The Australian Journal of
Agricultural and
Resource Economics

Journal of the Australian
Agricultural and Resource
Economics Society

Australian Journal of Agricultural and Resource Economics, 59, pp. 116–132

A modified production possibility frontier for efficient forestry management under the New Zealand Emissions Trading Scheme

Todd Hale, Viktoria Kahui and Daniel Farhat[†]

Carbon sequestered through increased forest biomass provides a low cost means to curb emissions and has become a major focus of New Zealand's Emissions Trading Scheme. We present a forest planning optimisation model where land use is governed by forest owners maximising the returns to both timber harvest and carbon sequestration. By varying carbon prices, we model efficient trade-offs between the two forest activities along a modified production possibility frontier for four distinct wood supply regions in New Zealand. Results show that while more productive regions such as the Central North Island (CNI) and Northland have a greater capacity as a carbon sink, it is the less productive regions that have a comparative advantage in carbon sequestration in terms of a lower cost of wood production revenue foregone. However, moderate increases in carbon uptake can be achieved in the CNI at low opportunity cost by subtle changes in forestry management. The implication for policy-makers is that initial increases in carbon sequestration will be achieved at the lowest cost to society by favouring high volume timber production in some productive woodland areas and/or by more carbon farming in less productive areas.

Key words: carbon sequestration, optimal forest management, production possibility frontier.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has established two undisputed facts: (i) greenhouse gases (GHGs) trap energy, which warms the atmosphere, and (ii) human activity increases the atmospheric concentration of many GHGs (IPCC 2007). Details about the negative, sometimes irreversible, ecological and socioeconomic consequences have been the focus of debate (Stern 2006; IPCC 2007). New Zealand is no exception to the environmental impacts of climate change. However, the economy's reliance on an emissions-intensive, export-oriented agricultural sector makes it sensitive towards any GHG reduction policy (Ministry for the Environment (MfE) 2012a; Bertram and Terry 2010). New Zealand's 2002 commitment to reducing GHG levels under the Kyoto Protocol will likely lead to a net welfare loss regardless of the policy instrument used (New Zealand Institute of Economic Research (NZIER) and Infometrics 2009), so the central challenge for New Zealand policy-makers has become to decrease GHG levels at *least* cost to society.

[†] Todd Hale, Viktoria Kahui (e-mail: viktoria.kahui@otago.ac.nz) and Daniel Farhat are with the Department of Economics, University of Otago, Dunedin, New Zealand.

doi: 10.1111/1467-8489.12047

Emission trading, among other instruments, has been advocated as an efficient means to meet Kyoto emission reduction targets, and New Zealand's all-GHG, all-sector Emission Trading Scheme (ETS) is the first of its kind. The domestic unit of trade, the 'New Zealand Unit' (NZU), is a defining aspect of the ETS. Each NZU represents one tonne of carbon dioxide (CO_2), and participants are required to surrender NZUs equivalent to their annual carbon release or face a costly penalty (Ministry for the Environment (MfE) 2012b). Comparable international units can also be used for surrender; therefore, the ETS does not have an absolute cap (Bertram and Terry 2010). The linkage with international markets is significant; arbitrage will align domestic with international carbon prices and effectively place a ceiling on the price of an NZU (or carbon).[1]

With New Zealand's Kyoto obligation established, each extra tonne of carbon emissions that can be avoided or offset will save New Zealand tax payers the international cost of carbon (Kerr and Sweet 2008). The inclusion of forestry in the ETS in 2008 as the first sector was therefore an economic consideration. The carbon sequestered by trees as they grow is a by-product of timber production and serves as a low-cost means to reduce emissions. Forecasts estimate the net carbon uptake by forestry to be approximately 90 million tonnes between 2008 and 2012, almost enough to offset all of New Zealand's growth in GHG emissions since 1990 (Ministry for the Environment (MfE) 2012c). While the ETS is yet to be fully operationalised,[2] price signals emanating from a strong carbon market in the future will significantly affect the size of this net carbon uptake. Forest owners are issued one NZU for each tonne of carbon sequestered, the equivalent of which must be surrendered upon harvesting. Due to the favourable timing of the NZUs received (when trees are first planted) and the time value of money (discounting), the expected value of commercial forests has been shown to increase with participation in the ETS (e.g. Evison 2008; Manley and Maclaren 2010).

Forest owners can increase the expected value from NZUs by changes to forest treatment schedules[3] that favour timber volume per hectare[4] (Kerr and Sweet 2008) and/or carbon farming (where timber harvest no longer occurs) but such changes come at the cost of reduced wood production revenue; either because revenue from the production of high-volume unpruned logs is lower than that of low-volume pruned logs, and/or no timber revenue is generated under carbon farming.

---

[1] As a small player in the international market, New Zealand will effectively be a price taker (Bertram and Terry 2010).

[2] The delay is due to the expected future entry of waste and agriculture, which contribute approximately 52 per cent to New Zealand's emission profile (Ministry for the Environment (MfE) 2012d).

[3] Forest treatment schedules include (a combination of) spraying, pruning, production thinning, etc.

[4] Higher timber volume per hectare allows for higher levels of carbon fixation.

In this paper, we consider the changes in commercial land use of forests in response to carbon price signals. We present a forest planning optimisation model where land-use is predominately governed by profitability. The objective of forest owners is to maximise the returns to both timber harvest and carbon sequestration, which is a coupled production process (i.e. carbon sequestration impacts upon wood revenue). By varying carbon prices, the model can identify *efficient* trade-offs between the revenue from timber production and the quantity of carbon sequestered along a modified production possibility frontier (mPPF)[5] for distinct wood supply regions in New Zealand.

