Chapter 9:
Removing carbon from our atmosphere

Contents

Getting to net zero emissions of long-lived greenhouse gases for Aotearoa will require removals of carbon dioxide from the atmosphere. This could mean establishing more forests or using carbon capture and storage. Whichever measure we decide to take, we must explore options for removing carbon from our atmosphere and the steps we need to take to get there.

This chapter outlines those options in detail, discussing opportunities and challenges and quantifying them when possible.

9.1 Introduction

Achieving net zero emissions of long-lived greenhouse gases and limiting global warming will require the removal of carbon dioxide from the atmosphere and the management of existing carbon stocks. Emissions removals are critical because even with a focus on gross reductions in emissions, there will likely still be residual emissions stemming from hard to abate sectors such as carbon dioxide from cement manufacturing and nitrous oxide from agriculture.

The extent to which Aotearoa relies on carbon dioxide removals to meet net emissions targets is dependent on the scale of emissions reductions in other sectors. A strong reliance on offsetting emissions through carbon dioxide removals could divert action and investment away from reducing gross emissions in other sectors.

There are three broad approaches which could be used for removing carbon dioxide from the atmosphere:

1. Increasing biological uptake and storage of carbon (e.g. through plants, soils and oceans)
2. Engineering direct capture from the atmosphere
3. Increasing inorganic reactions with rocks

The approaches above are explored through our analytical framework explained in our Advice, *Ināia Tonu Nei*. Opportunities and challenges for removals under approaches one and two above are explained in *sections 9.2* to *9.4* of this chapter.

9.1.1 Increasing biological uptake and storage of carbon

Increasing biological uptake and storage of carbon on land, particularly in forests, is the most well-known and used options for emissions removals. Forests store large amounts of carbon in the trees themselves and in the soil of the forest floor. They can be a source of carbon neutral energy when processed into biofuels and used to generate process heat, electricity or motive power. In Aotearoa, the establishment of new and management of existing forests is currently the lowest-cost emissions removal option.

There are challenges to the use of forests for removing carbon dioxide in Aotearoa, including competition for land, social and community acceptance and risks of unintended carbon release as the result of extreme events. The Parliamentary Commissioner for the Environment has warned that the frequency and magnitude of storms, floods, or pest infestations, will increase as the physical impacts of climate change intensify.[1] Apart from forests, this chapter also discusses the potential to stop or reverse emissions from other carbon reservoirs such as organic soils, wetlands and the oceans.

9.1.2 Engineering direct capture from the atmosphere

Carbon capture and storage (CCS) is the process of direct capture of emissions from the atmosphere (for example, from fuel combustion or large-scale industrial processing activities) followed by permanent storage in a reservoir. The steps involved in CCS include emissions capture, purification and compression, transport and injection and storage. The application of CCS combines a number of processes and technologies – many of which are mature and used in oil and gas production activities. Others are in various stages of technological readiness. The readiness of CCS is at a markedly different stage compared with forestry.

Traditionally, depleted or producing oil and gas reservoirs are used for long-term storage in CCS as they are known not to leak – having held methane and carbon dioxide for millennia. Deployment of CCS and the extent to which carbon dioxide is sequestered in geological formations may be limited by social and community acceptance. This would include perceptions around potential although unlikely induced seismicity, uncertain land and resource requirements, and sensitivities around the inappropriate use of land (a taonga) by placing waste material into Papatūānuku.[2] However, this may not be an issue if it involves reinjecting the fields' own gases, such as in geothermal power generation.

Bioenergy with carbon capture and storage (BECCS) combines biological capture (typically forests) with various capture and storage methods. Emissions are sequestered from the atmosphere through forest and non-forest vegetation. Once mature enough for the intended use, forest or non-forest vegetation are harvested and the biomass is burned for energy. Carbon dioxide emissions from the biomass combustion are captured, compressed and stored using conventional CCS technology. BECCS carries many of the same risks as both forestry and CCS.

