Manaaki Whenua
Landcare Research

Examining the effect on sediment loss by differential pricing in the ETS to encourage land use change on highly erodible land

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Examining the effect on sediment loss by differential pricing in the ETS to encourage land use change on highly erodible land

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Summary

Project and client

- The National Science Challenge 'Our Land and Water' expressed interest in examining the effect on sediment loss by differential pricing in the New Zealand Emissions Trading Scheme (NZ ETS) to encourage land use change on highly erodible land.

Objectives

- We will address three questions.
  - What is the area under exotic forestry, native forests, an alternative forest option, and pasture in highly erodible areas?
  - What is the reduction in erosion if land under pasture or exotic forestry is converted to natives or the alternative option?
  - What is the estimated carbon (C) sequestration rate and profitability of each land use class?

Methods

- We defined three land use change scenarios on highly erodible land to address the questions above:
  - highly erodible land under pasture converted to native forest
  - highly erodible land under pine production converted to native forest
  - the 'alternative forest option', which is defined as highly erodible land under pine production that will not be clear-fell harvested and instead retained as permanent exotic carbon forest (PECF).
- Land cover categories were defined using Landcover Database version 5 (LCBD5), where possible, and overlaid with the 'Highly Erodible Land' (HEL) layer to determine landcover on HEL.
- The empirical erosion model NZeem® was used to estimate erosion under existing land cover and for each of the land use scenarios named above.
- The process growth model CenW was used to estimate C sequestration of pines and mānuka/kānuka shrubland as a representative of native forest.
- The NZ-FARM model was used to estimate the profitability of each land use change scenario.

Results

- There are >1 million hectares (ha) on HEL under pasture, with the highest amount of land in Manawatū–Whanganui, Canterbury, Hawke's Bay, and Gisborne. There are c. 0.5 million ha on HEL under pines, mostly in Northland and Gisborne. There are c. 0.03 million ha on HEL under PCEF. There are c. 2.2 million ha on HEL under native forest.

- Converting pasture to native forest would decrease average annual sediment loads delivered to the stream network by 50 Mt/yr at the national scale; Gisborne and Northland would show the biggest regional decreases.
- Converting pine to native forest would decrease average annual sediment loads delivered to the stream network by 6.1 Mt/yr, mostly in Gisborne.
- Converting pines to PCEF will have minor improvements on erosion rates under current modelling assumptions.
- Look-up tables from the Ministry of Primary Industries (MPI) overestimate pine C sequestration and underestimate native C sequestration when trees are 30 years old.
- If the NZ ETS price was the same for pine and native trees, the conversion of HEL to natives would greatly increase in many regions.

Discussion and conclusions

- Converting HEL pasture to native forests should be prioritised to reduce erosion across New Zealand, and Gisborne and Northland have the highest priority to have the greatest impact.
- Converting pines to native forests will have a greater impact in Gisborne than other regions.
- MPI look-up tables should be updated to better represent C sequestration in pines and native trees; these land covers may also require the same NZ ETS price to be applied to facilitate land resilience.
- Within the NZ ETS there would need to be a mechanism to apply a higher price for natives than pines to HEL land only. This will involve a step that identifies erosion-prone land suitable for planting native trees and incentivises the planting of this land with a higher NZ ETS price for carbon sequestrated by native trees.
- This could be viewed as an 'erosion credit' and may need to be facilitated in a framework outside of the NZ ETS to ensure that on-the-ground impact is made on erosion-prone land

1 Introduction

New Zealand has been highly affected by a series of cyclones which have resulted in considerable damage to land and infrastructure, particularly tropical Cyclone Gabrielle (McMillan et al. 2023). A rapid assessment estimated Cyclone Gabrielle generated over 300,000 landslides in the eastern North Island of New Zealand, contributing 300 million tonnes of sediment to waterways, with an estimated economic cost of NZ$1.5 billion (McMillan et al. 2023).

Much of the debris and sediment comes from productive land, whether that be under grazing or forested land, as these are predominant land uses in many regions across New Zealand. Land under pasture is more vulnerable to extreme weather events than forested land (Marden et al. 1991, 1995; Phillips et al. 1991; Marden & Rowan 1993; Bergin et al. 1995; McMillan et al. 2023; Smith et al. 2023) and naturally reverted stands of mature mānuka/kānuka (*Leptospermum scoparium*/*Kunzea ericoides*). Planted exotic forests also provide considerable mitigation of erosion during extreme weather events (Marden & Rowan 1993) but with clear-felled harvest operations there is a c. 8-year window of vulnerability after harvest and before the next rotation of trees is established enough to provide erosion mitigation (Marden & Rowan 1993; Phillips et al. 2018; Marden et al. 2023). McMillan et al. 2023 found the reduction of landslide probability under native forest was 90% but ranged between 50% and 80% for exotic forestry during Cyclone Gabrielle, reflecting previous estimates (Dymond et al. 2016; Basher et al. 2020).

The New Zealand Emissions Trading Scheme (NZ ETS) is the accounting framework used to reduce greenhouse gas emissions (GHG), by tracking increases and decreases of emissions, to meet climate aspirations and obligations (Leining 2022). Changes in land cover are important factors determining New Zealand's emissions, whereby total emissions decrease with increasing tree cover (Leining 2022). Within the NZ ETS, increases in the price of carbon (C) have driven an increase in exotic forest planting. Therefore, there is potential for the NZ ETS to encourage native forest planting in the highly erodible landscapes that may reduce sediment yield to waterways. The National Science Challenge 'Our Land and Water' expressed interest in examining the effect on sediment yield by differential pricing in the NZ ETS to encourage land use change on highly erodible land.

2 Objectives

We will address three questions.

- What is the area under exotic forestry, native forests, an alternative forest option, and pasture in highly erodible areas?
- What is the reduction in erosion if land under pasture or exotic forestry is converted to natives or the alternative option?
- What is the estimated carbon (C) sequestration rate and profitability of each land use class?

3 Methods

3.1 Land use definitions

We have defined three land use change scenarios for highly erodible land to address the questions above:

- highly erodible land under pasture converted to native forest
- highly erodible land under pine production converted to native forest
- the 'alternative forest option', which is defined as highly erodible land under pine production that will not be clear-fell harvested and is instead retained as permanent exotic carbon forest (PECF).

Pasture was defined as the Landcover Database version 5 (LCDB5) land cover classes 'high producing exotic grassland' plus 'low producing grassland' (Thompson et al 2003).

Exotic forest was defined as the LCDB5 land cover classes 'exotic forest' plus 'harvested forest'. This assumes 'harvested forest' will be replanted into rotational exotic species (Thompson et al. 2003).

Native forest was defined as the LCDB5 land cover classes 'indigenous forest' plus 'mānuka and/or kānuka' plus 'matagouri or grey scrub' plus 'broadleaved indigenous hardwoods' (Thompson et al 2003). Mānuka/kānuka is included as it is usually the first stage of natural succession into broadleaf forest. Matagouri/grey scrub is included as it reaches 6 m in height and where mature stands are present it would probably be the predominant canopy cover.

*Permanent exotic carbon forest (PEC*F) is not a category in LCDB5 and was entered into the NZ ETS in January 2023 (Ministry for Primary Industries 2023). The Ministry for Primary Industries (MPI) has defined permanent forestry as post-1989 forests that will not be clear-felled and must remain in permanent forestry for at least 50 years. Further, MPI does not yet have a database of where permanent exotic carbon forests are in New Zealand. Manley (2018) surveyed New Zealand forest owners and found that 6.1% of the existing forest estate is not intended to be harvested and will remain predominantly as PECF. The spatial distribution of the landowners intending to retain existing forests as PECF was not described by Manley (2018) and it has been assumed that 6.1% of existing exotic forest estate will be PECF in each region. We recognise that there is likely to be more PCEF in areas that are more highly impacted by erosion.

3.2 Highly erodible land

The 'Highly Erodible Land' (HEL) layer (Page et al. 2005; Dymond et al. 2006) was overlaid with LCDB5 (2018) and land cover in each of the HEL classifications determined. HEL classifications include 'high landslide risk – delivery to watercourse', 'high landslide risk – non-delivery to watercourse', 'moderate earthflow risk', 'severe earthflow risk' and 'gully risk'. Not all HEL classes were present in each region. Land cover was summed across the HEL classifications to summarise highly erodible land at the national and regional scale under exotic forestry, native forest, and pasture. Data are presented as the total hectares under each land cover and as a percentage of the total 'land' excluding water, water courses and unspecified land cover areas.

3.3 NZeem

We used the New Zealand empirical erosion model (NZeem®, Dymond et al. 2010) to estimate erosion under existing land cover (baseline scenario), as represented by the 2018 class in LCDB5, and to estimate the reduction in erosion if land under pasture or exotic forestry is converted to permanent native forest. In this report, we define erosion as the average annual sediment load (tonnes) delivered to the stream network (i.e. t/yr). For these two scenarios the absolute and proportional reductions in erosion on HEL is calculated relative to the baseline scenario, summarised by region and at the national scale. For the land use change scenarios, pasture and exotic forest in LCDB5 intersecting HEL land are converted to permanent native forest.

