Implications of Changes in Albedo on the Benefits of Forests as Carbon Sinks

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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

- Increased carbon storage by forests leads to a decrease in atmospheric carbon dioxide concentration, slowing the rate of warming of the atmosphere. However, the change in land use from 'lighter' pasture to relatively 'darker' conifer forest also results in a decrease in albedo (fraction of short-wave radiation that is reflected from vegetation surfaces) from about 0.18 to 0.13. This extra radiation absorption results in warming of the atmosphere.

- The net impact of afforestation on warming depends on the relative magnitude of the two direct, but opposing effects of decreased albedo and the removal of carbon dioxide from the atmosphere. In addition, afforestation results in indirect effects on warming the atmosphere through increased evaporation from wet canopies and cloud formation, though this is more difficult to quantify.

- As a further complication, increased carbon storage in trees lowers the atmospheric carbon dioxide concentration, which reduces the rate of uptake and storage in other natural carbon reservoirs, including the oceans. The carbon content of the atmosphere is therefore reduced by less than the amount stored in the trees.

- We show that, to offset the atmospheric warming caused by the direct effect of a decrease in albedo of 0.05, a value which appears likely with conversion of pasture to exotic forest in New Zealand, requires storage of about 18 tC ha^{-1} in newly established forest. This is equivalent to about 2 years of growth for typical *Pinus radiata* plantations in New Zealand, when averaged over the full rotation.

- There is only one site in New Zealand with long-term, ground-based measurements of albedo over the whole short-wave spectrum following a land-use change from pasture to *Pinus radiata* forest. This site is located at Puruki, in the Central North Island. Data from this site, supplemented with preliminary satellite-derived estimates of albedo for nearby pastures, were used to calculate the direct effects of decreasing albedo on atmospheric warming for a period of 24 years as the forest grew. Measurements of increasing biomass in the trees were used to estimate the decrease in the rate of warming due to the removal of carbon dioxide from the atmosphere. Calculations were done with and without the inclusion of carbon-cycle-feedback effects. We show that the two effects are roughly equal for young stands but the carbon storage effect dominates as the stand grows older. Averaged over a 24-year period, the changes in albedo discount the benefits from increased carbon storage by only 10% (carbon cycle effects ignored) to 20% (including carbon cycle effects).

Data Gaps

- Our conclusions are based on measurements from one site in the central North Island, New Zealand, where rates of tree growth are high. With the unavailability of ground-based data before the trees were planted at this site, the values of albedo for pasture were estimated from data derived from satellite imagery.

- Further work using ground-based measurements is needed to validate the use of satellite data to estimate albedo for different land cover types. These estimates can then be used to determine the variability in the discount in benefits of increased carbon storage resulting from decreasing albedo with land-use change to forestry across New Zealand.

- We were not able to quantify the indirect effects of changing land-use on radiative forcing. Changes in hydrological components can lead to surface warming or cooling, depending on the relative magnitude of the processes involved. Based on the international literature, the net effect for afforestation is likely to be important (possibly as large as the direct effect of decreasing albedo), but its magnitude for New Zealand is not yet known. Additional work is currently underway to determine the importance of these effects using a regional climate model.

1. Introduction

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 the period March to June 2008.

2. Background and Objectives

Recent reports (Betts 2000; Gibbard et al. 2005; Bala et al. 2006, 2007) using sophisticated models to investigate the effects of large-scale afforestation or deforestation on radiative forcing have shown that extensive replacement of pasture by forest, especially at high latitudes with extensive snow cover, could have a net warming effect. However, the results of these large-scale studies cannot be applied directly to New Zealand conditions where the duration of seasonal snow cover is very limited in areas where forests are likely to be established.

Values of albedo for 'light' pasture are usually about 5 to 10% higher (i.e. more reflective) than those for 'darker' coniferous forests, which lie in the range 0.08 to 0.15 (Jarvis et al. 1976). So a change in land use from pasture to conifer forest results in a decrease in albedo with a *direct effect* on the surface radiation balance resulting from decreased reflected short-wave radiation. This leads to an increase in radiative forcing, resulting in warming of the atmosphere. In addition, land-use change can have *indirect effects* on surface radiation balance through changes in evaporation that subsequently affect cloud formation with effects on both short- and long-wave components.

The paper by Bala et al. (2006) used a full-carbon-cycle climate model to demonstrate that the indirect effects of afforestation on surface energy balance can be very important. The authors found that increased forest cover at southern hemisphere mid-latitudes was associated with a warming of surface air temperature that was greater than could be explained by the direct albedo effect alone. They showed that this extra warming could be attributed to an increase in down-welling radiation, caused by increased water vapour concentration and cloud cover. This increase dominated the decrease in short-wave radiation associated with increased cloud cover.

- Building on an earlier report by Dean (2007), here we provide the best assessment of the impacts of changing albedo on radiative forcing. Our focus is on land-use change from pasture to *Pinus radiata* forest under New Zealand conditions.

- Changes in the surface radiation balance resulting from land-use change are the principal determinants of the surface temperature. In this report we identify the properties of vegetation and the atmosphere that regulate the radiation balance and explain how these are modified by land-use change.

Conventionally, the net radiation, Q_n, retained by a surface is given by the conservation of energy equation:

$$Q_n = Q_s\downarrow - Q_s\uparrow + (Q_l\downarrow - Q_l\uparrow) = (1 - \alpha)\, Q_s\downarrow + (Q_l\downarrow - Q_l\uparrow), \tag{1a}$$

where the radiation components are $Q_s\downarrow$ downward short-wave radiation (300 to 4000 nm), $Q_s\uparrow$ upward reflected short-wave radiation, $Q_l\downarrow$ downward long-wave radiation, and $Q_l\uparrow$ long-wave radiation emitted from the surface and α is the albedo of the surface, defined as the fraction of downward short-wave radiation that is reflected from the surface (Landsberg & Gower 1997).

Considering the Earth as a whole, incoming long-wave radiation is negligible, so we can simplify and extend Equation 1a to give

$$Q_s\downarrow - Q_s\uparrow = (1 - \alpha)\, Q_s\downarrow = - Q_l\uparrow = f(T^4), \tag{1b}$$

where T is the surface temperature. This shows that the long-wave radiation emitted from the Earth is a function of surface temperature raised to the fourth power and demonstrates that any decrease in albedo must lead to a decrease in outgoing long-wave radiation and an increase in surface temperature.