9.1.3 Increasing inorganic reactions with rocks

Carbon removal through increased inorganic reactions with rocks includes enhanced terrestrial weathering and mineral carbonation. These processes accelerate the natural break down of silicate rocks to carbonate minerals. When these rocks break down, a chemical reaction takes place with carbon dioxide in the atmosphere (enhanced terrestrial weathering) or from a separately supplied source, for example, from a captured industrial emissions stream (mineral carbonation). However, these processes are not accounted for in national or international carbon accounting frameworks and are not considered in our emissions budgets in our first *2021 Draft Advice for Consultation*.

9.1.4 Future work

Robust measurements and accounting frameworks are required to include the following options in emissions budgets. These options have not been considered in this first round of advice but require further investigation as the international accounting guidelines develop and relevant local knowledge is further acquired.

[1] (Parliamentary Commissioner for the Environment, 2019)

[2] (Jaram, 2009).

Blue carbon

There are opportunities to remove carbon dioxide from the atmosphere and store it in the oceans and coastal marine habitats, also known as ‘blue carbon’.[3] Human actions can impact blue carbon through climate feedback mechanisms (e.g. climate change impacting the amount of carbon the ocean can hold) and through more direct actions (such as bottom trawling releasing benthic carbon).[4]

The carbon stored or released by direct actions is most relevant for our emissions budgets and targets, although it is not yet included in domestic or international reporting or accounting frameworks.

Examples of direct actions that can impact blue carbon are:

- Growing seaweed to rapidly sequester carbon and potentially store it indefinitely if it sinks into the deep ocean.[5]
- Fisheries practices, such as bottom-trawling, could release this carbon from the seafloor back into the ocean water and potentially into the atmosphere,[6] but how much of this carbon is ultimately released to the atmosphere is unknown.
- Maintaining and protecting mangroves and seagrasses are also effective methods of retaining and removing carbon dioxide, and also provide adaptation benefits.[7]
- Marine protection could help maintain stores of carbon in marine environments such as sea grasses, salt marshes and marine sediment.[8]

More work needs to be done on the scale and permanence of these emissions and removals and how they could be accounted for before considering them in future emissions budgets. See *Chapter 3: How to measure progress.*

Soils and peatlands

There are emissions and opportunities for emissions removals outside of forests. The soils in Aotearoa are naturally high in soil carbon.[9] It is important that we retain this soil carbon both for climate benefits and soil health.[10] While changing land use (for example from pastoral to cropping) can decrease soil carbon, the evidence base for management change (e.g. irrigation) impacts on soil carbon is still being built.[11]

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[3] ’Blue carbon‘ involves both the organic matter captured by marine organisms, and how marine ecosystems could be managed to reduce greenhouse gas emissions (Lovelock & Duarte, 2019).
[4] (Friedlingstein, 2015)
[5] (Lovelock & Duarte, 2019)
[6] (Sala et al., 2021)
[7] (Smithsonian Ocean Portal, 2018)
[8] (Beaumont et al., 2014)
[9] (McNally et al., 2017; Schipper et al., 2017; Smith et al., 2020)
[10] (Schipper et al., 2017)
[11] (Smith et al., 2020)

A small percentage of the soils in Aotearoa are classified as organic, and some of these soils are losing carbon stock rapidly.[12] This includes drained peatlands, some of which are shrinking and dropping below rising sea levels. Rewetting peat soils can halt and reverse these emissions. This would also lead to co-benefits, particularly for biodiversity and water quality. More information about this from an emissions accounting perspective can be found in *Chapter 3: How to measure progress.*

9.2 Forests and harvested wood products

This section describes the potential for forests and harvested wood products (HWPs) in Aotearoa to remove carbon dioxide. The intent is to provide an indication of the scale and feasibility of different options for increasing carbon dioxide removals by forests.[13]

Net carbon dioxide removals in forests can be enhanced by:

1. Increasing the amount of land in forest
2. Avoiding deforestation
3. Increasing the amount of long-term carbon stored by existing forests and their products

This section describes the different sequestration rates of different types of forest, the amount of land suitable for new forests and opportunities to increase sequestration through avoiding deforestation. It also discusses increasing the amount of carbon stored in each hectare of forest and increasing the volume of carbon stored in long-life wood products. This section identifies potential challenges involved with forestry as an emissions reduction option. It does not discuss issues such as accounting, biofuels, policies and how forest sequestration would be used alongside emissions reductions in budgets and targets. These are discussed in other chapters of this document.