Dymond et al. (2010) used cover factor values of 1 for woody vegetation and 10 for non-woody vegetation (typically pasture), representing a 90% reduction in erosion under forest relative to pasture. We added an additional cover factor for exotic forest of 2 to represent the lower effectiveness of plantation forests for reducing landslide erosion, estimated as an 80% reduction relative to pasture (Vale et al. 2021). This lower effectiveness relates to the 'window of vulnerability' that occurs after harvest (Phillips et al. 2018).

We show the spatial distribution of the reduction in sediment yield (t/km^2/yr) and the percentage reduction compared to the baseline contemporary land cover post land use change in map form.

3.4 Carbon sequestration

Carbon (C) sequestration for pine trees and native forests was modelled using the process-based growth model CenW (version 6.0). The model is described in Kirschbaum (1999).

Pinus radiata (pine) growth was modelled as described in Kirschbaum and Watt (2011). For pines, we started with 1000 stems/ha that were thinned at ages 5 and 8 down to 300 stems/ha. No further tree deaths were included, and simulations continued to age 30 at 300 stems/ha. The C sequestration rate for 'pines' in this report is representative of both production forestry undergoing clear-felling and of PCEF.

Native forests were represented in this growth modelling by mānuka/kānuka shrublands. Mānuka/kānuka shrublands were used to represent native forests as they are often the first stage of natural regeneration before taller native forests typically replace mānuka/kānuka stands after several decades (Wilson 1994; Funk et al. 2009; Payton et al. 2010; Overdyck & Clarkson 2012). The growth of mānuka/kānuka stands has been documented in several comprehensive data sets. The simulations for mānuka/kānuka started with 100,000 stems/ha that were reduced through self-thinning over time. The data we show are for the simulations at 30 years. The simulations modelled C sequestration over 0.05-degree (0.05°) pixels, using one set of weather data from the NIWA's virtual climate-change network (VCSN) for each 5 × 5 km square and assumed flat terrain. Differences in growth rates between pixels were related to soil properties as reflected in the national soils data layers but did not include slope or other factors that determined landscape erodibility.

The CenW layers for pine and mānuka/kānuka growth were overlaid with the HEL layer to define the growth of these forest types on highly erodible land and compared to non-HEL at the regional and national scales.

We also compared CenW modelling with the C sequestration rates used in the NZ ETS (MPI look-up tables; New Zealand Government 2022) at 30 years of age for both pines and natives. This was to understand the differences between CenW process modelling results and the data used for estimating sequestration rates in carbon accounting. We chose 30 years to be representative of the average length of a pine rotation.

3.5 Economic modelling

The New Zealand Forest and Agriculture Regional Model (NZFARM) is a comparative-static, non-linear, partial equilibrium mathematical programming model that accounts for all major farming and land uses in New Zealand. In this study, we use NZFARM to assess the financial impacts of proposed differential pricing in the NZ ETS on each land use change scenario.

The model's objective function maximises the net revenue from agricultural and forestry production subject to feasible land use area and land management options, production costs and output prices, and environmental policies (e.g. NZ ETS).

NZFARM facilitates a 'what if' scenario analysis by showing how the proposed differential C pricing in the NZ ETS could influence land use change, agricultural production and net revenues. The 'what if' scenario analyses are performed first for a baseline or status quo economic optimal condition, and then impose specific policies or other changes on the system – after which the model is rerun to derive a new economic optimal condition consistent with the scenario. Performance indicators tracked within NZFARM for this analysis include economic (e.g. net revenue, production) and environmental (e.g. carbon sequestration and GHG emissions) parameters.

The model includes the following land uses: dairy, sheep and beef, arable, fruit, vegetables, exotic forestry, permanent exotic forestry, native forestry, and scrub. In this study, land use changes are only for conversions from dairy, sheep and beef, exotic forestry to either permanent exotic or native forestry. The average C sequestration levels over all regions for exotic forests, permanent exotic forests, and native forests are 13t CO_2e/ha, 25t CO_2e /ha, and 6.5t CO_2e /ha, respectively (Ministry for Primary Industries 2017; Yao et al. 2019).

The land use areas were derived using LCDB5 (2018) incorporated with the information obtained from the 2020 AgriBase dataset (Newsome et al. 2017; Manaaki Whenua – Landcare Research 2018; AssureQuality 2020). In the baseline, the C sequestration payments for exotic forest registered in NZ ETS are included; the C sequestered by native forest is not paid; and there are no other environmental policies included. The NZU (emission unit) price was assumed to increase over time with the interest rate[1]. A carbon price of NZ$87.72/t CO2e in 2023 equated to NZ$108.62/t CO2e in 2030.

We modelled five differential pricing schemes in the NZ ETS for native forests to encourage land use change in HEL. Specifically, the land use change from pasture and exotic forest to native forest in HEL can receive a different carbon price based on mānuka/kānuka in the MPI look-up tables (Ministry for Primary Industries 2017). Five differential pricing schemes for native forest are 0.5, 1, 1.5, 2, and 2.5 times the NZ ETS carbon price for exotic forest. Both active and passive regeneration of native forest are included in this study (Mason et al. 2013). The annualised costs[2] are NZ$402/ha for active regeneration, and $NZ108/ha for passive regeneration (Dewes et al, 2022).

4 Results

4.1 Highly erodible land

The distribution of highly erodible land (HEL) is displayed in Figure A1. At the national scale, there are over a million ha of HEL under pasture, the most extensive areas are in Manawatū–Whanganui, Canterbury, Hawke's Bay, and Gisborne (Table 1; Figure A2). At the national scale there are nearly 500,000 ha of HEL under exotic forests, with the largest areas in Northland and Gisborne (Table 1; Figure A3). At the national scale there are over 2 million hectares of HEL under native forest (Table 1; Figure A2), with the largest areas in Manawatū-Whanganui and Bay of Plenty. The Taranaki region has the highest proportion of HEL under native forest. Nationwide, we estimate that c. 30,000 ha of HEL land under existing exotic forest estate will be PECF (Table 1).

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[1] Interest rates are assumed to be 3.2% in 2023 with a constant rate (3.1%) until 2030.

[2] The total regeneration costs, NZ$9,950/ha for active regeneration and NZ$4,500/ha for passive regeneration, are annualised over 50 years with a 3.2% interest rate in this study.

Table 1. Highly erodible land (hectares; ha) under pasture, exotic forest, and native forest (and as a percentage of highly erodible land) at the national and regional scale. Theoretical permanent exotic carbon forests (PECFs) are 6.1% of existing forest estate that is estimated not to be harvested (Manley 2018).

Region	Pasture (ha, % total)	Exotic forest (ha, % total)	Theoretical PECF (ha)	Native forest (ha, % total)
New Zealand	1065280 (5.1)	493128 (2.4)	30081	2239352 (10.7)
Northland	100804 (8.5)	61478 (5.2)	3750	147064 (12.4)
Auckland	6842 (1.7)	5555 (1.4)	339	23107 (5.7)
Waikato	80181 (3.6)	34943 (1.6)	2132	161987 (7.2)
Bay of Plenty	7122 (0.6)	34000 (3.0)	2076	262980 (23.1)
Gisborne	125339 (15.9)	108843 (13.8)	6639	126524 (16.1)
Hawke's Bay	126613 (9.7)	44687 (3.4)	2726	132840 (10.1)
Taranaki	51398 (7.3)	15963 (2.3)	974	212418 (30.1)
Manawatū-Whanganui	249607 (12.3)	55493 (2.7)	2385	284098 (13.9)
Wellington	56724 (7.8)	34468 (4.8)	2103	90167 (12.4)
West Coast	540 (<0.1)	1678 (<0.1)	102	188025 (11.0)
Canterbury	138171 (5.1)	15744 (0.6)	960	103247 (3.8)
Otago	49617 (2.5)	10882 (0.6)	664	43480 (2.2)
Southland	10278 (0.4)	1660 (<0.1)	101	181250 (7.6)
Tasman	5845 (0.7)	20676 (2.5)	1261	134767 (16.3)
Nelson	621 (1.7)	4642 (13.0)	283	7090 (19.9)
Marlborough	55572 (7.4)	42408 (5.6)	2587	140301 (18.6)

4.2 NZeem

Nationwide, the conversion of HEL under pasture to native forest would lead to a decrease in erosion (average annual sediment load delivered to the stream network) of 50 Mt/yr, with the largest decrease occurring in the North Island (Table 2; Figure A4). The largest absolute decrease in erosion was predicted to occur in the Gisborne region, and the highest proportional reduction was in Northland. These decreases in average annual sediment load (yield) delivered to the stream network equate to 26% nationally, with reductions above 45% for most of the North Island regions except for Bay of Plenty and Auckland (Table 2; Figure A5).