Increased carbon storage resulting from afforestation of pasture has the net effect of lowering atmospheric carbon dioxide concentration and thus decreases total radiative forcing, resulting in cooling of the atmosphere. The net impact of the opposing processes of increased radiative forcing resulting from changes in surface radiation balance and decreased radiative forcing attributable to the removal of carbon dioxide in forest sinks depends on the relative magnitude of the two effects.

Further, if the feedback via carbon uptake in the global carbon cycle is considered, then the beneficial effect of carbon storage in trees and its associated decrease in radiative forcing are reduced. This is attributable to a lowering of the atmospheric carbon dioxide concentration and that reduces the inherent carbon uptake by natural carbon reservoirs, including the oceans (Kirschbaum 2003, 2006).

- In this analysis, we derive a theoretical approach to quantify the direct effects of albedo changes and apply this using a case study to show the increase in radiative forcing as the forest grows. For the same case study, we calculate the reduction in radiative forcing attributable to removing carbon from the atmosphere and converting it into biomass, showing how this is dependent on global carbon storage in other natural reservoirs. Our conclusion is based on comparison of these two opposing impacts on radiative forcing as the forest develops. Except for short periods in winter, snow cover is absent from most areas where *Pinus radiata* forest is established in New Zealand, so the reflective properties of snow are not included in our analysis.

- A quantitative assessment of the indirect effects of changing land cover on radiative forcing from changes in the hydrological cycle for New Zealand is beyond the scope of work in this report. However, we do provide an updated assessment of recent internationally published reports and set the framework for undertaking such studies for

New Zealand conditions using a nested regional version of a global climate change model.

The case study used in our analysis is the Puruki Rua catchment that forms part of the Purukohukohu Experimental Catchment in the Central North Island (Beets & Brownlie 1987). This is the only site in New Zealand where ground-based measurements of albedo over the whole relevant short-wave spectrum have been made continuously from the early stages of forest development. Corresponding data on changes in tree biomass with forest development were also available. Within the scope of this report we were not able to estimate the effects for other land-use changes due to the lack of available data. Measurements of incident short-wave and net radiation are available for other research sites with a wide range of both natural and managed vegetation, but the instruments used for measurements of reflected short-wave radiation restricted to visible wavelengths (400 to 700 nm). For assessing the radiative effects of changes in albedo, the whole short-wave spectrum is relevant including the near-infrared region at wavelengths from 300 to 4000 nm.

Measurements of albedo were not available for the first four years after the trees had been established at Puruki, so we have derived estimates of albedo for pasture at the site from satellite data. At this stage, these estimates are preliminary and we intend to undertake future work to improve confidence in these values and their comparison with ground-based measurements.

3. Methodology and Literature Search

3.1 Energy balance and radiative forcing

The direct and indirect effects of changes in albedo associated with conversion of pasture to forest are described in Fig. 1 (modified from Findell et al. 2007). When water supply to the roots is not limited, the direct effect of decreasing albedo is in decreased upward short-wave radiation leading to increased net short-wave radiation being absorbed (term C in Fig. 1). The indirect effect of increased evaporation and possible cloud formation results in decreased net short-wave radiation (term B) but increased net long-wave radiation (term A).

Simplified studies, such as that by Betts (2000), quantify the perturbation to the radiation balance resulting from the lower albedo for forests compared with crops or pasture (term C). However, the surface radiation balance is complicated by feedbacks resulting from changes in the partitioning of available energy into latent and sensible heating (terms A and B). Conversion from pasture to forest usually results in increased evaporation. Transpiration from the two vegetation types is similar, but increased interception of rainfall by forests results in increased total evaporation or latent heat flux (Beets & Oliver 2007). This leads to less energy available for sensible heat flux and a decrease in surface temperature.