9.2.1 Context

Aotearoa was once almost entirely covered in forests, with just the mountain tops, low-lying wetlands and some natural tussock land free from tree cover.[14] This began to change following the arrival of the first people on the shores of Aotearoa more than 700 years ago, as some forests began to be cut and burned to make way for tracks, settlements and crops. With the arrival of the first European settlers, land clearance accelerated for timber, settlements and to create grassland. Land clearing accelerated as agriculture grew, with large areas of native forest burned to make way for pasture.

There is now around 10 million hectares of forest in Aotearoa, spread across public and private land (See *Box 9.1*). The 7.8 million hectares of natural forest in Aotearoa are made up of about 6.5 million hectares of mature native forest and much of the rest is land that was once cleared, but where

[12] (Schipper et al., 2017)
[13] Emissions removals by forests refers to the net effect of carbon released from deforestation and carbon sequestered from forest growth.
[14] Prior to the arrival of humans, about 80% of Aotearoa was covered in forests. (Ministry for the Environment, 2019)

native forest is regenerating.[15] Tall natural forests store around 920 tCO_2e per hectare while forests classed as regenerating natural forest store around 230 tCO_2e per hectare and could eventually hold the same carbon stock as tall natural forests.[16] Some conifers have naturalised in Aotearoa and are accounted for as natural forests (see *Box 9.2*).

The 2.1 million hectares of production forest is 90% *Pinus radiata* which is mostly harvested through clear-fell at 25 to 30 years of age. Around 1.4 million hectares of these forests were established prior to 1990 (pre-1990 forests) and the remaining 0.7 million hectares were established after 1989 (post-1989 forests). Production forests generally have well established markets for their products, provide employment and ensure Aotearoa has a sustainable supply of wood products, now and in the future.

Carbon accumulates in forests as trees grow. Post-harvest, most of the carbon is removed off site, then stored in wood products. The amount and timing of carbon release back into the atmosphere depends on the product mix. Some of the carbon remains on site as slash, stump and roots. The life of the carbon post-harvest is determined by the wood product and the time it takes to decay. Radiata pine forests harvested at 28 years, then replanted, could store an average of around 517 tCO_2 (not including HWPs) to 752 tCO_2 (including HWPs) per hectare.[17] For the storage of carbon dioxide to be retained at this average level, the cycle of planting and harvesting would need to continue indefinitely.

Box 9.1: Forest definition and permanent forests

In the New Zealand Greenhouse Gas Inventory (the GHG Inventory), forests are defined as areas with at least 30% tree cover and being at least 1 hectare in size and 30 metres in width. For a shrubland area to be classed as post-1989 forest (and hence *Afforestation*), it must meet the forest definition and have the potential to reach 5 metres in height within a 30- to 40-year timeframe under current land management.[18]

'Permanent forests' under the current New Zealand Emissions Trading Scheme (NZ ETS) regulations are established in post-1989 forest land and registered in the NZ ETS for at least 50 years. This commitment can be renewed at the end of this period, for at least 25 years.[19]

See also our Advice, *Ināia Tonu Nei,* for definitions of different types of forests.

[15] Under UNFCCC reporting guidelines, self-sown exotic trees such as wilding conifers and grey willows established before 1 January 1990 are classified as 'natural forests' in the Land Use and Carbon Analysis System (LUCAS).
[16] Estimates based on carbon stocks in 2019 in pre-1990 natural forests: 252.1 ± 5.2 tC per hectare in tall natural forest and 62.3 ± 4.5 tC per hectare in regenerating natural forest (Ministry for the Environment, 2021a, p. 314).
[17] The 2020 long term average carbon stocks for a 28-year rotation radiata pine are estimated to be 205.2 tC per hectare with HWPs at 23.5 years, and 141.0 tC per hectare without HWPs at 17.5 years. In both cases, without soil carbon change (Wakelin, Paul, et al., 2020, p. 11).
[18] (Ministry for the Environment, 2021a, pp. 465, 486)
[19] Pecuniary penalties may be imposed if the land is clear-felled or deforested during that period (Climate Change Response (Emissions Trading Reform) Amendment Bill, 2019).