Nationwide, the conversion of HEL under pine to native forest would lead to a decrease in erosion by 6.1 Mt/yr (Table 2; Figure A6). The largest absolute and proportional decrease was predicted to occur in the Gisborne region. The decreases in erosion equate to 3.1% nationally and would lead to just over a 10% decrease in the Gisborne region (Table 2; Figure A7).

Table 2. Total erosion (average annual sediment load delivered to the stream network) under current land cover, and total erosion and reduction achieved relative to current landcover if i) highly erodible land (HEL) currently under pasture (PA) is converted to native forest (NF) and ii) HEL currently under exotic production forestry (PF) is converted to native forest (NF).

Area	Total erosion[a] under 2018 land cover (Mt/yr)	Total erosion[a]: HEL PA→ NF (Mt/yr)	Erosion reduction[b] if HEL PA → NF (Mt/yr)	Erosion reduction[b] if HEL PA → NF(%)	Total erosion[a] if HEL PF → NF (Mt/yr)	Erosion reduction[b] if HEL PF → NF (Mt/yr)	Erosion reduction[b] if HEL PF → NF (%)
New Zealand	195	144	50	26.0	189	6.1	3.1
Northland	16	5.6	10	65.2	15	1.0	6.5
Auckland	0.55	0.40	0.15	27.9	0.54	0.005	0.9
Waikato	6.9	3.6	3.4	48.4	6.9	0.043	0.6
Bay of Plenty	2.0	1.8	0.21	10.7	2.0	0.032	1.6
Gisborne	41	21	21	50.0	37	4.4	10.6
Hawke's Bay	9.6	4.6	5.0	52.3	9.4	0.14	1.5
Taranaki	3.2	1.8	1.4	44.0	3.2	0.03	0.9
Manawatū-Wanganui	12.6	6.7	5.9	46.9	12.5	0.11	0.9
Wellington	5.9	3.1	2.8	48.0	5.7	0.25	4.2
Nelson	0.04	0.039	0.0011	2.8	0.038	0.0016	4.1
Tasman	2.8	2.7	0.066	2.3	2.8	0.015	0.6
Marlborough	1.7	1.6	0.095	5.5	1.7	0.016	0.9
Canterbury	17	16	0.26	1.6	17	0.0039	<0.1
Otago	18	18	0.069	0.4	18	0.0021	<0.1
West Coast	49	49	0.022	<0.1	49	0.0044	<0.1
Southland	8	8	0.017	0.2	8	0.00047	<0.1

[a] Erosion rounded to 2 significant figures.

[b] Proportional reduction rounded to 1 decimal place.

The PCEF scenario assumes that only 6.1% of pine forests on HEL are converted to PCEF and the remaining pine forests remain in rotation harvest; and that conversion is not targeted to the most erodible forest blocks, but instead distributed across the range of erosion severities (but all on HEL). As converting pines to native forest and retaining pine trees for PCEF is assumed to have the same erosion reduction effectiveness, we therefore assume that erosion reduction under the PCEF scenario would be 6.1% of the reduction achieved by converting all pine forests to native. We present the results for this scenario below in Table 3.

Table 3. Total erosion (Mt/yr) if 6.1% of existing pines (PF) on highly erodible land (HEL) are retained for permanent exotic carbon forest (PCEF) and none are converted to native forest. Note: units are kt/yr (not Mt/yr as displayed in Table 2).

Area	Total erosion if HEL PF → PCEF (kt/yr)	Erosion reduction if HEL PF → PCEF (%)
New Zealand	372.1	0.19
Northland	61.0	0.38
Auckland	2.6	0.06
Waikato	1.9	0.04
Bay of Plenty	268.4	0.01
Gisborne	8.5	0.65
Hawke's Bay	1.8	0.09
Taranaki	6.7	0.06
Manawatū-Wanganui	15.2	0.05
Wellington	0.1	0.26
Nelson	0.9	0.24
Tasman	1.0	0.03
Marlborough	0.2	0.06
Canterbury	0.1	0.01
Otago	0.3	0.01
West Coast	0.3	0.01
Southland	0.1	0.01

Converting pasture on HEL will result in a considerably larger reduction in sediment load delivered to the stream network than converting pine trees to either native forest or PCEF.

4.3 Carbon sequestration

Carbon sequestration (productivity) by pine trees ranged across the country with lowest rates in the West Coast of the South Island and highest in the Taranaki region (Table 4; Figure A8). At the national scale there was greater C sequestration in pine trees on HEL compared to non-HEL. Carbon sequestration in mānuka/kānuka shrubland (as a representative of native forest) was lower than the sequestration potential of pine trees. For mānuka/kānuka shrublands, carbon sequestration was highest in Taranaki and lowest in Otago/Canterbury (Table 4; Figure A9).

If we compare the sequestration rates for pines modelled by CenW to those presented in the MPI look-up tables, there were some substantial differences between the rates at 30 years of growth. Across the country, the MPI tables suggest about a 25% higher sequestration potential than the CenW simulations (Table 4). That may reflect a bias in the look-up tables towards more productive regions that provided the bulk of observations, whereas the CenW simulations also estimated the growth potential for less productive sites even if they provided few observations.

These differences are also reflected in greater regional differences, with the regions with highest growth potential, Taranaki and Auckland, exceeding the reported values in the MPI tables, whereas the least productive regions, West Coast, Otago and Canterbury had lower rates in the CenW simulations than in the MPI tables. Low rates in the CenW simulations were mostly due to excessive moisture on the West Coast and limiting water availability in Otago and Canterbury. CenW simulations included all sites in these respective regions, including those where these limitations were severe and where pines would not actually be planted. However, sequestration rates in the MPI tables would have been based on more favourable sites within those regions that could have supported higher growth rates.

Sequestration rates for native (indigenous) forest at 30 years old in the look-up tables were lower than those modelled by CenW (Table 4). This is partly due to the CenW simulations explicitly modelling sequestration rates from stands of mānuka/kānuka whereas the rates listed in the MPI tables include data collected for all 'native' forest types/species combined into a single category and is therefore an average of sequestration potentials for a wide range of different forest types and terrains.

Looking at specific regions, the discrepancies were particularly strong for Otago and Canterbury, where the CenW modelled rates were less than half of the rates in the MPI tables. The reasons were probably similar as for the pine simulations and are therefore likely to be most pronounced in regions with severe growth limitations. In regions with a better average growth potential, even less favourable sites could have still supported stands so that observations across the sites with different productive potential could have been included in constructing the MPI tables.

Landowners use the MPI look-up tables to determine the value of their carbon stocks, and so we used the look-up tables in our NZ-FARM modelling. The discrepancies in sequestration rates between those modelled in CenW and those in MPI's look-up tables could result in undervaluing the C sequestration potential at the more productive sites within any given region and overvaluing of C sequestration potential at less productive sites. To avoid this, it would be preferable to account for small scale variations in estimates of the productive potential of different types of vegetation cover across a range of different sites where climatic and physical site factors can have a significant influence on growth rates. For native forests, there is the additional problem in that sequestration rates for all species are combined into a single category ('natives') and estimates of carbon stocks based on these rates do not account adequately for differences in growth and sequestration potential of stands comprising diversely different combinations of species.

In pasture systems, carbon is predominantly sequestered in the soil (Parsons et al. 2009). Soil sequestration is not included in this report, and the situation is further complicated by fodder conversion to animal products, most of which do not stay within the farm boundary (e.g. meat, milk; see Moscovici-Joubran et al. 2021).

Table 4. Rate of C sequestration in *Pinus radiata* (pine) on all land and highly erodible land (HEL), and the rate of C sequestration in mānuka/kānuka (M/K) on all land and highly erodible land at the regional and national scale in New Zealand. Cumulative pine and native sequestration at 30 years for CenW and MPI look-up tables (MPI 2017) was used to determine carbon stocks for the NZ Emissions Trading Scheme.