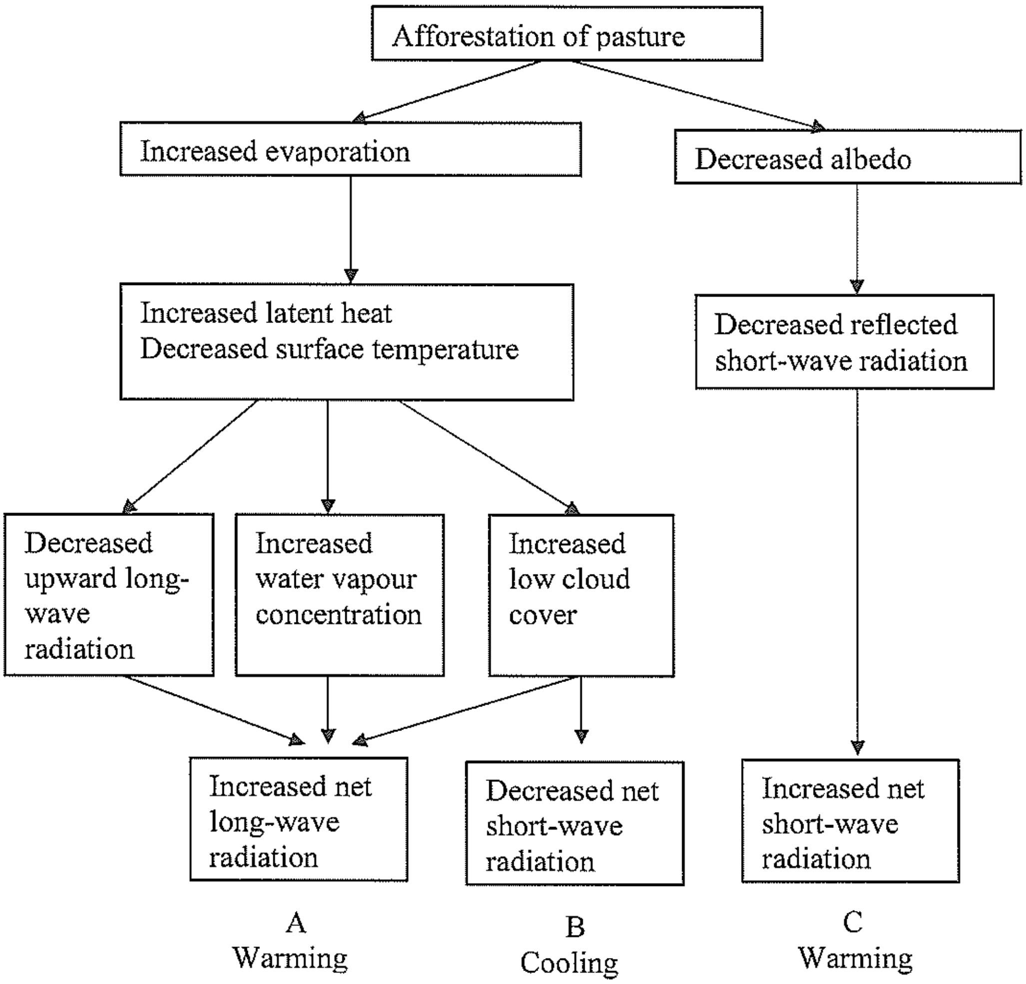

Fig. 1 Schematic representation of the direct (term C), and indirect (terms A, B) radiative effects associated with conversion from pasture to forest. All the radiative fluxes described are at the surface and the convention is that fluxes are positive for energy moving towards the surface.

The increase in latent heat flux and decreases in sensible heat flux and surface temperature are usually accompanied by an increase in low cloud cover resulting from the increased water vapour concentration of the near-surface atmosphere. The decreased surface temperature is accompanied by a decrease in the amount of long-wave radiation leaving the Earth's surface but, because of the increased low cloud cover and water vapour, more long-wave radiation is returned to the surface. These two effects lead to an increase in net long-wave radiation at the surface (term A). However, the increased low cloud cover also allows less incoming short-wave radiation to reach the surface (term B). Increased evaporation also tends to lead to local cooling, but this is not relevant in a global context because the heat is released somewhere else in the atmosphere when that water condenses again.

In summary, the direct effect of decreasing albedo (term C) will increase radiative forcing at the surface. However, increased evaporation (terms A and B) can result in an increase or decrease in radiative forcing. The final combined effect is determined by the relative sizes of the two components (terms A and B). If the combined net surface radiative balance is positive, then both latent and sensible heat fluxes may increase and surface temperatures may increase even more than that due to the albedo effect alone (term C).

Changes in rainfall are not included in Fig. 1 due to the uncertainty in likely changes. In some cases, increases in latent heat flux have been shown to result in increased rainfall, while, in other regions, increases in sensible heat flux are required for this to occur. Changes in rainfall will result in feedback responses in evaporation but the resulting change in radiative forcing will depend on the magnitude of the increase in evaporation. Such changes will be greatest when the canopy is wet after rainfall and will be smaller when the canopy is dry.

3.2 Direct effects on radiative forcing

Radiative forcing of an extra unit of carbon

The radiative forcing of an extra unit of carbon in the atmosphere can be calculated from first principles. The change in radiative forcing for a square metre of ground, R_m (J m^{-2} d^{-1}), can be calculated as

$$\Delta R_m = 86\,400 \times 5.41 \times \{\ln[([C] + \Delta[C])/280] - \ln[([C])/280)]\}, \tag{2a}$$

which can be simplified to

$$\Delta R_m = 86\,400 \times 5.41 \times \ln\{([C] + \Delta[C])/[C]\}, \tag{2b}$$

where $[C]$ is the background atmospheric carbon dioxide concentration, $\Delta[C]$ is the change in atmospheric carbon dioxide concentration that is investigated here, and 86 400 is the number of seconds in a day. The conversion '5.41' (W m^{-2}) converts from units of carbon dioxide concentration to radiative forcing (Harvey et al. 1997). This corresponds to a radiative forcing of about 3.75 W m^{-2} for a doubling of carbon dioxide concentration, which is a mid-range climate sensitivity.

A change in carbon stocks on the ground (tC) needs to be converted to a concentration change in the atmosphere, considering that 1 ppm in carbon dioxide concentration corresponds to 2.123 GtC (Joos et al. 1996) in the atmosphere, such that

$$\Delta[C] = \Delta C / (2.123 \times 10^9). \tag{3}$$

Because of the logarithmic dependence of radiative forcing on carbon dioxide concentration, the conversion from a unit of carbon to a change in radiative forcing depends on the background concentration so that 1 tC would have a radiative forcing of 78.6 mJ m^{-2} d^{-1} at a background carbon dioxide concentration of 280 ppm, but only 56.5 mJ m^{-2} d^{-1} under the present-day 390 ppm, and only 31.4 mJ m^{-2} d^{-1} under a possible future carbon dioxide concentration of 700 ppm.

The total radiative forcing over a year and for the Earth as a whole, ΔR_E, can then be calculated as

$$\Delta R_E = \Delta R_m \times 510 \times 10^{12} \times 365, \tag{4}$$

where 510×10^{12} m^2 (or 510 million km^2) is the surface area of the Earth and 365 is the number of days in a year. With the present-day atmospheric carbon dioxide concentration of about 390 ppm, and for the Earth as a whole, the radiative forcing of one tonne of carbon, ΔR_{E}, can be calculated as

$$\Delta R_{\mathrm{E}} = 86\,400 \times 5.41 \times \ln\{[390 + 1/(2.123 \times 10^{9})] / 390\} \times 510 \times 10^{12} \times 365 \quad (5)$$

$$= 105 \text{ GJ tC}^{-1} \text{ yr}^{-1}.$$

With carbon storage in trees, it is also necessary to consider possible interactions with the global carbon cycle. In essence, the carbon stored in trees lowers the atmospheric carbon dioxide concentration, which, in turn, reduces the carbon dioxide uptake by the natural components of the global carbon cycle, especially the oceans. The atmospheric carbon dioxide concentration is therefore reduced by less than the amount of carbon stored in trees. These are important considerations with respect to the timing of the beneficial effect of carbon removal by vegetation (Kirschbaum 2003, 2006).

Immediately after any initial removal by growing trees, the atmospheric carbon content is reduced by almost as much as the amount of carbon stored in trees, but over time thereafter, the carbon content of the atmosphere increases again as the various natural exchange mechanisms have time to operate and adjust to the changing atmospheric carbon content. The radiative effect of the removal of one tonne of carbon by trees therefore varies with time after the removal. The calculations done in the following analysis are done both with and without consideration of these carbon-cycle feedback processes as either approach can be the most meaningful in its specific context.