Our results aid policy-makers in meeting the challenge of decreasing GHG levels at least cost to society. A strong emissions trading market with high prices of carbon raises the returns to carbon-oriented land use. However, these come at the cost of wood production revenue forgone. We find the optimal proportions of timber and carbon-oriented management depend on the opportunity cost. Initially, increases in carbon sequestration will be achieved at the lowest opportunity cost by changes to silvicultural management favouring low-value, high-volume timber production in highly productive forests. More substantial increases in carbon sequestration in response to higher carbon price signals, however, are likely to occur by ceasing harvest for some proportion of commercial forests in less productive regions, which have a comparative advantage due to their lower opportunity cost. Our results extend a growing literature of silviculture under the ETS (e.g. Maclaren and Manley 2008; Turner *et al.* 2008; Manley and Maclaren 2010).

The following section provides details on the methodology, followed by the study area and data in section 3, the results in section 4, and the discussion and conclusion in sections 5 and 6, respectively.

2. Methodology

2.1. Efficient combinations of wood production and carbon sequestration

The objective of our long-range forest planning model is to maximise the returns to commercial wood production and carbon sequestration for a range of carbon prices to trace out a mPPF. The analysis draws on a number of papers deriving modified PPFs for timber production and biodiversity-related measures (such as Lichtenstein and Montgomery 2003; and Nalle *et al.* 2004). Two particular papers, which derive PPFs for timber production and carbon sequestration in Norway (Hoen and Solberg 1994) and Sweden (Backeus *et al.* 2005), have been instrumental in the design of our methodology. Hoen

---

[5] The conventional PPF is a concave curve that depicts the maximum quantity (rather than revenue) of wood production for a given maximum quantity of carbon sequestration assuming constant levels of inputs, that is, the PPF assumes that all inputs are used efficiently.

and Solberg (1994) derive a ‘shadow price’ for carbon from associated decreases in the returns to wood production, and assess the efficiency of carbon sequestration based on this shadow price through simulating alternative forest treatment schedules at five-year intervals. They use linear programming (LP) to calculate the optimal treatment schedule for a particular forest stand at a particular interval to maximise the returns to the forestry. Backeus *et al.* (2005) extend Hoen and Solberg’s model by including explicit carbon prices under the European Union emission trading scheme and higher resolution tree data. Both studies plot ‘PPFs’ with the net present value of wood production on the vertical axis and a measure of carbon sequestration on the horizontal axis for their respective study area. The mPPFs display the conventional concave frontier shape and represent the efficient trade-off between increased carbon sequestration and reduced returns to timber production.

In this paper, we consider single age-class forest stands across four regions in New Zealand and assume all rotations start with the planting of trees in the same year. Our study fits into a large literature of single age-class stand level analyses (e.g. Karjalainen 1996; Liski *et al.* 2001; Minkkinen *et al.* 2001; Van Kooten *et al.* 1995), which utilise Faustmann’s (1849) seminal forestry rotation model to determine optimal harvest policies.[6] Faustmann-type models, which are built on restrictive assumptions,[7] value the return from timber prodution of a single stand as discounted cash flows (net present value) and have served as a basis for many harvesting decision models in more realistic settings (Mendoza 2012).

The New Zealand Institute of Forestry (NZIF) has adopted the Faustman model due to limited availability of forestry data (Maclaren and Manley 2008) and has commonly used discounted cash flows of a representative stand to analyse the impact of the ETS on forest management (e.g. Evison 2008; Maclaren and Manley 2008; Manley and Maclaren 2010). Further justification for a single stand approach is given by the fact that the bulk of Kyoto compliant trees in New Zealand were planted between 1992 and 1998, that is, new plantings have been low since then and the current age-class of forests is very narrow (Manley and Maclaren 2010). The government has encouraged afforestation (e.g. Permanent Forest Sink Initiative Afforestation Grant) to combat the imminent carbon liability when this narrow age-class reaches maturity in 2020 (Manley and Maclaren 2010; Karpas and Kerr 2011) and

---

[6] Hoen and Solberg (1994) and Backeus *et al.* (2005) apply sample-based data for existing multiple-age forest stands in Norway and Sweden, respectively, to simulate optimal treatment schedules for a large number of treatment options, which requires the use of complex forestry-specific optimisation software. More sophisticated valuation techniques to include forest stands of multiple age-classes have also been developed by other studies, such as Uusivuori and Kuuluvainen (2005) and Uusivuori and Kuuluvainen 2008. These studies utilise detailed national data and suit a more economy-wide rather than a landowner preference-based analysis (Amacher *et al.* 2010).

[7] These assumptions include forest homogeneity, constant forest management and deterministic variables.

our single-stand analysis may match a surge of new plantations that could be expected to follow.

We modify the Faustman valuation method to include the net present value of carbon revenues similar to Van Kooten *et al.* (1995) and evaluate the three forest treatment schedules of pruning (i.e. active tending), plant-and-leave (i.e. no active tending), and carbon farming (i.e. no tending or harvest activities). These treatments match silvicultural regimes in New Zealand and available data on growth and yield projections. The intertemporal problem of finding the optimal forest planning model over multiple periods is formulated using an LP method[8] similar to Hoen and Solberg (1994) and Backeus *et al.* (2005). In line with previous studies (e.g. Evison 2008; Maclaren and Manley 2008) that simulate (nonoptimised) generic treatment schedules to assess forestry profitability in New Zealand under the ETS, we identify optimal proportions of the three treatment schedules at a rotation interval of approximately 30 years to apply to a given forest stand. The LP model chooses these proportions such that the discounted overall returns to wood production and carbon sequestration (the net present values) are maximised for a given carbon price over an infinite number of rotations. Repeating this algorithm for a range of carbon prices provides an optimal set of treatment schedules that varies along the mPPF.