Region	Pine on all land tC/ha/yr	Pine on HEL tC/ha/yr	CenW pine on all land @30 year (tC/ha)	CenW pine on HEL @ 30 year (tC/ha)	MPI pine @ 30 year (tC/ha)	M/K on all land tC/ha/yr	M/K on HEL tC/ha/yr	CenW M/K on all land @ 30 year (tC/ha)	CenW M/K on HEL@ 30 year (tC/ha)	MPI native @ 30 year (tC/ha)
New Zealand	5.3	6.1	159	183	206	1.5	1.7	45	51	71
Northland	8.2	8.5	246	255	232	2.2	2.2	65	66	71
Auckland	8.3	8.3	249	249	232	2.1	2.1	62	63	71
Waikato	7.9	8.1	237	243	220	2.1	2.1	62	63	71
Bay of Plenty	7.0	6.9	210	207	205	2.0	2.0	60	60	71
Gisborne	6.8	6.8	204	204	234	1.9	1.9	57	57	71
Hawke's Bay	5.9	6.2	177	186	231	1.5	1.8	45	54	71
Taranaki	9.5	9.2	285	276	231	2.3	2.1	68	63	71
Manawatū-Whanganui	7.4	7.9	222	237	231	1.9	1.9	56	57	71
Wellington	6.1	6.2	183	186	231	1.7	1.7	51	51	71
West Coast	3.0	2.3	90	69	154	1.4	1.3	42	37	71
Canterbury	3.4	3.7	105	111	154	1.1	1.2	33	36	71
Otago	3.6	3.7	108	111	183	1.1	1.1	32	33	71
Southland	4.6	2.7	138	81	206	1.3	1.1	40	33	71
Tasman	4.7	4.9	141	147	187	1.4	1.4	41	42	71
Nelson	5.5	5.4	165	162	187	1.6	1.6	47	47	71
Marlborough	4.4	5.2	132	156	187	1.2	1.4	36	42	71

4.4 Economic modelling

There is a similar land use trend for all modelled NZ ETS carbon prices. The direction of land use change for all land uses is consistent across all modelled NZ ETS carbon prices. As the price paid for carbon sequestered by native forestry increases so will the land area established in permanent exotic and native forestry increase, while land in dairy, sheep and beef, and exotic forestry decreases relative to the corresponding baseline (Table 5). The changes in land use are mainly driven by two factors: (i) the profitability of the carbon sequestration payments to native forestry; (ii) the higher per hectare carbon sequestration level used for permanent exotic forestry relative to[3] pine production. Reductions in production and net revenues forecast for dairy and sheep and beef reflect predicted increases in the conversion of pastoral land to permanent exotic and/or native forest (Table 5).

Table 5. Relative changes (%) of land use, production and net revenue in modelled scenarios with the corresponding baseline

Land use (ha) [a]	Baseline	0.5*ETS	1*ETS	1.5*ETS	2*ETS	2.5*ETS
Dairy	2268281	-1.6%	-1.8%	-1.8%	-1.8%	-1.8%
Sheep and beef	8728775	-0.4%	-8.8%	-9.9%	-9.9%	-9.9%
Exotic forestry	1966846	-1.2%	-1.2%	-1.0%	-1.2%	-1.4%
Permanent exotic forestry	29062	120.3%	225.3%	216.7%	219.8%	224.5%
Native forestry	6860491	0.8%	11.2%	12.5%	12.6%	12.7%
Production (t)						
Milk solids	2171758639	-1.4%	-1.6%	-1.6%	-1.6%	-1.6%
Lamb	897450480	-0.4%	-9.0%	-9.7%	-9.7%	-9.7%
Beef	684166605	-0.5%	-10.0%	-12.6%	-12.7%	-12.7%
Wool	355247961	-0.4%	-8.5%	-9.3%	-9.3%	-9.3%
Net Revenue (NZD)						
Dairy	3762374598	-1.6%	-1.7%	-1.7%	-1.7%	-1.7%
Sheep and beef	1535081026	-0.9%	-11.5%	-11.8%	-11.8%	-11.8%

[a] Land use changes all happen in HEL in this study.

When native forest is compensated for carbon sequestration, the expansion of native forest distribution spans the entire country (Table 6). If the same price for carbon sequestered by exotic forests was applied to native forests, the expansion in native forest is predicted to increase across all regions particularly in Gisborne (>53%), Canterbury (>41%), and in Manawatu-Whanganui (>31%) (Table 6).

[3] The large percentage change in permanent forestry is due to its low baseline area and the land use conversion cost from pasture to permanent forest is not included in this modelling.

Table 6. Regional relative changes (%) in native forestry in modelled scenarios with the corresponding baseline

Region	Baseline (ha)	0.5[a]ETS	1[a]ETS	1.5[a]ETS	2[a]ETS	2.5[a]ETS
Northland	271602	4.9%	25.0%	25.9%	25.9%	25.9%
Auckland	76802	0.8%	5.5%	5.6%	5.6%	5.6%
Waikato	524372	0.7%	10.8%	12.0%	12.0%	12.0%
Bay of Plenty	566478	0.3%	0.8%	0.8%	0.8%	0.9%
Gisborne	187224	4.1%	48.7%	53.5%	53.5%	53.5%
Hawke's Bay	321287	2.0%	27.1%	30.9%	30.9%	30.9%
Taranaki	250949	1.1%	13.0%	15.2%	15.2%	15.2%
Manawatu-Wanganui	520626	1.7%	31.2%	32.7%	33.1%	34.0%
Wellington	213055	1.6%	21.0%	23.4%	23.4%	23.4%
West Coast	1441806	0.0%	0.0%	0.0%	0.0%	0.0%
Canterbury	334759	0.8%	32.2%	41.5%	41.5%	41.5%
Otago	207043	0.8%	22.7%	26.1%	27.0%	27.0%
Southland	1128416	0.1%	0.9%	1.0%	1.0%	1.0%
Tasman	545131	0.1%	0.8%	1.0%	1.0%	1.0%
Nelson	15696	0.5%	2.2%	3.0%	3.1%	3.1%
Marlborough	255249	0.6%	18.0%	19.3%	19.3%	19.3%

[a] Land use changes all happen in HEL in this study

A back-of-the-envelope calculation in which the C sequestration rate for pines is divided by the C sequestration rate of native trees indicates that the break-even carbon price for pines and natives would be 1.9–3.5 times that of pine trees (with an average value of 2.9 times). The NZFARM modelling indicates that where the NZ ETS price for pine and native trees is the same there will be a large increase in conversion of pastoral areas to native forest in some regions. These regions will be where profitability is currently low and where there is likely to be a small increase in land conversion if the increase in C were to increase by 1.5 times the current NZ ETS rate.

5 Discussion and conclusions

Aotearoa has a substantial amount of land on HEL that – if retired to native forest –would reduce erosion considerably and improve the economic, social and environmental heath of NZ and New Zealanders. The retirement of pasture on HEL to native forest will have a greater effect on reducing erosion than will the conversion of areas in production pines to a permanent native forest. This is due to the higher rate of landscape protection already provided by pine trees compared to pasture. Permanent exotic carbon forestry will have little impact on erosion rates compared to other land use changes, due to the small scale of this land use change.

The regions with the highest estimated decreases in erosion when pasture is converted to native forest were Gisborne and Northland. Proportional reductions nearing 50% were noted for many regions in the North Island. Regions with the highest estimated absolute and proportional decreases in erosion when pines are converted to native forest were again Gisborne and Northland. These results reflect the extent of HEL in these regions. These two regions are also expected to experience significant increases in erosion under a warming climate (Neverman et al. 2023). It is therefore critical that Gisborne and Northland are supported to facilitate the shift from pasture and pines to native permanent forest on the most highly erosion-prone land.

In particular, there is likely to be significant variability of sequestration rates both within regions and between different species within the broad native forest category. Applying the MPI look-up tables might encourage the establishment of new forests in unproductive sites or establishment of less productive native species. It would therefore be desirable to provide MPI look-up tables with greater disaggregation by species and region to reflect the actual sequestration potential more accurately across the country. The MPI tables should also include secondary broadleaf forests with larger, longer-lived, tree species than just mānuka/kānuka. The largest improvement in uptake of conversion to native forest was seen when pine and native trees had the same NZ ETS price; increasing the accuracy of the MPI look-up tables would start to move towards this.

Within the NZ ETS, if a higher value were given to native forest across all of Aotearoa's landscapes this may not be adequate to facilitate retirement of HEL land. It is likely that some landowners would take advantage of a higher price for native trees on landscapes that are not on HEL, which would minimise the impact of using the NZ ETS to retire HEL. To better target HEL, the NZ ETS would need to define areas of land that would be eligible for an increased price for native trees. This could be done using the HEL layer, although this is somewhat coarse. Finer scale modelling of erosion susceptibility is available for some parts of NZ and would need to be rolled out for the remainder of Aotearoa.

We consider that NZ ETS scenarios may include:

- no change in the price of pines and natives on non-HEL (i.e. status quo for non-HEL land)
- increased price for natives on HEL land only
- decreased price for pines on HEL land only.

Another option would be to operate an 'erosion credit', whereby landowners would be paid higher prices for native trees planted on HEL land only. This may also help with funding weed and pest control, which can dramatically increase the productivity of a native forests and increase C sequestration (Brignall-Theyer et al. 2008; Hackwell & Robinson 2021). With the dissolution of the Erosion Control Funding Programme, if the NZ ETS is not suitable for targeting HEL land, another framework may have to be established to adequately target appropriate land which interacts with the NZ ETS.