The carbon cycle feedback can be described following Kirschbaum (2003) by defining five notional pools, P_1 to P_5, that represent five global carbon reservoirs, such as deep oceans, shallow oceans and the undisturbed biosphere. When the atmospheric carbon dioxide concentration increases or decreases, it changes the equilibrium between the atmosphere and the effective concentrations in these various pools. Atmospheric concentrations subsequently change as the carbon in these pools changes in an attempt to regain an effective equilibrium.

Several studies have shown that the complex patterns in the full global carbon cycle can be approximated adequately by a simpler system with just four dynamic pools and a residual airborne fraction (Wigley 1991; Joos et al. 1996). Inherent natural carbon dioxide uptake, C_{c}, is thus described as

$$C_{\mathrm{c}} = P_1 + P_2 / \tau_2 + P_3 / \tau_3 + P_4 / \tau_4 + P_5 / \tau_5 , \quad (6)$$

where $P_1 \ldots P_5$ correspond to five natural carbon reservoirs that require different time constants (τ_2 τ_5) to reach equilibrium with atmospheric carbon dioxide concentration. These pools are set to 0 at the time of forest establishment, and the rate of change of each notional pool for each subsequent year is then given (Wigley 1991) as

$$\mathrm{d}P_1/\mathrm{dt} = f_{\mathrm{i}}\ (\Delta B) \quad (7a)$$

$$\mathrm{d}P_{\mathrm{i}}/\mathrm{dt} = f_{\mathrm{i}}\ (\Delta B) - P_{\mathrm{i}} / \tau_{\mathrm{I}} , \quad (7b)$$

where ΔB is the amount of carbon removed by a biospheric sink, i (2…5) represents the four notional pools, $P_2 \ldots P_5$, f_{i} is the fraction of emissions that is eventually absorbed by pool i, and τ_i is the time constant for that pool to come to equilibrium with atmospheric concentrations. Pool 1 represents the emissions that are permanently retained in the atmosphere and therefore have no relaxation time constant associated with them. The fractions and relaxation time constants in Equations 6 and 7 are given in Table 1.

The approximation used here is based on the relationships of Meier-Reimer and Hasselmann (1987) and Wigley (1991) with the parameters given by Noble et al. (2000) and Fearnside et al. (2000).

Radiative forcing due to a change in albedo

The change in daily radiative forcing due to a change in albedo, ΔR_d, can be calculated as

$$\Delta R_d = Q_s\!\downarrow \Delta\alpha \, (1 - a_{Atm}), \qquad (8)$$

where $Q_s\!\downarrow$ is total daily downward solar radiation, $\Delta\alpha$ is the difference in albedo between two different land-use types integrated over the whole short-wave spectrum, and a_{Atm} is the proportion of short-wave radiation absorbed by the atmosphere. Montenegro et al. (2008) put the fraction absorbed by the atmosphere at 23%. Other papers have used a slightly lower number of 20%, and that value is used here.

Table 1 Critical constants used to define the global carbon cycle model used in the analysis.

Pool	f_i	τ_i (yr)
Pool 1	0.176	-
Pool 2	0.137	421.1
Pool 3	0.186	70.6
Pool 4	0.242	21.4
Pool 5	0.259	3.4

This calculation can, in principle, be done at any scale, but for comparative purposes against the radiative forcing of a tonne of carbon, scaling the numbers to a hectare is useful. Since radiation is usually given in units per square metre of ground area, a value of radiation needs to be converted to a hectare basis. Since radiation also follows a distinct seasonal cycle, it is necessary to sum these calculated values over at least a year. Hence, the difference in radiative forcing for a hectare and over a year can be calculated as

$$\Delta R_{yr} = \sum^{365} 10\,000 \, \Delta R_d \,, \qquad (9)$$

where 10 000 is the number of square metres in a hectare and 365 is the number of days in a year.

For albedo-based changes in radiative forcing, calculated values change with the difference in albedo between two land-use types. This, in turn, is strongly affected by the extent of snow cover, when albedo changes between land-use types are most pronounced, and by the average radiation received by specific locations. In New Zealand, snow cover generally plays a role only in the higher alpine areas, but not in the regions where most land-use changes can be contemplated.

Average annual incoming radiation changes with latitude and with the extent of cloudiness. In New Zealand, mean daily radiation (averaged over a whole year) ranges from about 11–12 MJ m^{-2} d^{-1} in the wet and cloudy parts of the far south of the South Island to about 15 MJ m^{-2} d^{-1} over most of the North Island (Leathwick et al. 2002, unpubl.). There is a distinct seasonal cycle, with minimum values in June (~5 to 6 MJ m^{-2} d^{-1}) and maximum values in December and January (~22 MJ m^{-2} d^{-1}).

Using a mean annual incident solar radiation of 13.5 MJ m^{-2} d^{-1} and an albedo difference between two land-use types of 5% (values of albedo of 0.1 and 0.15), this translates into an annual radiative forcing of

$$\Delta R_{\mathrm{yr}} = 13.5 \times 0.05 \times (1 - 0.2) \times 10\,000 \times 365 = 1971 \text{ GJ ha}^{-1} \text{ yr}^{-1}. \qquad (10)$$

Comparing the radiative forcing of 1 tC (105 GJ tC^{-1} yr^{-1} (Equation 5) with that of a change in albedo of 5% (1971 GJ ha^{-1} yr^{-1}, Equation 10), it becomes possible to calculate the required amount of carbon storage needed, B, to balance the increase in albedo from increased radiation absorption as

$$B = \Delta R_{\mathrm{yr}} / \Delta R_{\mathrm{E}} = 1971 / 105 = 18.8 \text{ tC ha}^{-1}. \qquad (11)$$

3.3 Summary of results from recently published literature

Climate models that incorporate land surface properties have been used to estimate the relative contributions of the feedback responses represented in Fig. 1, with differing results.