2.2. Forest planning model

Following Hoen and Solberg (1994), the problem to be solved by the forestry sector is to identify the mix of treatment schedules that are applied to a woodland area to maximise the value of wood production and carbon sequestration subject to selected harvest constraints. If N treatment options are available and the region of interest consists of K homogeneous forest stands, this problem can be formally written as:

Choose p to maximise

$$Z = Kc^{T}p \tag{1}$$

subject to

$$A_1 p \leq b_1 \tag{2}$$

$$A_2 p \leq b_2 \tag{3}$$

$$p \geq 0 \tag{4}$$

where Z is the objective function representing the returns to wood production and carbon sequestration, p is a N × 1 vector of proportions, one for each treatment option, and c^{T} is the transposed N × 1 vector of marginal net income related to each treatment option. As forest stands are assumed to be

---

[8] This method is largely analogous to constrained optimisation problems routine in economics, with the exception that functions are restricted to be linear (Hess 2002).

of homogeneous age and composition, solving this problem for a single stand (measured by one hectare) is sufficient to characterise the solution for an entire forested area. In Equation (1),

$$\mathrm{c} = [\mathrm{c}_1 \quad \mathrm{c}_2 \quad \ldots \quad \mathrm{c}_\mathrm{N}]$$

where c_n is the marginal net income from treatment option n. In this study, N = 3 (pruning, plant-and-leave and carbon farming). Following Hoen and Solberg (1994), Manley (2012), Turner *et al*. (2008) and the NZIF, we derive the net incomes in the c^T vector by computing the total net present value (NPV_n) of wood production and carbon sequestration resulting from the treatment option:

$$\mathrm{c}_\mathrm{n} = \mathrm{NPV}_\mathrm{n} = \mathrm{NPVW}_\mathrm{n} + \mathrm{NPVC}_\mathrm{n} \tag{5}$$

where NPVW_n and NPVC_n equal the net present value of a forest stand for wood production and carbon sequestration respectively. Both net present value streams are calculated using a Faustman-type discounted cash flow (DCF), which takes into account the expected accumulation of interest on costs and revenues (see Appendix S1 for details of computation[9]).

Equation (2) is an even-flow harvest constraint to emulate gradual changes in wood production.[10] For example, data suggest the largest variation in estimated volume of Radiata pine roundwood removals (m^3/ha) for the Central North Island, the largest wood growing area, has been approximately ±10 per cent per year between 1998 and 2008 (Ministry of Agriculture and Forestry (MAF) 2009). Likewise, we would expect changes in forest management behaviour in response to changes in carbon prices to occur gradually in New Zealand (Karpas and Kerr 2011). To incorporate this in the model given the assumption of same-age forest stands, which are all cut at the same year, we impose a constraint on the change in (optimal) timber harvest levels in response to varying proportions of treatment schedules.[11] A_1 is defined as a $\mathrm{M}\times\mathrm{N}$ matrix of variables related to the volume of wood production for a particular treatment schedule and b_1 is a $\mathrm{M} \times 1$ column vector of harvest constraints (see Appendix S2 for details).

Finally, constraints (3) and (4) are imposed to ensure treatment schedules are assigned to all forest stands. A_2 is a $1 \times \mathrm{N}$ vector of ones and $\mathrm{b}_1 = 1$ in this study, in which case constraint (3) guarantees the optimal proportions in p sum to one. Constraint (4) ensures the optimal proportions are non-negative.

---

[9] More details on Faustman-type discounted cash flows can also be found in Amacher *et al.* (2009).

[10] As in Backeus *et al.* (2005), an even-flow harvest constraint is included to ensure the magnitude of change in wood production is not unrealistic.

[11] Where pruning provides higher quality (pruned) logs at the expense of quantity while plant-and-leave provides lesser quality (unpruned and pulp) logs but at relatively higher quantity (Maclaren and Manley 2008).

Once K, c^T, A_1 and b_1 are established, the p matrix can be derived computationally. To determine these matrices, we use data on forestry growth, carbon fixation, log prices, costs, carbon prices and discount rates pertaining to four selected forestry regions within New Zealand at the time the ETS was established. The LP problem is then solved computationally using software designed for numerical analysis (MATLAB; MathWorks, Inc., Natick, MA, USA).

3. Study area and data

3.1. Commercial forestries in New Zealand

Commercial forestry contributes 3 per cent to New Zealand's GDP (Ministry for Primary Industries (MPI) 2012) and is the third largest export earner. The 1.751 million hectares of exotic forest that make up the industry's commercial plantation boast highly productive, sustainable management but efficient management schedules are not generic to all wood supply regions. Variations in both environmental conditions, which impact upon the productivity of forest growth (Turner *et al.* 2008; Kirschbaum and Watt 2011), and harvest costs result in managers choosing different treatment schedules in each area. Based on data availability, representation and sufficiently varying productivity rates, we choose to examine the four wood supply regions of the Central North Island (CNI), Northland, Marlborough and Otago forestland in New Zealand.

The CNI and Northland are located in the North Island and are subject to moderate temperatures and precipitation providing ideal growing conditions for Radiata pine, the most common exotic tree species (Kirschbaum and Watt 2011). At 532,900 hectares of forests (30 per cent of the national total), the CNI is the largest and most productive wood growing region (Ministry of Agriculture and Forestry (MAF) 2008a) generating high quality (pruned) timber logs. Most wood processors are spread within the CNI region leading to an advantage in producing timber in terms of reduced harvest costs (Ministry of Agriculture and Forestry (MAF) 2009). At 199,200 hectares (11 per cent of national total), Northland's forest plantations is the second largest wood growing region, producing high yields of unpruned logs relative to other wood regions (MPI 2011). Marlborough, at the top of the South Island (72,000 hectares), and Otago, at the bottom (130,200 hectares), are subject to high altitude and cooler conditions leading to less productive and more diverse forest plantations. Log densities are relatively low, resulting in the production of lower quality timber products (Kirschbaum and Watt 2011; Ministry of Agriculture and Forestry (MAF) 2008b).