Box 9.2 Wilding conifers – A legacy issue

Wilding conifers in Aotearoa are largely a legacy issue from historic plantations starting around 1880.[20] Wilding conifers are established tree weeds that can have negative economic and ecological impacts. They currently spread over 1.8 million hectares in Aotearoa, with the potential to expand to 20% of the country by 2035.[21] Wilding conifers include Douglas fir, certain species of pines, birch, cedar, cypress, larch and redwoods. *Pinus contorta* (lodgepole) is the most invasive.[22] Wildings are included in the national accounting as part of the estimates of 'natural forests'.[23]

Estimations of the carbon sequestered by wilding conifers alone are ongoing.[24]

Most of the wilding-prone conifer species are not planted commercially.[25] For those that still are, such as Douglas fir, wildings are a recognised and controlled issue. Importantly, many people do not distinguish between production conifers and wilding conifers in Aotearoa, as found in an online survey.[26]

Non forest vegetation

Small areas of trees and vegetation on other land, such as riparian planting along waterways or shelterbelts on farms, also remove carbon dioxide and store carbon. In these areas trees and vegetation also provide other important ecosystem services, such as enhancing water quality, recreation and biodiversity conservation.

Although they do store carbon, these small areas of vegetation are often not part of the overall net emissions for target accounting in Aotearoa in the same way as forests. This is for several reasons, such as the ability to reliably count small areas of planting, as well as track their harvesting and/or deforestation.

There are different ways of accounting for carbon losses and gains within forests, depending on the purpose. These include international accounting for our targets, and domestic accounting in the NZ ETS. *Chapter 3: How to measure progress* gives more information on accounting approaches.

9.2.2 Options for increasing forest carbon dioxide removals from the atmosphere

A range of exist to increase the net carbon dioxide that forests can remove from the atmosphere. These include:

- New native and exotic forests

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[20] (Ledgard, 2001)
[21] (Ministry for Primary Industries, 2020b)
[22] See Schedule 7, Forest species that are tree weeds. (*Climate Change (Forestry Sector) Regulations 2008 (SR 2008/355)*, 2010)
[23] Under UNFCCC reporting guidelines, wilding conifers established before 1 January 1990 are classified as natural forests in the Land Use and Carbon Analysis System (LUCAS).
[24] Thomas Paul, Scion, Pers. Comms.
[25] (Froude, 2011)
[26] (Greenaway et al., 2015)

- Avoiding deforestation
- Increasing carbon stocks in natural and planted forests
- Increasing the proportion of long-lived wood products

The various options have different rates of carbon removal and storage and vary in their costs, co-benefits and interactions with other removal options. They also have quite different impacts on local communities and differ in their social and cultural acceptability.

Policies have provided incentives for planting exotic forests, and to a lesser extent, for native afforestation.[27] While there is currently a higher focus on native plantings and restoration, there is limited knowledge on native forests' cash flow, carbon benefits and co-benefits, along with limited processing infrastructure and markets.

Forest management alternatives

The carbon benefits and other co-benefits that different types of forests provide vary with their growth cycle, type of forest management or silvicultural system applied and the site location. While most production forests in Aotearoa are clear-felled, there are other forest management options available such as:

- **Selective harvesting/continuous cover forests** in which trees are harvested individually or in small groups, providing a more even cash flow when compared to clear-felling.[28] This approach requires individual tree inventories and skilled staff.[29] It has been applied in Canterbury with radiata pine[30] and is widely practiced in some European countries[31] and in tropical forests.[32]Currently native forests in Aotearoa can be selectively harvested under Sustainable Forest Management plans and permits.[33] These forests can be considered as 'permanent' if they continue to meet the definition described in Box 9.1.
- **Rotation coppicing** comprises the regrowth of trees from stumps (coppicing) means that replanting is not required, which reduces a major cost. The carbon removal value depends on the density of planting and frequency of harvest. Pilots using willow in Aotearoa show potential for producing biomass that could be used for energy generation or chemical production.[34,35] Redwoods are known for coppicing vigorously after thinning.[36]