In a previous report (Dean 2007) a number of studies that used climate models to study afforestation (or deforestation) were reviewed extensively. The conclusion of this report was that almost all studies found afforestation in mid-latitudes to cause a warming in local temperatures, and that this warming was detectable in the global mean temperature. The global cooling resulting from carbon sequestration ranged from being somewhat smaller to being considerably larger than the simulated warming effect. It was also highlighted that feedbacks due to changes in cloud formation were important in the model responses at mid-latitudes. Here we update this report with a summary of papers that have been published since the review by Dean (2007), and consider any affect on the conclusions that were drawn then.

Bala et al. (2007) have considered complete deforestation simulations for the tropics, mid-latitudes and polar regions under a future emissions scenario. By using a fully coupled carbon-cycle climate model they were able to take into account the direct albedo affect of forests, the indirect hydrological effects, and the effect on other carbon sinks such as the ocean. The global cooling associated with complete deforestation at mid-latitudes in both hemispheres (latitude 20–50°) was found to be identical in magnitude to the global warming associated with the release of all the carbon in the trees into the atmosphere as carbon dioxide (316 Pg C). This led the authors to conclude that afforestation at mid-latitudes might be of little benefit in reducing atmospheric carbon dioxide concentrations. The importance of snow cover to this conclusion was not considered by the authors, but is likely to be significant.

Montenegro et al. (2008) used high-resolution-satellite datasets of land cover, snow cover, albedo and short-wave flux data to investigate afforestation in terms of equivalent carbon drawdown. Between latitudes of 40° S and 60° N afforestation almost always resulted in a net cooling, which is in contrast to previous studies (e.g. Betts 2000; Bala et al. 2007) that had suggested that, in snow-covered areas at least, the warming effect from decreasing albedo could be greater than the cooling effect from removing carbon dioxide from the atmosphere.

The difference between this conclusion and the results of Betts (2000) appears to be attributable to three issues. The study by Montenegro et al. (2008) (a) restricted afforestation to 'realistic' areas. The definition of these areas comes from a reconstruction of the vegetation types that would naturally exist in the present day if there had been no human influence, (b) used higher rates of carbon uptake, and (c) used smaller changes in albedo when converting pasture to forest. Justification for (a) is questionable on the grounds that very similar reconstructions have been used in previous climate model simulations that have agreed with the findings of Betts (2000). The higher rates of carbon uptake (b) and smaller change in albedo with land-use change (c) require further investigation before any conclusion can be drawn, and Montenegro et al. (2008) provide little support for their use of these very different estimates.

Feedbacks from clouds and evaporation were also ignored in this analysis, and it should be noted that the author's claim that afforestation always results in a decrease in cloud cover is incorrect. While the study can be compared directly with the work of Betts (2000), a comparison with the study by Bala et al. (2007) is more difficult since the indirect effects of afforestation were not included.

Zhang & Walsh (2007) used the ARPEGE-CLIMAT model to consider idealised simulations in which leaf area index, L, (the surface area of leaves per surface area of ground), and vegetation coverage are increased by up to 100% in all areas polewards of 60°N. They concluded that increasing vegetation coverage resulted in an increase in surface air temperature by up to three degrees. Increasing L resulted in an increase in precipitation but no change in temperature.

Davin et al. (2007) use the IPSL model to conduct simulations with prescribed pre-industrial, present and future distributions of vegetation. In all simulations, greenhouse gas concentrations and aerosols were fixed to pre-industrial levels. The analysis showed that historical deforestation resulted in a cooling of -0.05 K while future deforestation (largely in the tropics) would result in a cooling of -0.14 K. The authors did not consider the warming effect of the carbon dioxide released by deforestation, which means that their findings are not directly comparable to those of the other studies discussed here.

These changes in temperature reported by Davin et al. (2007) are small compared with those in previous studies as outlined in the report by Dean (2007), but similar to the results from Findell et al. (2007), who used the GFDL climate model for a similar analysis. This model was used to compare the effects of present natural vegetation distribution with potential distribution. Greenhouse gas concentrations were fixed at 1990 levels. Globally, the surface air temperature was 0.008 K warmer with 1990 land cover and, as such, the authors concluded that there was little impact on atmospheric temperature by converting forests to cropland or pasture. There were, however, significant changes in some local areas.

Betts et al. (2007) summarise results from these previous studies by the same authors and conclude that, in large parts of the temperate and boreal forest areas, the decrease in surface albedo by afforestation could be equal in magnitude to the effects of increasing carbon sequestration on climate forcing. This conclusion principally draws on the results outlined by Betts (2000).

Shi et al. (2007) used the McGill palaeoclimate model to investigate the effects of historical deforestation. The finding using this model with an intermediate degree of complexity was that historical deforestation had led to a decrease in global mean temperature of 0.09–0.16°C.

Two further modelling studies have been undertaken for specific sites. Bird et al. (2008), used stand-scale modelling for selected Canadian stands. In one example site where there was significant winter snow cover, the albedo effect reduced the benefits of carbon sequestration by 45% after 200 years. The authors used a complex approach to account for effects such as observed local cloud cover and sun elevation, but were not able to deal with indirect feedback responses such as evaporation or cloud changes.

In quite a different study, Juang et al. (2007) combined modelling and observations and concluded that the physiological effects of converting a grass field to pine or hardwood forest resulted in a decrease in ground surface temperature by 2.1 to 2.9 K, while the decrease in albedo resulted in an increase in surface temperature (not air temperature) by 0.7 to 0.9 K.

This study highlights the apparent contradiction where forests can ‘feel’ cooler than neighbouring pasture, primarily because of the effects of evaporation, which cool the local environment. However, that local cooling is not relevant in the global context as evaporation simply transfers heat from the surface to the atmosphere. When the water vapour condenses as liquid in clouds or rain, the heat is returned to the atmosphere, although not necessarily at the measurement site. On the global scale, the effects of evaporation and condensation cancel each other out with no net effect. Only the effects on the radiative balance remain. As such, site-specific studies are not directly comparable with results from climate models that address global questions. Heat transfer by evaporation and condensation and sensible heat transfer across neighbouring land-cover types may have important consequences locally, but they cancel out and are thus irrelevant in a global context.