3.2. Timber yield projections

We use yield tables from the MPI's National Exotic Forest Description (NEFD) (MPI 2011) to project the volume of Radiata pine forest over time in each area. A yield table containing total standing volume (TSV) and total recoverable volume (TRV) over 40 years is provided for each crop-type, which refers to aggregate forest stands with the same species, wood supply region and stand tending treatment schedule. The data show various regimes for Radiata pine, which are combinations of the treatment schedules of pruning and production thinning producing three generic wood types – pruned logs, unpruned logs and pulp. We abridge the available growth projections such that the three treatment schedules of pruning, plant-and-leave and carbon farming represent the generic wood types (see Zhang 2010). For example, a representative Radiata pine stand aged 30 years in the CNI under the pruning treatment schedule has a TRV of 735 m^3/ha and yields higher quality, higher-priced pruned logs at harvest. A stand under plant-and-leave, however, generates a larger TRV of 752 m^3/ha, but is made up of lesser quality unpruned logs and pulp wood that yield lower prices. Yields are expressed in cubic metres per hectare (m^3/ha) and other relevant data (e.g. log prices, silvicultural costs, etc.) are converted accordingly.

We assume all harvesting will occur at a rotation interval of 30 years. As the national average age for 2008 was 27.9 years (Ministry of Agriculture and Forestry (MAF) 2008a), the slightly higher rotation age of 30 is intended to approximate a later, more efficient clear-cutting of NZ forest within the ETS (e.g. Maclaren and Manley 2008; Turner *et al.* 2008). The rotation age is only relevant for the treatment schedules of pruning and plant-and-leave, where a discounted cash flow is calculated for an infinte set of rotations. Carbon farming, on the other hand, entails a single time horizon for a discounted cash flow of 40 years. Regardless of the difference in cash flow timing, discounting to the current time period allows the comparison of profitability.

3.3. Other relevant data

Carbon fixation and emissions are derived according to calculations under the current regulations of the ETS (see Appendix S3 for details). We assume that any carbon sequestered is instantly released into the atmosphere once the forest stands are clear-cut. Under the treatment schedules of pruning and plant-and-leave, however, some positive amount of the value of carbon sequestered remains when the forests are cut due to the time value of money in the discounting process. Under carbon farming, however, all accumulated carbon is assumed to remain in forest biomass in perpetuity, despite eventual decay. This assertion can be justified through the expected regeneration of forests, either natural or managed (see Permanent Forest Sink Initiative, Ministry of Agriculture and Forestry (MAF) 2011).

Details on the domestic and export price for Radiata pine used in this study, forestry costs, the discount rate of 8 per cent and a discussion on carbon prices can be found in the Appendix S3. We map the mPPFs in this study by reiterating the LP problem for carbon prices in the range of \$0 to \$100, at intervals of \$5. This range is likely to represent a full range of potential forestry behaviour; for example, forest management with no ETS at a price of $0 or carbon farming only at exceptionally high carbon prices as in Van Kooten *et al.* (1995).

4. Results

The total net present value (NPV) representing the marginal net income in Equation (1) for each of the three treatment schedules (see Appendix S1, eqns (A.6) and (A.11)) can be plotted against carbon prices to get an 'index of profitability'. Figure 1 confirms that forest stand profitability increases with an increasing price of carbon, regardless of location and treatment schedule. The slopes of the total NPVs reflect the capacity of a forest stand's carbon sink. Schedules that are more carbon-oriented, such as plant-and-leave and carbon farming, have steeper slopes reflecting higher marginal profitability for rising carbon prices.[12] For example, Figure 1 shows the total NPVs for the three treatment schedules in the CNI region increase from NZ$3,649, NZ $3,570 and NZ$0 for pruning, plant-and-leave and carbon farming, respectively, to NZ$6,047, NZ$6,431 and NZ$3,929 when carbon prices increase from NZ$0 to NZ$25.

Qualitatively similar results apply to Otago. A point of difference, however, emerges for Northland and Marlborough, where plant-and-leave NPVs are higher than the pruning NPVs for any given carbon price at a discount rate of 8 per cent. This is the result of high costs of stand tending relative to the price for pruned logs, that is, the production of unpruned logs generates consistently higher returns than pruned logs.

Figure 1 also indicates that the treatment schedules of pruning and plant-and-leave have higher total NPVs relative to carbon farming for low to moderate carbon prices. This trend reverses at a carbon price of NZ$60 in the CNI when carbon farming becomes more attractive. It is important to note that the total NPVs in Figure 1 are highly sensitive to the assumed discount rate. Lowering the discount rate leads to more pronounced differences in total NPVs (curves are further apart), while the opposite is true for higher discount rates when less value is placed on future flows of costs and revenues (see Hale (2012) for details on sensitivity analyses).

4.1. LP optimisation

The quantities of the LP forest planning optimisation are expressed per hectare in 2008 terms for a discount rate of 8 per cent. For conciseness, we discuss the optimisation results for the CNI, New Zealand's largest wood supply region. Further details on Northland, Marlborough and Otago can be

---

[12] Pruning represents the trade-off between high quality logs and lower quantities of timber while plant-and-leave produces lower quality logs at a higher volume of wood. The latter allows for higher levels of carbon sequestration making it a more carbon-oriented profitability schedule.