6 Acknowledgements

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Appendix 1 – Maps

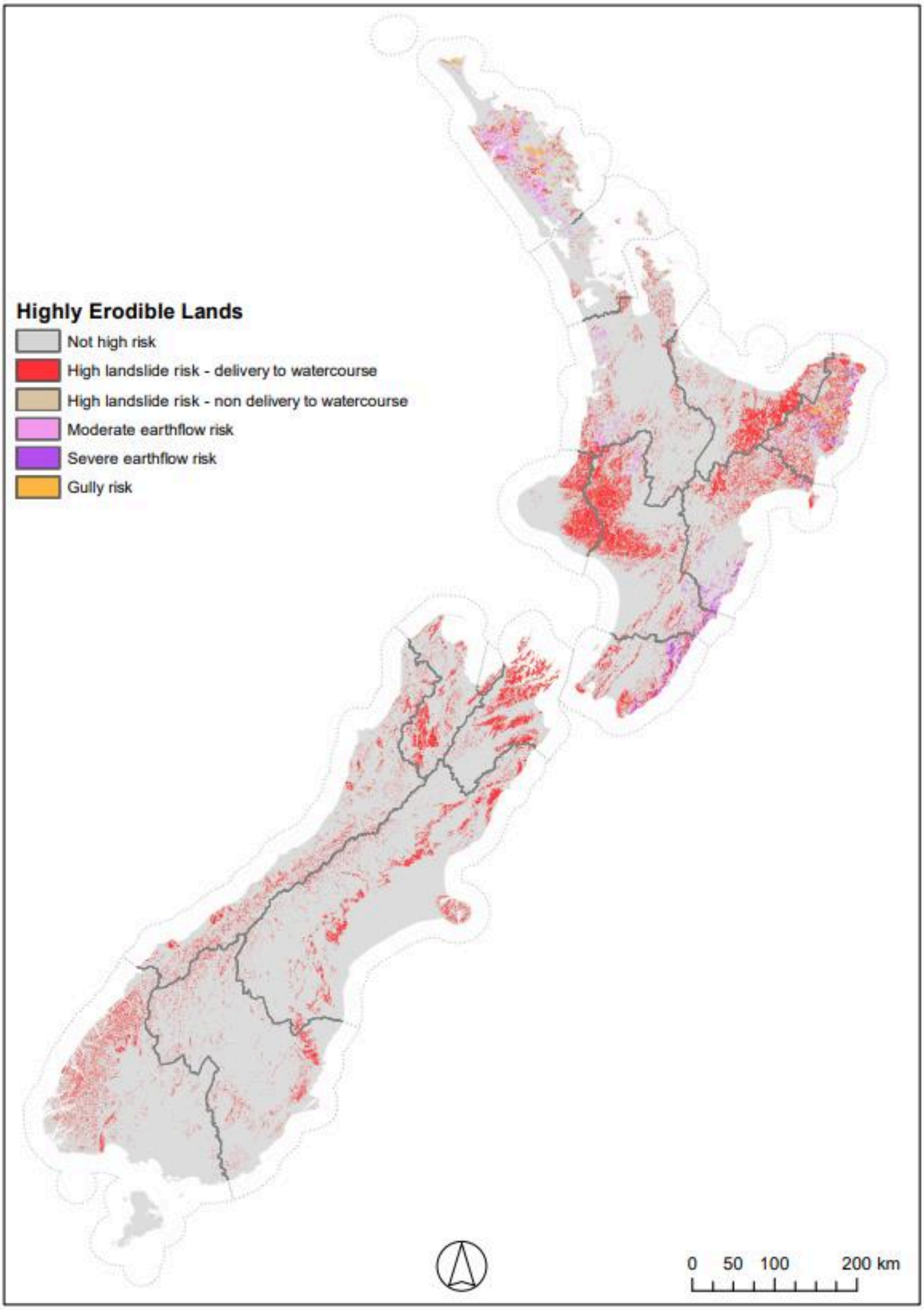

Figure A1. Highly erodible land across New Zealand.

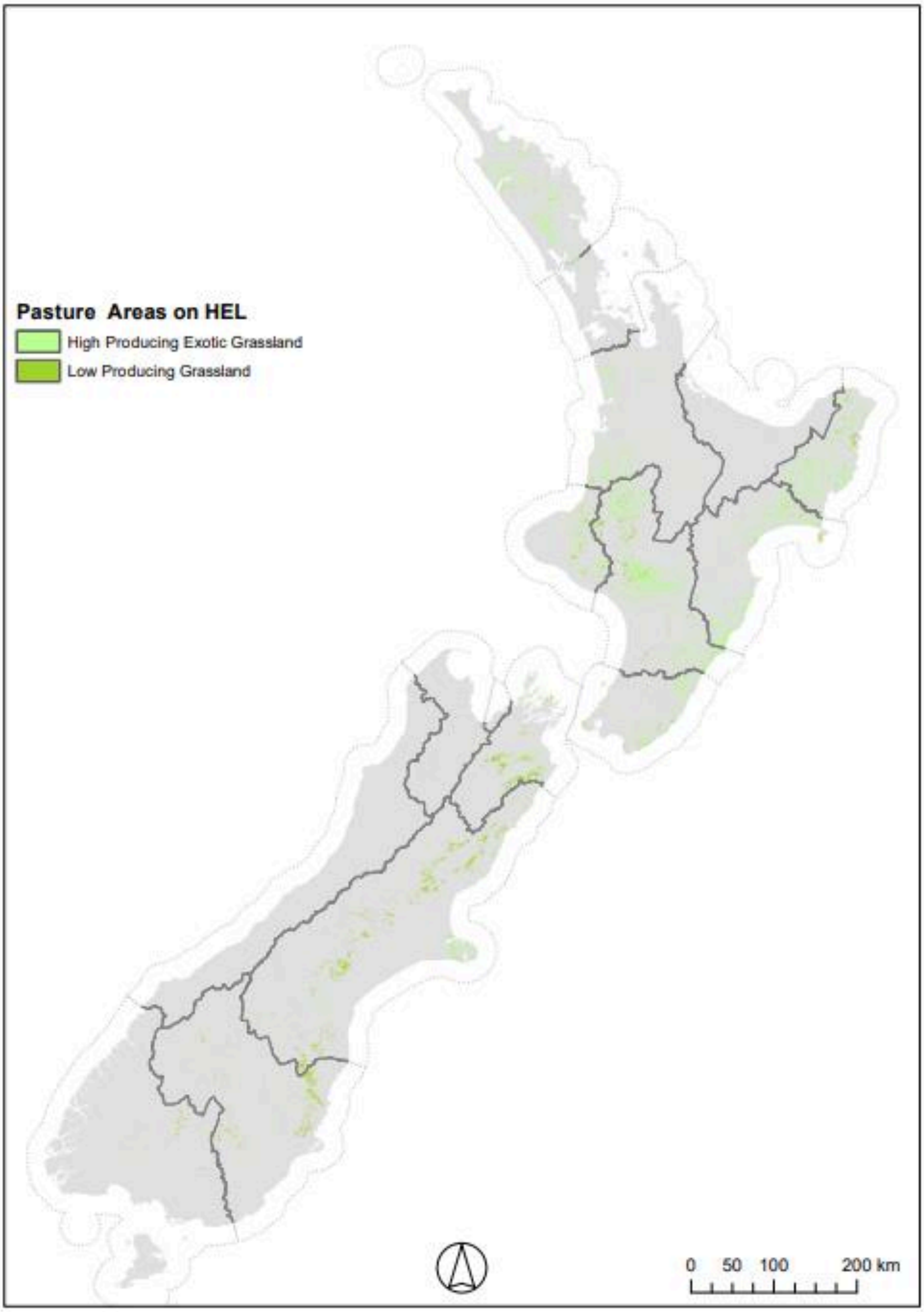

Figure A2. Pasture areas on highly erodible land.