In conclusion, the recent studies considered in this review used global climate models to address historical deforestation and found that this resulted in slight global cooling. These studies did not compare this effect to the warming associated with the increased emissions of carbon dioxide, though previous studies suggest the warming effect from extra carbon in the atmosphere is likely to be greater than the relatively small global cooling reported in these studies (Dean 2007). The papers by Bird et al. (2008) and Montenegro et al. (2008) found that even in snow-covered regions, the cooling effect due to increased carbon sequestration from afforestation was greater than the warming effect from decreased albedo, which is in direct conflict with the previous studies such as Betts (2000). These studies did not consider the indirect feedbacks from the hydrological cycle. A study incorporating these effects that could be compared directly with the findings of Bala et al. (2007) has not yet appeared in the literature.

4. Case Study

4.1 Description of the Puruki site

Puruki is a 34.4-ha catchment located in the Purukohukohu Experimental Catchment at the southern end of the Paeroa Range in the Central North Island of New Zealand (latitude 38° 26' S, longitude 176° 13' E, elevation above sea level 530–650 m). Puruki was originally a pasture catchment that was planted with *Pinus radiata* at a nominal tree number of 2200 trees ha^{-1} in 1973. Due to some early mortality, actual tree number was 1483 trees ha^{-1} in 1976 (Beets & Brownlie 1987). A meteorological mast was installed in the 8.7-ha Rua subcatchment and measurements of weather variables began in 1976. The Rua subcatchment was subsequently thinned to 550 trees ha^{-1} and the trees were pruned to 2 m height in 1980, with no further silvicultural operations undertaken after 1980. A new 37.5-m meteorological tower was installed about 30 m from the original mast in 1980. Tree height data are given in Beets & Brownlie (1987). The mean top height of the stand increased by approximately 1.5 m yr^{-1}. The Rua stand was harvested during 1997 when the stand was 24 years old. Changes in carbon stocks (excluding soil carbon) at the Puruki Rua site were estimated from biomass measurements and the C_Change model (Beets et al. 1999).

Methods used to estimate albedo

Measurements of incident and reflected short-wave radiation were measured using paired solarimeters (Solar Radiation Instruments SRI5) installed above the canopy at 35 m height. These instruments have a spectral response range across the full short-wave range from 300 to 3500 nm. Data were recorded as hourly averages using a data logger (Campbell Scientific Inc., Model CR7). Values of albedo were calculated from the ratio of daily total reflected to incident short-wave radiation.

The pine plantation was established in 1973, and albedo measurements commenced in 1977 at a time when leaf mass was about 4.2 t dry matter per hectare (Beets & Pollock 1987). Albedo measurements were continued through to the end of 1992.

The analysis done here depends critically on the albedo difference between pasture and forest. While there is a long sequence of ground-based measurements at Puruki, the sequence does not extend back to the time of forest establishment so that the pasture albedo was estimated from satellite measurements, which constitute a very different approach, relying on a range of assumptions and corrections that need to be applied. For example, satellite data can be obtained only under cloud-free conditions, but for estimating the radiative forcing effect of changes in albedo, estimates are needed for cloudy conditions as well. This requires angular corrections to the original satellite measurements. Similarly, albedo changes throughout the day with the angle of the sun. As satellites usually obtain only one image on a given day with a particular sun angle, another correction needs to be applied to estimate a total full-day albedo from just one particular measurements at one time of the day.

Consequently, it is difficult to develop full confidence in the specific satellite-derived albedo estimate for pasture and its comparability with ground-based measurements. Work is still continuing in refining the understanding of the veracity of the various adjustments that need to be applied. While we currently calculate the albedo difference between pasture and pine forest to be about 15%, this estimate might potentially still change by a few percent, and if it changes, the difference is more likely to increase than decrease. The calculations in the following analysis are based on our current best estimate of the relevant values for albedo.

4.2 Results throughout the rotation

Measured values of albedo at the Puruki Rua site (Fig. 2) follow a distinct seasonal cycle due to the changing angle of the sun, which changes the proportion of incident radiation being absorbed or reflected. In winter, with a more oblique sun angle, a slightly higher proportion of incident radiation is reflected. Albedo also changes greatly with stand development from a typical albedo for pasture of about 0.18 (based on satellite observations) to about 0.12 to 0.13 when the forest was about 8 years old.

These differences in albedo, together with observation of stand-carbon storage over time, can be used to calculate changes in radiative forcing of the two components (Fig. 3). Albedo forcing undergoes a strong seasonal cycle, primarily due to seasonal changes in incident solar radiation. The values for radiative forcing are positive, indicating that the change in albedo from pasture to forest leads to an increase in radiation absorption and, through that, constitutes positive forcing, leading to a warming effect.

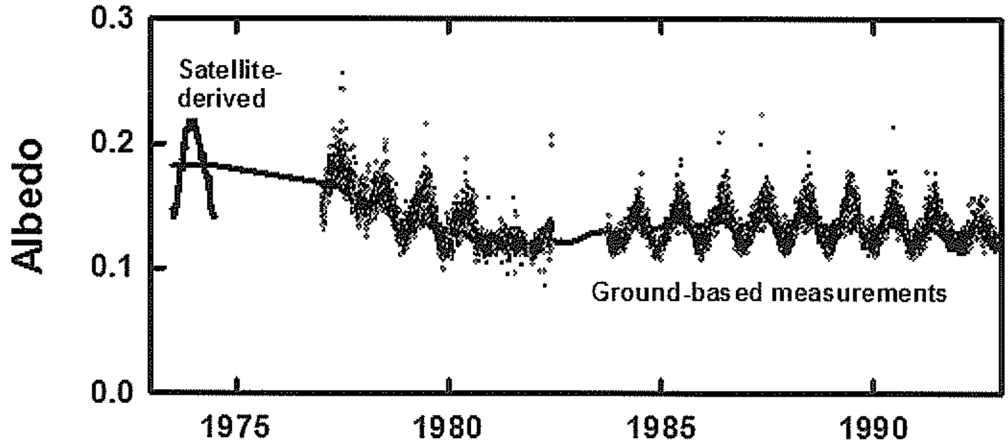

Fig. 2 Albedo changes measured at Puruki, and satellite-derived albedo estimates for a pasture. Satellite data were not available for 1973 (when the stand was established), but the data showed little year-to-year variability (data not shown). Also shown are a 365-day running mean for the forest data and a linear interpolation between the pasture data from the end of 1973 and the beginning of the trend line for the forest data. The forest was thinned in 1980.