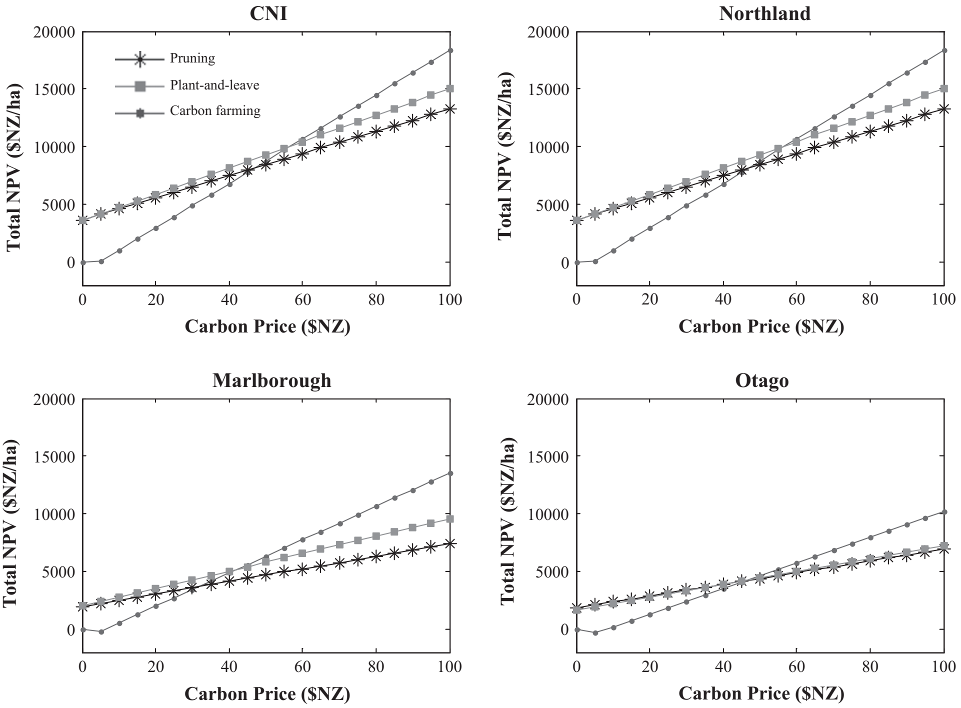

Figure 1 Total net present value (NZ$/ha) vs. carbon price (NZ$) for treatment schedule by wood supply region.

found in Hale (2012). Unless explicitly mentioned, qualitative results are understood to be consistent across the four regions, but a general comparison is provided at the end of this section.

Optimisation shows that efficient management entails assigning a treatment schedule of pruning for all the forest stands in the CNI area (i.e. $p_{\text{pruning}} = 1$ as shown in Figure 2a) at a carbon price of zero (the equivalent to no ETS). The optimal strategy instantly switches to a plant-and-leave schedule once the carbon price of NZ$5 is introduced to the LP problem (i.e. $p_{\text{plant-and-leave}} = 1$). The switch demonstrates that as long as solutions are not restricted by the 'even-flow' harvest condition of Equation (2), the LP will prescribe all forestland to the treatment schedule that achieves the highest return. Once the carbon price reaches NZ$60, the even-flow constraint becomes binding (the shift to carbon farming results in considerably lower harvest levels) and the optimal proportions are 0.9 and 0.1 for plant-and-leave and carbon farming, respectively. At the limit (NZ$100), the optimal proportions are 0.61 and 0.39.

Figure 2b shows the total NPV summed across all treatment schedules plotted against carbon prices and its composition of wood and carbon NPV (see Appendix S1 for derivation). Refer to Table 1 for numerical results. For low carbon prices, the optimal treatment schedule remains unchanged and any increase in total NPV is due to an increase in the value of carbon

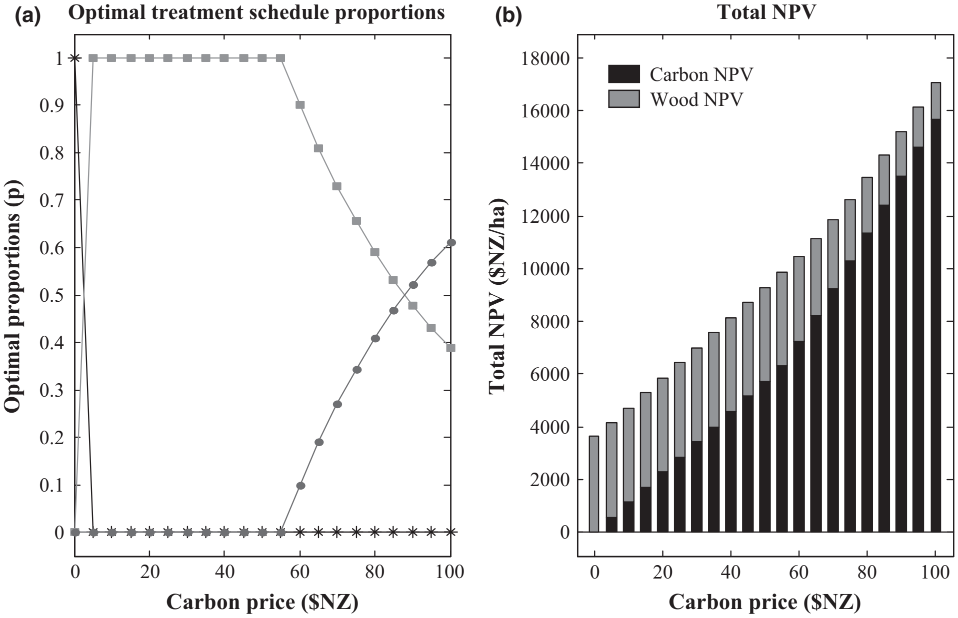

Figure 2 Linear programming optimisation output for Central North Island forestland.

Table 1 Linear programming optimisation output for Central North Island

Carbon price	Proportions			NPVs (NZ$/ha)			Harvest volume (m^3/ha)	Physical carbon NPV (t/h)
	Pruning	Plant-and-leave	Total	Carbon	Wood	Total	Total	Total
0.00	1.00	0.00	0.00	0.00	3649.13	3649.13	735.40	132.70
5.00	0.00	1.00	0.00	572.33	3570.02	4142.35	752.00	156.80
20.00	0.00	1.00	0.00	2289.32	3570.02	5859.34	752.00	156.80
40.00	0.00	1.00	0.00	4578.63	3570.02	8148.65	752.00	156.80
60.00	0.00	0.90	0.10	7247.52	3213.02	10460.54	676.80	165.20
80.00	0.00	0.59	0.41	11349.98	2108.06	13458.04	444.00	191.30
100.00	0.00	0.39	0.61	15681.52	1383.10	17064.62	291.30	208.40

sequestration. For example, a rise in carbon prices from NZ$5 to NZ$20 produces an increase in the total NPV from NZ$4142 to NZ$5859 (due entirely to a rise in carbon NPV by NZ$1717). For carbon prices above NZ $60, the optimal mixture of treatment schedules changes. We see a marked decline in wood NPV (as wood production necessarily decreases from 752 m^3 to 676.8 m^3 at NZ$60, and to 291 m^3 at NZ$100) and an increase in carbon NPV to NZ$15,682 at NZ$100.