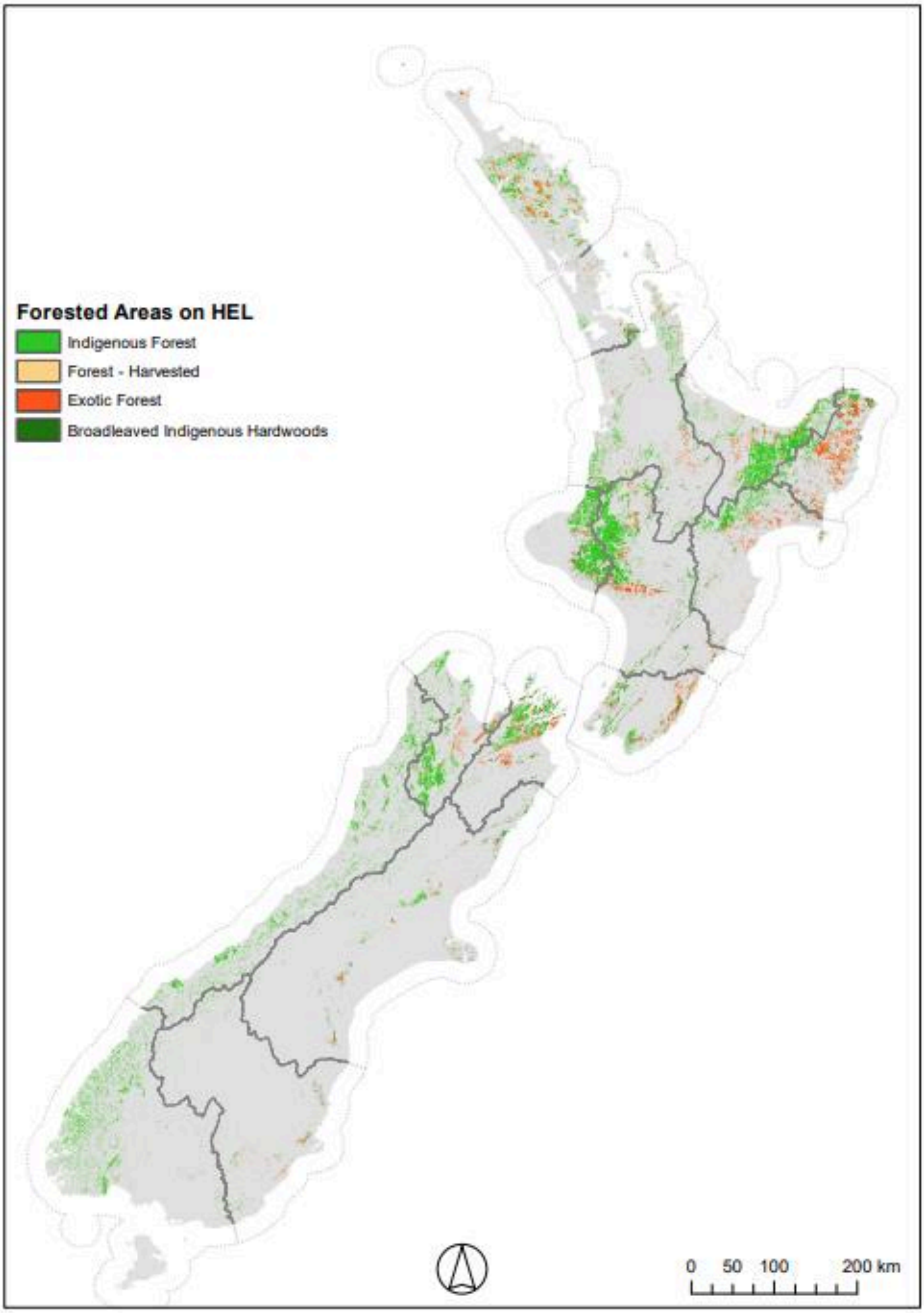

Figure A3. Forested areas on highly erodible land.

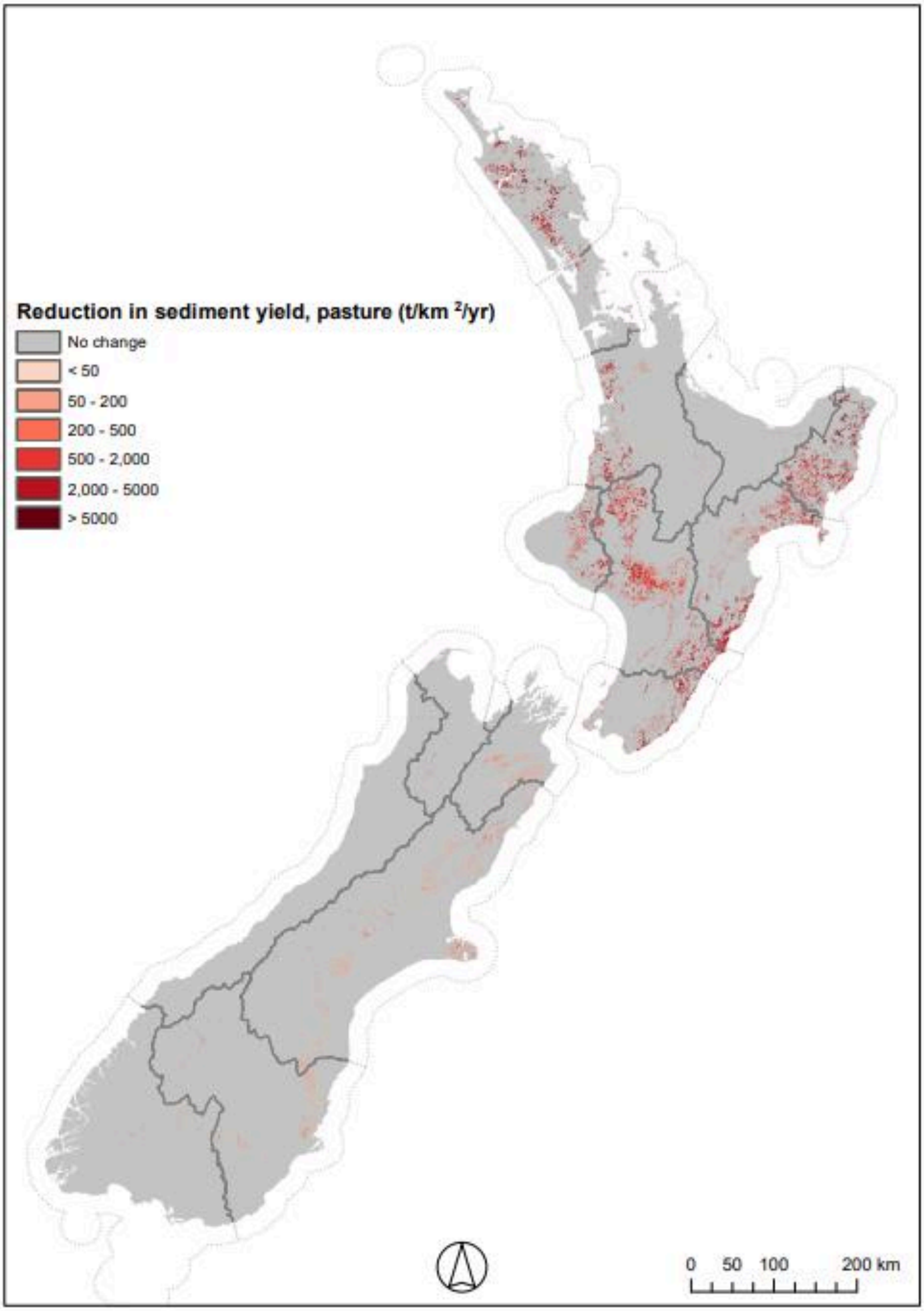

Figure A4. Reduction in sediment yield after pasture converted to native forest (tonnes per km^2 per yr)