Carbon-storage-based radiative forcing follows the changes in carbon stored in the forest (Fig. 3). There is a lag for the first few years as trees slowly establish themselves at the site, followed by an increase that was temporarily slowed as a result of stand thinning in 1980, and a sustained growth period thereafter. Radiative forcing is negative (cooling effect) as the amount of carbon stored in trees reduces the amount of carbon in the atmosphere and thereby reduces the radiative forcing in the atmosphere.

Further, if the feedback via carbon uptake in the global carbon cycle is considered, then the beneficial effect of carbon storage and its associated radiative forcing are reduced compared with calculated numbers without its inclusion. In essence, when carbon is stored in trees, it lowers the atmospheric carbon dioxide concentration and that reduces the inherent carbon uptake by natural carbon reservoirs. The atmospheric carbon dioxide concentration is therefore reduced by less than the amount of carbon stored in a stand of trees. As that carbon uptake takes some time, the feedback effect becomes stronger over time, and by the end of the rotation, the carbon-cycle feedback is of almost the same magnitude as ongoing further carbon uptake by the stand of trees so that (negative) radiative forcing is increasing only slightly. Carbon-cycle feedbacks reduce the beneficial effect of carbon storage in trees by about on-third by the end of the rotation (Fig. 3).

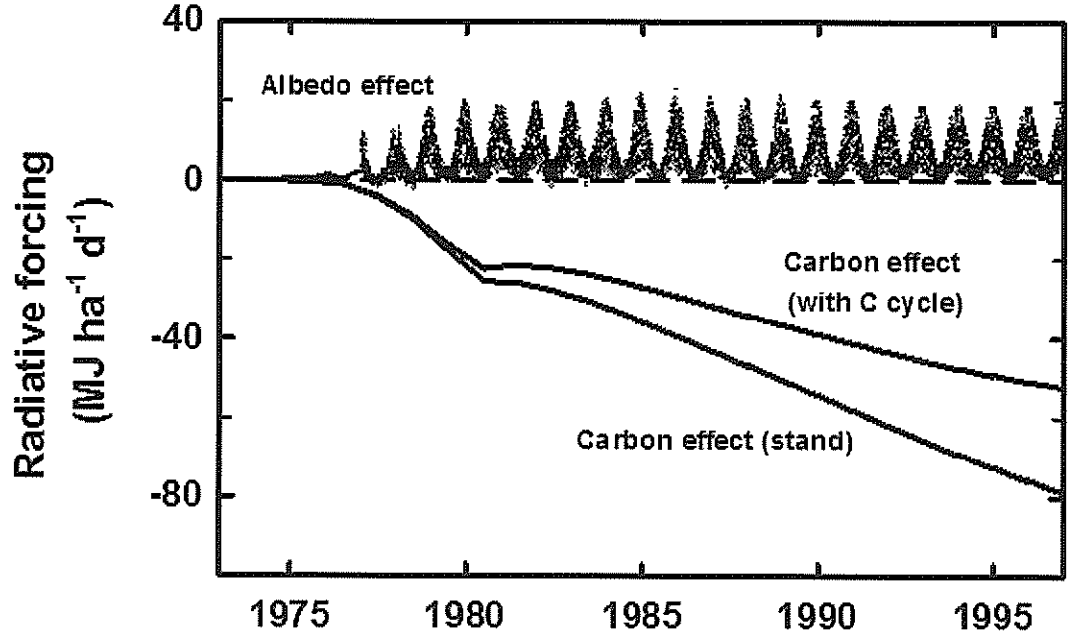

Fig. 3 Calculated radiative forcing due to changes in albedo and carbon storage. Albedo-based forcing is calculated daily from measured albedo and incident solar radiation. Carbon dioxide concentration is distributed globally so that daily factors are evened out. However, carbon-based calculations are done considering stand-level carbon storage only (stand), and after calculating carbon cycle feedback effects (with C cycle).

The net effect of albedo changes and carbon-storage are comparable for the first few years after stand establishment, but stand biomass continues to increase even after albedo changes have reached their maximum so that the carbon storage overwhelmingly dominates for older stands. The effect is not quite so pronounced if carbon-cycle feedbacks are included. In this case, the carbon-storage benefit does not keep increasing because further stand-level storage is offset by ongoing atmospheric adjustments with other carbon reservoirs.

Using the numbers calculated here (but keeping in mind the remaining uncertainty about satellite-derived albedo estimates), this gives an offset of the carbon storage benefit through albedo changes by the end of the rotation by an average of 8% if the carbon stored in the forest is considered alone (Fig. 4c) and 13% if the carbon storage by the carbon-cycle feedbacks is discounted (Fig. 4d). Averaged over the whole length of the rotation, the offset is 14% if one considers carbon storage in the forest only and 19% if one includes carbon-cycle feedbacks. We emphasise that this analysis is limited to the direct effects of decreasing albedo with land-use change from pasture to forest.