The optimal proportions derived from the LP optimisation allow us to plot a modified PPF for timber revenue and carbon sequestration in the CNI (Figure 3). Note we derive a mPPF in that revenue of timber, not quantity, is

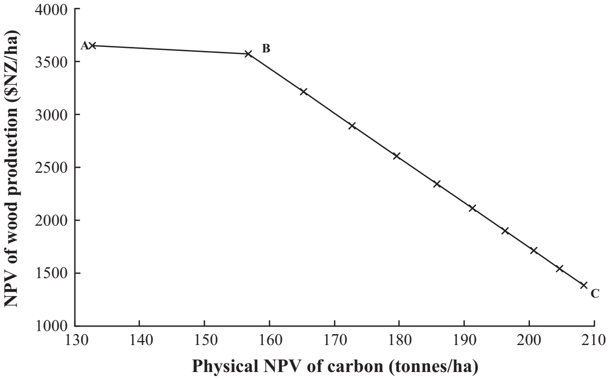

Figure 3 Modified production possibility frontiers for Central North Island forestland.

plotted against the quantity of carbon sequestered. In essence, the forestry sector selects a combination of treatment schedules which produces a point on the frontier that maximises discounted profits at current timber and carbon prices. The carbon price is then changed and the problem is re-solved. The modified PPF allows the presence of constraints and cost structures (see Burkett (2006) for an example). Figure 3 measures the NPV from wood production on the vertical axis, whereas the horizontal axis shows the *physical* NPV of carbon sequestration as in Hoen and Solberg (1994) to represent the extent to which the physical carbon sink is unaffected by the carbon price (see Appendix S1, Eqn (A.11)).

Moving from point A to B on Figure 3 (the flatter section of the frontier) shows the efficient response of management for an increase in carbon prices from NZ$0 to NZ$5 (i.e. moving from all pruning to all plant-and-leave). The resulting increase in the physical NPV of carbon by 24 tonnes (from 133 to 157, see Table 1) and decrease in the wood NPV by NZ$79 (from NZ$3,649 to NZ$3,570) translates to a reduction, or cost, of just over NZ$3 per one tonne of physical carbon NPV. At B, for a carbon price of NZ$5 to NZ$55, the optimal proportions of wood and physical carbon NPV remain unchanged. For increases in carbon prices above NZ$55, the transition of efficient management toward carbon farming is illustrated by moving from point B to C where successive increases in the physical NPV come at the cost of decreases in the returns to timber harvest by NZ$357, reflecting a constant cost of approximately NZ$42 per one tonne of physical carbon NPV. The higher opportunity cost associated with a carbon farming treatment schedule is recognised by the steeper slope of the mPPF. The corresponding opportunity costs for Northland, Marlborough and Otago are NZ$42, NZ $27 and NZ$28, respectively.

Responses for efficient management in Northland, Marlborough and Otago generally mimic those in the CNI; carbon farming becomes the most profitable at carbon prices of NZ$60, NZ$50 and NZ$45, respectively. The switch to include some proportion of carbon farming occurs at successively

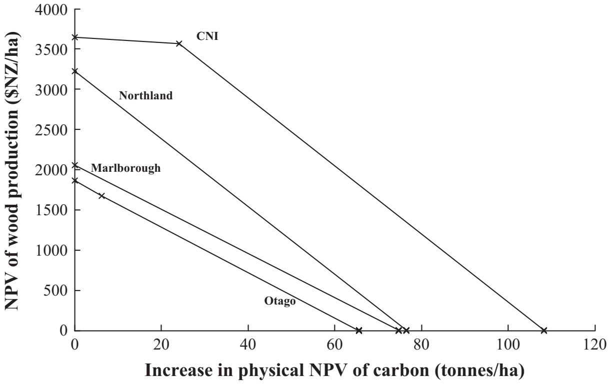

Figure 4 Modified production possibility frontiers for forestland by wood supply region (8 per cent discount rate).

lower prices between regions as the result of a 'gradient of productivity' (Backeus *et al.* 2005). Regions with higher wood NPVs such as CNI and Northland require a higher carbon price in order for carbon farming to become the more lucrative treatment schedule, while less productive regions such as Marlborough and Otago have a lower opportunity cost.

Figure 4 superimposes the mPPFs for all regions. CNI, the most productive wood supply region, is able to sequester the highest amount of carbon, shown by the higher positioning of its PPF. The trend continues for Northland, Marlborough and Otago, where initial wood NPVs of NZ$3,228, NZ$2,054 and NZ$1,863 translate into maximum increases in carbon sequestration of 76, 75 and 66 tonnes, respectively. Note the point of difference for Northland and Marlborough, where plant-and-leave is the optimal treatment schedule at a carbon price of zero and pruning is never optimal. This result is consistent with the findings in Figure 1, where the plant-and-leave NPVs are higher than the pruning NPVs for any given carbon price.

An interesting point emerges when comparing the slopes of the mPPFs. The relatively steeper sections of the mPPFs for the CNI and Northland imply a relatively higher opportunity cost in terms of timber revenue forgone than Marlborough and Otago. The approximate costs of NZ$42, NZ$42, NZ $27 and NZ$28 for an additional tonne of sequestered carbon in the CNI, Northland, Marlborough and Otago, respectively, show the trade-off between wood revenue and carbon. Despite the capacity to absorb more carbon in both CNI and Northland, the higher opportunity costs mean these regions are less efficient at pursuing carbon farming activities. However, the CNI does provide an exception. The less steep section of its mPPF implies an opportunity cost of just NZ$3 per tonne of carbon sequestered for moderate increases in carbon fixation. This is achieved by the more subtle shift in management from pruning to plant-and-leave, allowing for a higher production of forest biomass.