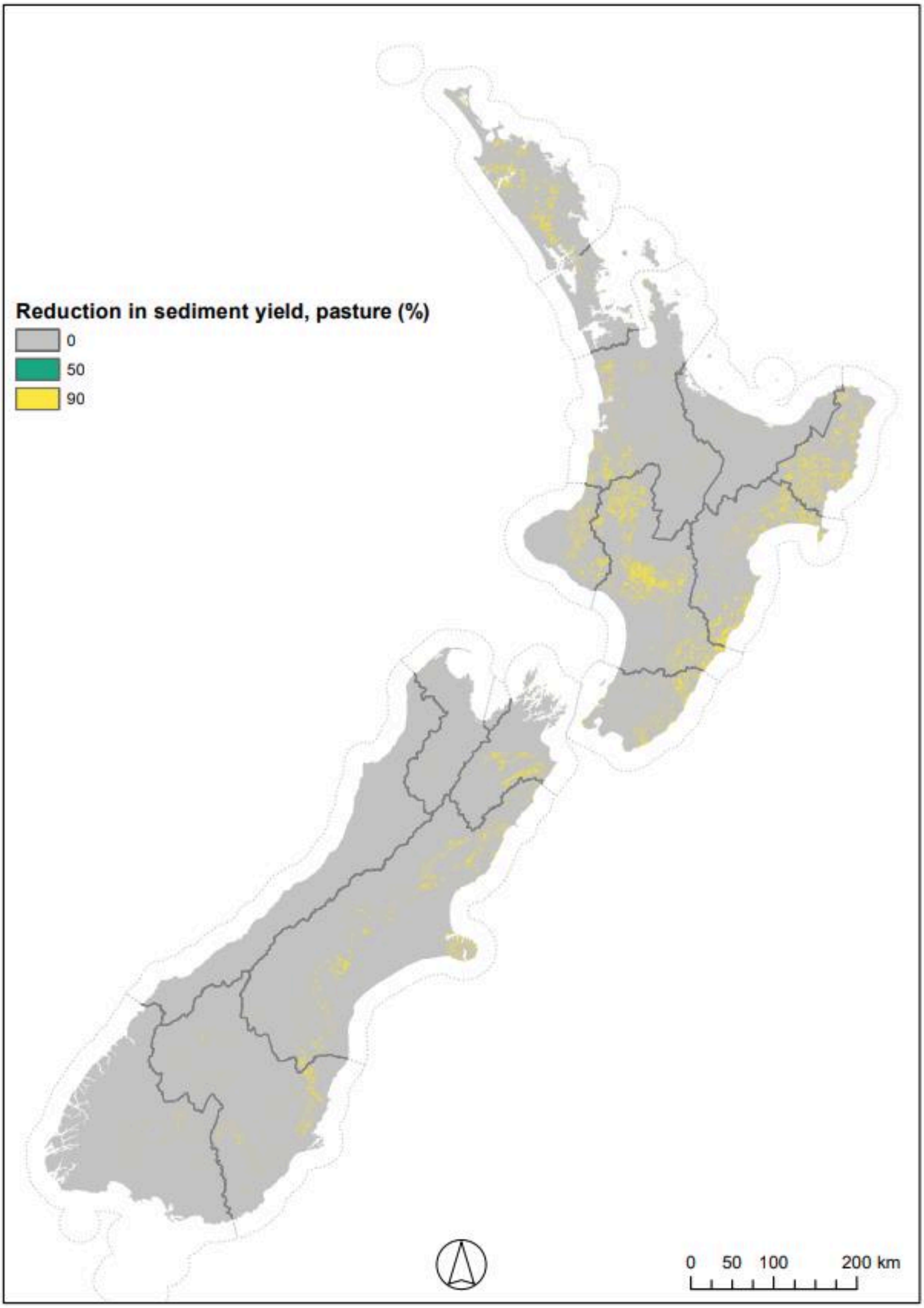

Figure A5. Reduction in sediment yield after pasture converted to native forest (%)

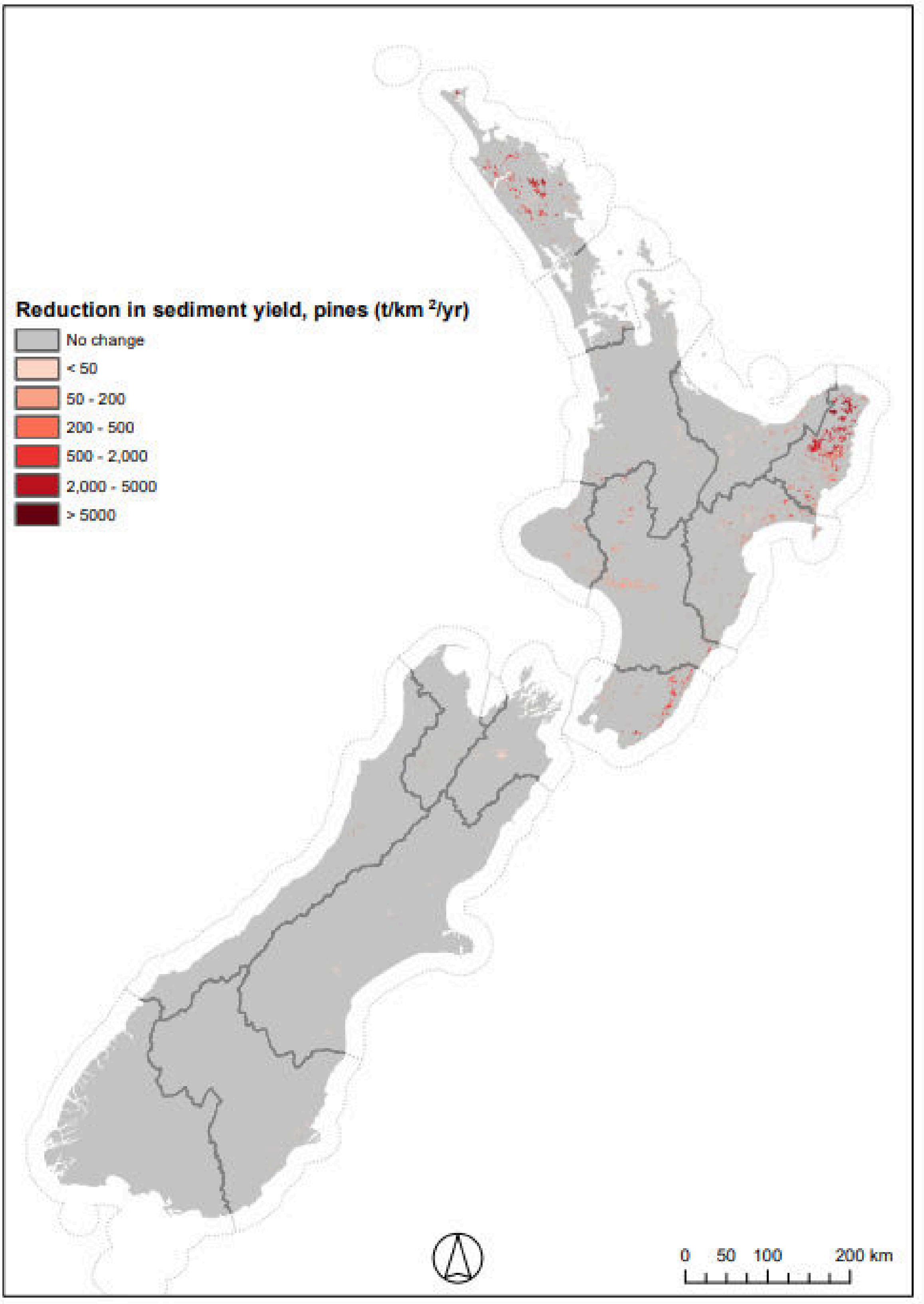

Figure A6. Reduction in sediment yield after pine forests converted to native forest (t/km^2/yr)

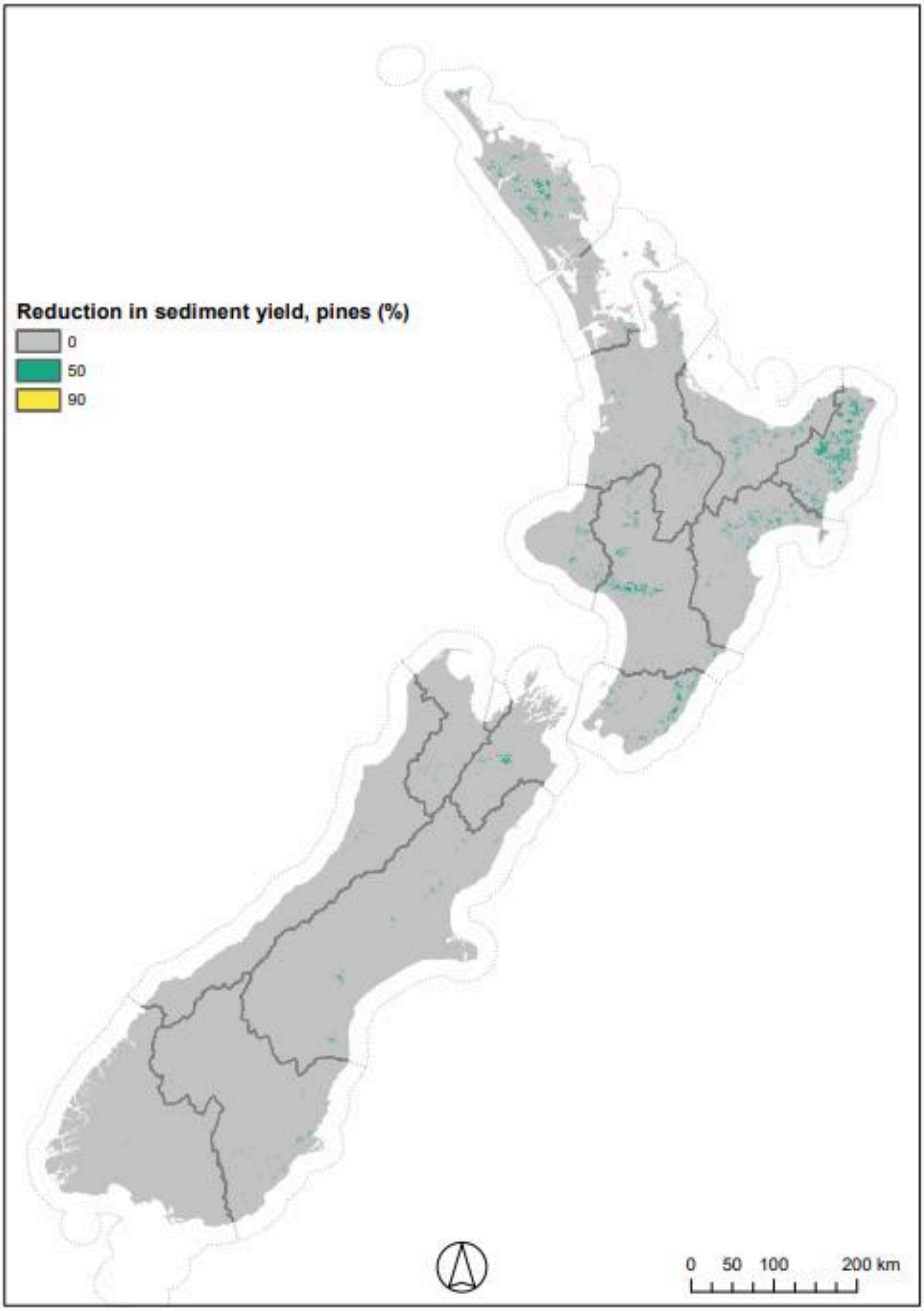

Figure A7. Reduction in sediment yield after pine forests converted to native forest (%)

