from a range of native New Zealand forests and reported a mean value of 1.9 mm. It is considered that the data of Rowe et al. (2002) are most appropriate for New Zealand native stands. A value of 2.0 mm is therefore suggested for native forests.

3.9 Leaf area index

Leaf area index, L , is the ratio of leaf area to total ground surface area. It is most commonly defined as the projected leaf area, but especially in some older literature, the L of needle-leaved vegetation is sometimes defined as the total surface area, which can result in numerically very different reported values (depending on the exact shape of needles).

For *P. radiata*, foliar mass is usually between 10 and 15 tDW ha⁻¹ (Madgwick 1994), and with specific leaf area between 4 and 5 m² kgDW⁻¹ (Thompson & Wheeler 1992), this translates into a range of L between 2 and 3.75, with 3 taken as an average value.

For native forests, L varies with the type and condition of forests, with forests growing in fertile, well-watered lowland areas tending towards higher L , whereas forests in higher elevation, or at drier or less fertile sites having lower L . Typical values are considered to be between $L = 2.9$ (Whitehead et al. 2002) and 3–4 (Walcroft et al. 2005) for rimu and $L = 4$ –7 for mountain beech (*Nothofagus solandri* var. *cliffortioides*) (Hollinger et al. 1994; Holdaway et al. 2008). It is suggested to use an average value of 4.

For pasture, L , as for height, depends critically on grazing frequency and intensity. L was reported as 2–12 by (Steyn-Ross et al., unpublished), and Breuer et al. (2003) list values for grasses from 0.4 for a grazed American grassland to a high of 16.2 for an ungrazed mixed grassland in Germany. Such differences arise from differences in rainfall, grazing intensity and fertiliser availability. Breuer et al. (2003), for example, reported L increases from 6.1 to 15.3 or from 1.5 to 6.7 with increase in the rate of fertiliser application. All these values are thus correct values within their own respective circumstances. For the conditions in New Zealand, and for the assumption that the value is intended for a grazed pasture, it is therefore suggested to use an average value of 3.

3.10 Vegetation fraction

Vegetation fraction is the proportion of ground covered by vegetation. It is closely related to L as the majority of a plant's visible biomass is in its foliage, especially in reasonably dense stands. Light transmission, T , can be calculated from L based on Cowan (1968) as:

$$T = e^{(-L)} \text{ if leaves are oriented horizontally} \quad (9a)$$

$$T = e^{[-0.5 (L / \cos(i))]} \text{ if leaves are oriented randomly} \quad (9b)$$

$$T = e^{\{-2 \sin(i) L / [\pi \cos(i)]\}} \text{ if leaves are oriented vertically} \quad (9c)$$

where L is leaf area index, and i is the angle of incident radiation (or the viewing angle for the present purpose). For calculating the vegetation fraction, we use a vertical viewing angle of 0.

Leaf angle distributions differ between canopy types. For pasture, we assumed a random orientation although the distribution is probably somewhat more vertically than a random distribution might suggest. The foliage of many native forests tends to be oriented more horizontally than randomly, and a value halfway between random and horizontal is used here. The distribution of pine needles is assumed to be well represented by a random leaf-angle distribution.

Light interception for a vertical viewing angle, or the vegetation fraction, V , can thus be calculated simply as:

$$V = 1 - T \quad (10)$$

So,

$$V = 1 - e^{(-0.5 \times 3)} = 0.78 \text{ for pines} \quad (11a)$$

$$V = 1 - e^{(-0.5 \times 3)} = 0.78 \text{ for pasture} \quad (11b)$$

$$V_r = 1 - e^{(-0.5 \times 4)} = 0.86 \text{ for native vegetation with randomly oriented leaves} \quad (11c)$$

$$V_h = 1 - e^{(-4)} = 0.98 \text{ for native vegetation with horizontally oriented leaves} \quad (11d)$$

Between these two estimates, an average value of 0.9 is suggested for native vegetation.

3.11 Infiltration factor

The infiltration factor is defined as the enhancement of soil water infiltration compared with bare soil. Infiltration rates are strongly related to porosity, especially the presence of macropores, and porosity tends to be high under forests, especially broadleaved forests, because of steady litter input that encourages bioturbation by earthworms and other soil fauna, because of the absence of disturbance from cultivation that acts to break down soil structure and thereby leads to soil compaction, and because of the absence of direct physical compaction from heavy animals, especially cattle, or farm machinery.

The relationship between infiltration rate and porosity is well illustrated in the data of Bharati et al. (2002) as shown in Fig. 10. It shows both a strong increase in infiltration rate with decreasing bulk density (which is inversely related to porosity). Forests, however, lie well above the fitted line indicating that there are additional factors, such as the presence of a thick litter layer, that further facilitate water infiltration.