5. Discussion

The comprehensive introduction of the ETS is set to change efficient forestry land use in New Zealand. Even if management remains unchanged, there is a financial gain to be made with wood production from carbon trading. Due to the time value of money, the net present value of NZUs received throughout a forest stand's rotation will be greater than the NZU liability at harvest (assuming a constant carbon price). Taking advantage of this carbon opportunity entails a shift from high quality wood production of pruned logs to more carbon-oriented production such as plant-and-leave and/or carbon farming.

The timber revenue forgone can be viewed as an investment to establish higher carbon storage. Like any other profit-maximising entity, the extent of this investment will depend on its returns: the monetary value of the carbon NPV. Aside from the physical amount of sequestered carbon, this value is a function of the carbon price and discount rate. Any increases in the carbon price, *ceteris paribus*, will raise the monetary carbon NPV and therefore strengthen the signal to pursue further carbon sequestration activity. As the discount rate rises, it becomes less costly (in terms of forgone timber revenue) to do so.

The strength of the signal very much depends on the total NPVs for the three treatment schedules. In the CNI and Otago, pruning is the most lucrative treatment schedule at low carbon prices, followed by plant-and-leave and carbon farming, while in Northland and Marlborough the order of magnitude is slightly changed with plant-and-leave being the most profitable. At high carbon prices, however, carbon farming is unanimously the most profitable schedule in all four regions.

The results of our LP optimisation demonstrate the capacity for efficient increases of carbon sequestration in New Zealand. At the lower carbon price range, more subtle shifts in management will occur by switching from pruning to plant-and-leave in the CNI and Otago. For higher carbon prices, it becomes more efficient to curb harvest activity subject to the even-flow constraint. The liability created from the release of CO_2 begins to exceed the revenues of any timber produced, and at carbon prices of NZ\$45, NZ\$50, NZ \$60 and NZ\$60 for Marlborough, Otago, Northland and CNI, respectively, optimal forestry land use entails a combination of plant-and-leave and carbon farming.

The extent of timber revenue forgone for increases in carbon sequestration is illustrated by the mPPFs for each region. We find the opportunity cost in terms of loss in wood production NPV per one tonne of increase in the physical carbon NPV to depend on the wood supply region. More productive regions such as the CNI and Northland have an absolute advantage in their capacity as a carbon sink, however, less productive regions such as Marlborough and Otago have a comparative advantage due to their lower opportunity cost. An exception is provided by the CNI where moderate increases in carbon uptake can be achieved by a subtle management change from pruning to plant-and-leave.

In the absence of specifying a social welfare function, the above results imply that initial increases in carbon sequestration will be achieved at lowest cost to society by changes in tending schemes in highly productive forests and/or by increases in carbon farming in less productive forestland. The shift to more carbon-orientated land use will come at the cost of wood production revenue forgone, but forest owners are more than compensated for these losses by the financial gains from carbon trading. However, the potential reductions in the production of high-quality timber and timber harvest in general are likely to have knock-on effects which are not considered within the scope of this study, such as the redundancy of traditional forest facilities and the potential loss of export revenues.

6. Conclusion

New Zealand's commitment to reducing GHG emissions will likely lead to a welfare loss. The mPPF analysis in this study provides an indication of how changes in efficient forestry management will contribute to achieving given emission goals at least cost to society. Most importantly, the analysis highlights an important point to the successful management of climate change under an ETS: the price signal. Recent amendments to the ETS in New Zealand together with the oversupply of cheap international credits have rendered the value of carbon sequestered by forests almost worthless with carbon prices being lower than NZ$5 per tonne (Hartley 2012). Our analysis shows that at such a price, increases in carbon uptake will be moderate but may be enough to encourage some changes in tending schemes. Our modelling exercise relies heavily on a number of simplifying assumptions that cannot capture the complexities of any given forest ecosystem. Increasing the sophistication of our model such as including individualised tree data or other timber products (e.g. biofuel or amenity services) presents future opportunities for this type of study. Furthermore, the use of a stochastic model or real options analysis can incorporate the uncertainty and flexibility of forestry decisions. Our analysis presents but a first step towards the efficient management of forestry land in New Zealand under climate change initiatives.

References

Amacher, G.S., Ollikainen, M. and Koskela, E. (2009). *Economics of Forest Resources*. The MIT Press, Cambridge, MA.

Backeus, S., Wikström, P. and Lämås, T. (2005). A model for regional analysis of carbon sequestration and timber production, *Forest Ecology and Management* 216(1), 28–40.

Bertram, G. and Terry, S. (2010). *The Carbon Challenge: New Zealand's Emissions Trading Scheme*. Bridget Williams Books, Wellington.

Burkett, J.P. (2006). *Microeconomics: Optimization, Experiments and Behavior*. Oxford University Press, Oxford, pp. 75–89.

Evison, D. (2008). The impact of carbon credits on New Zealand Radiata pine forestry profitability, *New Zealand Journal of Forestry* 53(1), 42–44.

Faustmann, M. (1849). Calculation of the value which forest land and immature stands possess, *Reprinted in Journal of Forest Economics* 1, 89–114.

Hale, T. (2012). Wood or carbon? A Production Possibility Frontier Approach to Post-Kyoto Forestry Decision Making in New Zealand. Masters of Business School thesis. University of Otago.

Hartley, S. (2012). Fears for emissions trading scheme. Otago Daily Times, [online] 17th September 2012. Available from URL: www.odt.co.nz/print/226151 [accessed 18 Sep 2012].

Hess, P. (2002). *Using Mathematics in Economic Analysis*. Prentice Hall, Upper Saddle River, NJ.

Hoen, H. and Solberg, B. (1994). Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural treatment, *Forest Science* 40(3), 429–451.

Intergovernmental Panel on Climate Change (IPCC) (2007). Climate Change 2007: Synthesis Report. [pdf] Available from URL: http://www.ipcc.ch/publications_and_data [accessed 20 Apr 2012].