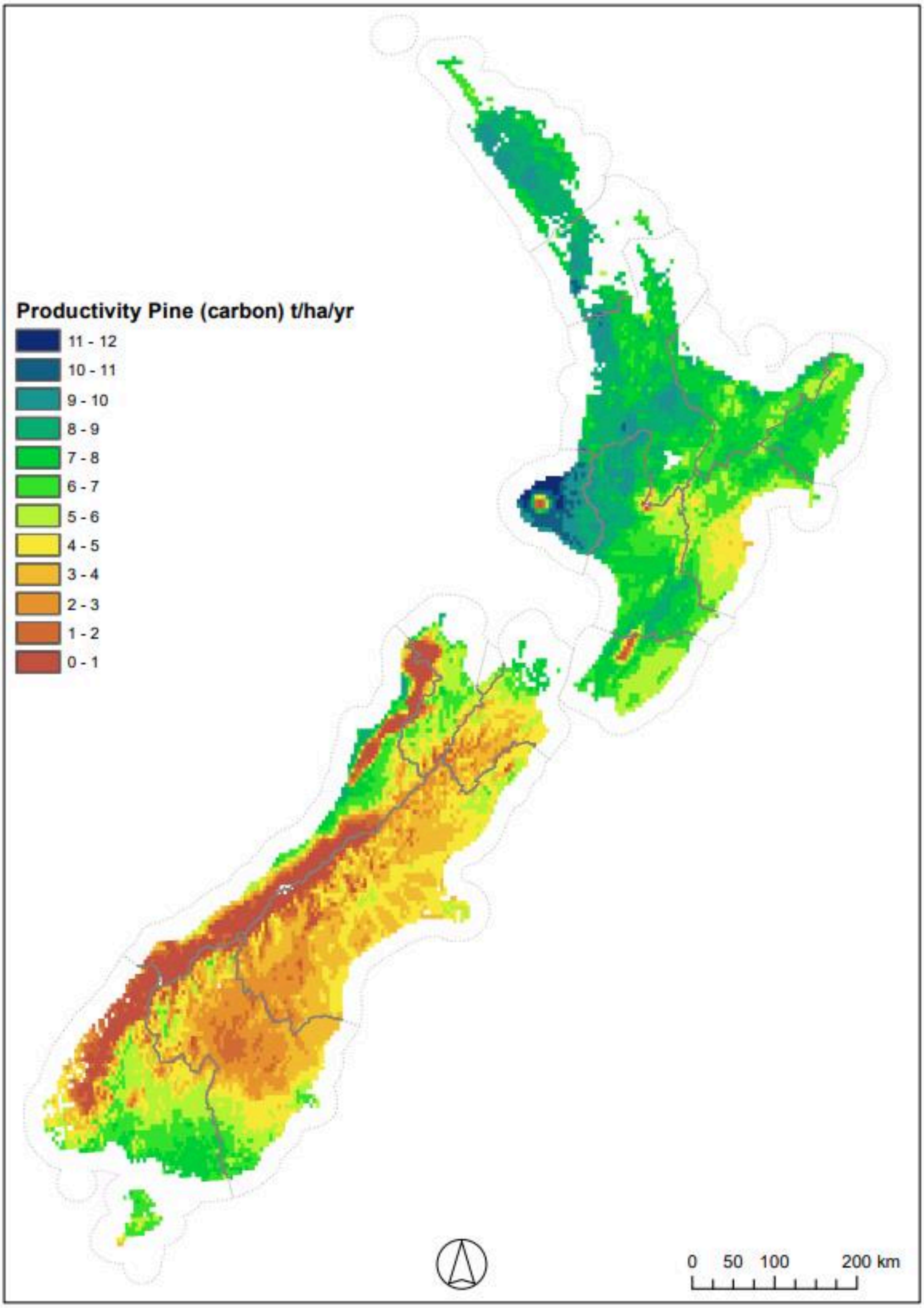

Figure A8. Productivity in *Pinus radiata* (pine) as carbon.

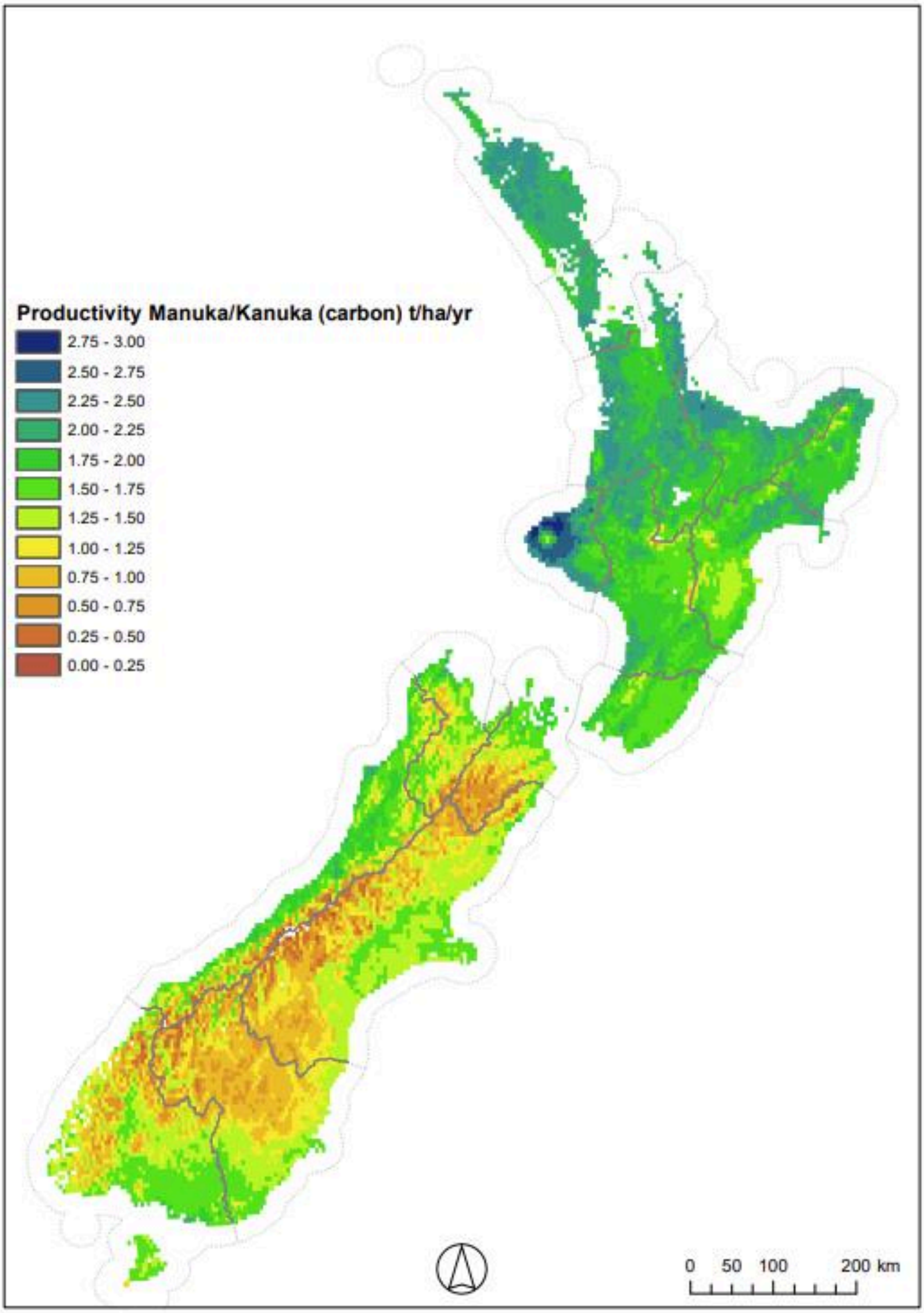

Figure A9. Productivity in mānuka/kānuka as carbon.