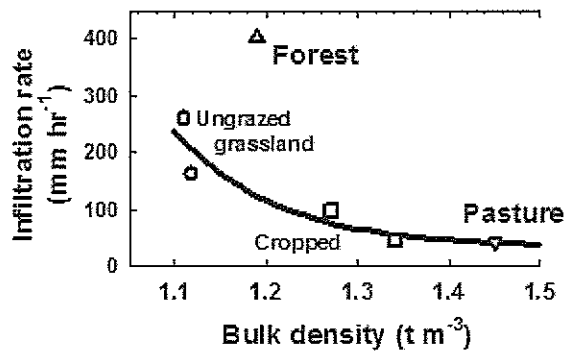


Fig. 10 Infiltration rate as a function of soil bulk density. Redrawn from Bharati et al. (2002). A curve is drawn through the non-forest data.

Changes in infiltration rate are related to changes in hydraulic conductivity that can extend deep into the soil profile (Fig. 11). It shows a difference in hydraulic conductivity between forest and pasture by about an order of magnitude. After 12 years of forest regrowth, the original forest hydraulic conductivity was approximately half restored.

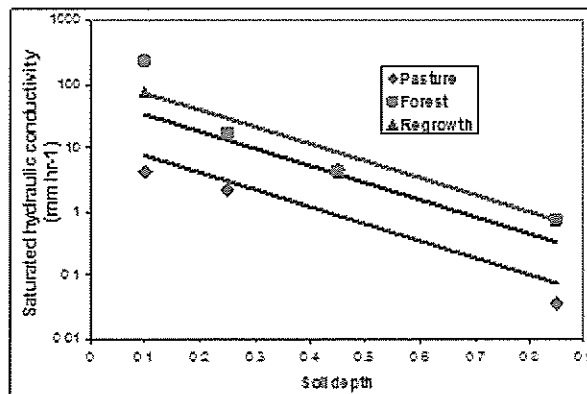


Fig. 11 Saturated hydraulic conductivity as a function of soil depth for pasture, forest and 12-year-old regrowth forest. Based on the data of de Moraes et al. (2006). Exponential lines were fitted to each data set but with the constraint of a common slope to all curves. Equations for pasture, $K_{sat(p)}$, forest, $K_{sat(f)}$ and regrowth, $K_{sat(r)}$ are given by:

$$K_{sat(p)} = 13.9 e^{-6.15d} \quad (12a)$$

$$K_{sat(f)} = 135 e^{-6.15d} \quad (12b)$$

$$K_{sat(r)} = 61.5 e^{-6.15d} \quad (12c)$$

Published absolute values and of the difference between vegetation types tend to differ considerably between studies. This is likely due to the large number of confounding factors, such as soil type, type and condition of vegetation within the broad classes of forest and pasture, and management effects that particularly affect pasture through the type and intensity of grazing and its interaction with seasonal factors that can lead to more or less soil compaction and thus affect infiltration rate.

In the model documentation ('Vegetation_ancillary.pdf'), it is stated that both coniferous and broadleaved evergreen forests have a relative infiltration factor of 6.0, with 'short grass and forbes' having a value of 1.5 and long grass 2.0. It is considered that managed pasture is best described as 'short grass' and that a value of 1.5 would be appropriate. For forests, a value of 6.0 seems appropriate.

4. Summary

Summary values for the key parameter values are given in Table 4. It simply summarises the values that are given, together with their respective derivation, in the detailed sections above. No value for rooting depth is provided because regionally varying values are used. Summary values for snow albedo are given here, but for completeness, a slight adjustment at temperatures just below 0°C should be used as well. That adjustment is given in Section 3.4 above.

Average values for direct-beam and diffuse albedo are given in Table 4, but more detailed information, including daily and seasonal variations in albedo, and distinct values for the albedos of the different components of short-wave radiations, are given in Table 1. The values for direct-beam albedo are estimated whole-day values obtained by a radiation-weighted summation of albedos over the whole day.

Table 4 Summary of key parameters for modelling different vegetation types for New Zealand. Rooting depth is supplied as a surface of values across New Zealand, and further details of albedo values are given in Fig. 4 and Table 1, which allow separate use of values of albedo for different wavelength ranges and for different times of the day and year.

	Pasture	Exotic forest	Native forest
Snow albedo	0.78	0.26	0.26
Direct beam albedo	0.204	0.121	0.103
Diffuse radiation albedo	0.198	0.116	0.101
Surface resistance (s m ⁻¹)	60	150	75
Height (m)	0.2	17	20
Roughness length (m)	0.02	0.85	1.0
Surface capacity (mm)	1.5	2.0	2.0
Leaf area index	3	3	4
Vegetation fraction	0.78	0.78	0.9
Infiltration factor	1.5	6.0	6.0

4.1 Conclusion

This reports constitutes the first step of a two-step process of assessing the importance of indirect effects of forest establishment. The second step will be the modelling work carried out by Sam Dean. As such, the work reported here constitutes no end-point in its own right but leads to meaningful outputs and conclusions only when the second step of the work has been completed as well.

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