Karjalainen, T. (1996). The carbon sequestration potential of unmanaged forest stands in Finland under changing climatic conditions, *Biomass and Bioenergy* 10, 313–329.

Karpas, E. and Kerr, S. (2011). Preliminary evidence on responses to the New Zealand forestry emissions trading scheme. Motu working paper 11-09. Motu Economic and Public Policy Research, Wellington.

Kerr, S. and Sweet, A. (2008). Inclusion of agriculture and forestry in a domestic emissions trading system: New Zealand's experience to date. Motu Working Paper 08-04. Motu Economic and Public Policy Research, Wellington.

Kirschbaum, M. and Watt, M. (2011). Use of a process-based model to describe spatial variation in Pinus radiata productivity in New Zealand, *Forest Ecology and Management* 262 (6), 1008–1019.

Lichtenstein, M. and Montgomery, C. (2003). Biodiversity and timber in the Coast Range of Oregon: inside the production possibility frontier, *Land Economics* 79(1), 56–73.

Liski, J., Pussinen, A., Pingoud, K., Makipaa, R. and Karjalainen, T. (2001). Which rotation length is favourable to carbon sequestration?, *Canadian Journal of Forest Research* 31, 2004–2013.

Maclaren, P., Manley, B. and final year School of forestry students (2008). Impact of the New Zealand Emissions Trading Scheme on forest Management, *New Zealand Journal of Forestry* 53(3), 33–39.

Manley, B. (2012). Impact of the New Zealand emissions trading scheme on forest valuation, *Forest Policy and Economics* 14(1), 83–89.

Manley, B. and Maclaren, P. (2010). Potential impact of carbon trading on forest management in New Zealand, *Forest Policy and Economics* 24, 35–40.

Mendoza, A.J. (2012). Impact of carbon offsets trading on optimal forest harvesting. Working paper, Fuqua School of Business, Duke University, Durham, NC.

Ministry for Primary Industries (MPI) (2011). National exotic forest regional yield tables. [Online] Available from URL: http://www.mpi.govt.nz/news-resources/statistics-forecasting/statistical-publications/nefd-regional-yield-tables.aspx [accessed 5 Jun 2012].

Ministry for Primary Industries (MPI) (2012). Forestry and the New Zealand economy. [Online] Available from URL: http://www.mpi.govt.nz/forestry [accessed 5 Jun 2012].

Ministry for the Environment (MfE) (2012a). Map of regional climate impacts.[online] Available from URL: http://www.mfe.govt.nz/issues/climate/resources/impact-map/index.html [accessed 18 Apr 2012].

Ministry for the Environment (MfE) (2012b). Emissions trading scheme policy and legislation. [Online] Available from URL: http://www.climatechange.govt.nz/emissions-trading-scheme/policy-and-legislation [accessed 5 Jun 2012].

Ministry for the Environment (MfE) (2012c). Greenhouse gas reports. [Online] Available from URL: http://www.climatechange.govt.nz/carbon-reports/index.html [accessed 18 Apr 2012].

Ministry for the Environment (MfE) (2012d). The New Zealand emissions trading scheme. [Online] Available from URL: http://www.climatechange.govt.nz/emissions-trading-scheme [accessed 18 Apr 2012].

Ministry of Agriculture and Forestry (MAF) (2008a). A national exotic forest description as at 1 April 2008. [pdf] Available from URL: http://www.mpi.govt.nz/news-resources/publications [accessed 20 Apr 2012].

Ministry of Agriculture and Forestry (MAF) (2008b). Otago/Southland forest industry and wood availability forecasts 2008. [pdf] Available from URL: http://www.mpi.govt.nz/news-resources/publications [accessed 5 Jun 2012].

Ministry of Agriculture and Forestry (MAF) (2009). Central North Island forest industry and wood availability forecasts. [pdf] Available from URL: http://www.mpi.govt.nz/news--resources/publications [accessed 5 Jun 2012].

Ministry of Agriculture and Forestry (MAF) (2011). Guide to the Permanent Forest Sink Initiative. [pdf] Available from URL: http://www.mpi.govt.nz/news-resources/publications [accessed 6 Jun 2012].

Minkkinen, K., Laine, J. and Hokka, H. (2001). Tree stand development and carbon sequestration in drained peatland stands in Finland – a simulation study, *Silva Fennica* 35, 55–69.

Nalle, D.J., Montgomery, C.A., Arthur, J.L., Polasky, S. and Schumaker, N.H. (2004). Modelling joint production of wildlife and timber, *Journal of Environmental Economics and Management* 48(3), 997–1017.

New Zealand Institue of Economic Research (NZIER) and Infometrics (2009). Economic modelling of New Zealand climate change policy, A report prepared for the *Ministry for the Environment*, [pdf] Available from URL: http://nzier.org.nz/publications [accessed 5 Jun 2012].

Stern, N. (2006). *Stern Review: The Economics of Climate Change*. HM treasury, London.

Turner, J., West, G., Dungey, H. *et al.* (2008). *Managing New Zealand Planted Forests for Carbon: A Review of Selected Management Scenarios and Identification of Knowledge Gaps*. Scion, Wellington.

Uusivuori, J. and Kuuluvainen, J. (2008). Forest taxation in multiple stand forestry with amenity prefernces, *Canadian Journal of Forest Research* 38, 806–820.

Uusivuori, J. and Kuuluvainen, J. (2005). The harvesting decision when a standing forest with multiple age classes has value, *American Journal of Agricultural Economics* 87, 61–76.

Van Kooten, G., Binkley, C. and Delcourt, G. (1995). Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services, *American Journal of Agricultural Economics* 77(2), 365–374.

Zhang, W. (2010). Forest profitability panel dataset. Data documentation obtained by Motu Economic and Public Policy Research. [Online] Available from URL: http://www.motu.org.nz/building-capacity/datasets [accessed 5 Jul 2012].

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Net Present Values.
Appendix S2. Model Calibration.
Appendix S3. Data.