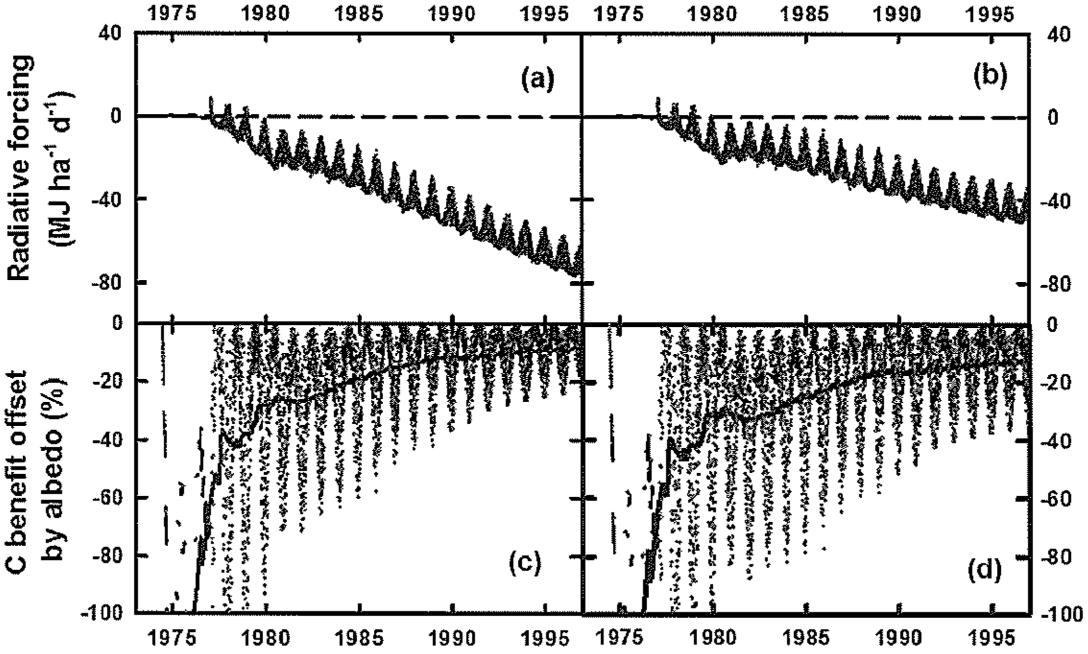

Fig. 4 Net radiative forcing effect combining albedo and carbon-storage effects. Calculations are done for either stand-level carbon storage (panels a, c) or with inclusion of carbon-cycle feedbacks (panels b, d) and are expressed as either net radiative forcing per hectare (panels a, b) or as a percentage offset on the carbon-storage benefit that would be calculated if the associated albedo changes were ignored (panels c, d).

5. Discussion of Findings

Carbon storage has the net effect of lowering atmospheric carbon dioxide concentration and, through that, total radiative forcing, but the decrease in albedo results in the absorption of more short-wave radiation, with an overall positive radiative forcing effect. These two effects are of comparable magnitude in young stands, but in older stands, the carbon-storage effect begins to dominate over the albedo effect. Based on our case study at Puruki, under New Zealand conditions, it can therefore be concluded that the albedo changes reduce the benefit from carbon storage in vegetation by only about 10–20%.

The exact percentage discount depends on a number of factors, firstly whether the effect is integrated over the whole life of a rotation or is calculated for the end of the rotation only. The discount percentage is obviously greater when it includes the early stages of stand establishment when both effects are of comparable magnitude. The longer the rotation length, the greater is the contribution of later growth stages when the carbon-storage effect more strongly dominates over the albedo effect. Our analysis was restricted to 24 years, when the trees at Puruki were harvested, so there is a need to extend the analysis to estimate the overall effects for mature stands. The discount percentage will also vary spatially across the country as it is dependent on incident solar radiation and the rate of carbon accumulation in biomass.

The discount percentage is also different for calculations done with or without consideration of carbon-cycle feedbacks. So, which should be used? The appropriate choice depends on the context within which specific questions are being asked. Calculations of stand-level carbon changes give the relevant net radiative forcing change of that particular forest. However, perturbation of the global carbon budget by forests leads to a change in the global carbon cycling that partly offsets the initial stand-level change in carbon storage. So, inclusion of the net effect of planting forest on natural adjustments in carbon pools is relevant.

If forest planting and fossil-fuel management are compared then the same carbon-cycle feedbacks apply to both. The emission of one tonne of carbon from fossil fuels leads to an increase in atmospheric carbon content by less than one tonne because some of that carbon will find its way into the oceans. So, in calculating the benefit of saving the emission of one tonne of fossil fuels against the benefit of storing one tonne of carbon in the biosphere, the comparison needs to be consistent in either including or excluding carbon-cycle feedbacks in both instances.

6. Conclusions and Recommendations

The detailed measurements available from the case study at Puruki allowed specific quantification of the ‘discount’ effect of changes in albedo on the benefits of carbon uptake and storage that accompany land-use change from pasture to exotic forest over a period of 24 years. The availability of these data highlights the importance and value of investing in the collection and maintenance of long-term datasets for research purposes.

This case study dealt only with the direct albedo changes and the associated change in the absorption of short-wave solar radiation. This was then compared with the global effect of reductions in atmospheric carbon dioxide concentration due to increased carbon storage. At this stage, there is still some uncertainty about the exact magnitude of satellite-derived albedo estimates, which are needed to estimate the albedo of pastures. While the uncertainty is not large in absolute terms, it is quantitatively important for the difference in values of albedo between pasture and forest as that is the key variable in calculating the albedo-based difference in radiative forcing between the two land-use types.

We are not able to quantify the indirect effects of changing land-use on radiative forcing. As shown in Fig. 1, the hydrological effects of land-use change can lead to surface warming or cooling, depending on the relative magnitude of the processes involved. Based on the international literature available, the net effect is likely to be important, but its magnitude for New Zealand is not yet known. However, progress to determine the importance of these effects using a regional climate model is underway.

Similarly, we were not able to quantify the magnitude of the effects of changing land-use from different pasture species or hill country tussock to forest or differences between establishing exotic and indigenous forest because the data are not yet available. However, work is underway to estimate values of albedo for a range of land cover types, using satellite data, and this could be used to develop an 'albedo map' for New Zealand, with this then used to estimate the effects of changing land-use at large spatial scales.

Based on the results from our analysis at Puruki, to further improve estimates of the direct and indirect effects of a decrease in albedo associated with a wide range of land-use change, we recommend the need for future research to:

- Set up new experimental sites in New Zealand to quantify the seasonal variability in estimates of albedo for key land-over types, including the effects of land-use change using continuous, long-term, ground-based measurements.
- Extend the present analysis of the direct effects of changes in albedo changes to older forest stands and for different land-use options such as reforestation with native species.
- Extend the analysis of the direct effects of changes in albedo spatially across the existing age distribution of plantations in New Zealand, and temporally to be consistent with reporting for the commitment periods set by the Kyoto Protocol.
- Undertake an analysis of the direct effects of changes in albedo spatially for a range of scenarios for establishing new forests and interpret this in relation to Kyoto commitments and long-term climate change mitigation.
- Do further work to improve confidence in the use of satellite data to estimate the variability in albedo at large spatial scales by developing algorithms and testing the estimates against ground-based data at key sites (work currently underway).
- Use satellite data to develop an 'albedo map' for New Zealand to record changes in albedo with land-use change.
- Determine values for the necessary parameters and run a series of afforestation simulations using a regional climate model for New Zealand to capture, in a simplified manner, the entire land surface and atmospheric direct and indirect effects relevant to quantifying local temperature change (work currently underway).

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