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[27] (Ministry for the Environment, 2020a)
[28] (Barton, 2008)
[29] Continuous cover forestry has many synonyms and semi-synonyms (Pommerening, 2004)
[30] (Perry et al., 2015)
[31] (Lundmark et al., 2016)
[32] (Hari Poudyal et al., 2018)
[33] These Sustainable Forest Management plans and permits must comply with Section 3A, Forests Act 1949 (Te Uru Rakau, 2019).
[34] (Snowdon et al., 2013)
[35] (Sims et al., 2001)
[36] (Nicholas, 2015)

- **Short rotation forestry** involves planting a site, then felling trees of typically 10 to 20 cm diameter after between 8 and 20 years.[37] This approach is not widely practiced in Aotearoa.[38] The trees are usually used for biomass for energy generation or chemical production.

In addition to timber, forests can be managed to obtain non-wood forest products. Some production forests in Aotearoa are already trialling growing ginseng,[39] truffles,[40] and medicinal plants.[41]

Table 9.1 outlines the key opportunities and challenges associated with carbon dioxide removals by forests and HWPs. More detailed considerations of the impacts and policy implications are contained in *Chapter 17: Impacts on environment, ecology, and the ability to adapt to climate change* and *Chapter 19: The direction of policy for Aotearoa.*

Table 9.1: Options for increasing carbon removals through forests and HWPs

Option	Opportunities and challenges
Exotic forests	From an environmental perspective, the main opportunities of exotic forests refer to their rapid growth and removal of carbon dioxide. When planted in the right place and adequately managed, these forests provide co-benefits such as improved water quality,[42] opportunities for recreation, avoided sedimentation[43] and habitat for some native species.[44] From an economic perspective, the well-established markets for timber, tree propagation know-how and processing infrastructure for exotic forests, mainly radiata pine, are key opportunities. On the other hand, the social and cultural acceptability of large-scale production forests is amongst their key challenges.[45] It is, however, difficult to disentangle the impacts of afforestation from the impacts of several other factors, such as urban drift and the evolving sheep and beef sector. See *Chapter 17: Impacts on environment, ecology, and the ability to adapt to climate change.* Exotic forests can also be integrated into farms. See *section 9.2.5 Small scale afforestation and mosaic landscapes.* **Exotic production forests**. There are exotic forests planted with an intention to harvest. In Aotearoa most production forests are radiata pine – almost all of which are in a clear-fell regime.

[37] (Forest Research, 2021)
[38] With some exceptions such as second rotation forests grown for structural timber in the Bay of Plenty (Peter Beets, pers.comms.)
[39] (Pure-Ora of New Zealand Ltd, 2016)
[40] (Guerin-Laguette et al., 2014)
[41] (Ministry for Primary Industries, 2015)
[42] (Baillie & Neary, 2015)
[43] (Yao et al., 2013, 2016)
[44] (Borkin & Parsons, 2010; Brockerhoff et al., 2001; Pawson et al., 2008; Pawson et al., 2010)
[45] Large scale afforestation will inevitably affect some communities in terms of the local workforce and culture (New Zealand Productivity Commission, 2019). The social licence of production forestry has been affected by extreme weather events, such as flooding (e.g. Tolaga Bay 2018 and 2020) where post-harvest residuals (slash) caused damage to neighbouring land.

Option	Opportunities and challenges
	Exotic production forests can sequester carbon quickly. One hectare of radiata pine could sequester carbon at an average rate of about 34 tCO2 each year, over the approximately 28 years of a standard rotation – although the rate of growth is much slower in the first five years.[46] Once the trees are harvested, some carbon is left on the ground and the carbon stored in the finished product decays over time and is ultimately released back into the atmosphere. The rate of release depends on what the harvested wood is used for (see *Increasing carbon storage in forest products* at the end of this table). If trees are replanted, the growth cycle begins again. If this cycle is repeated indefinitely, an area of land in production forest may be thought of as a long-term carbon sink. The long-term average carbon stock of about 752 tCO_2 per hectare is reached after around 23.5 years for a radiata pine forest that is on a 28-year rotation.[47] Carbon dioxide sequestration rates vary with location as different site conditions affect the establishment and growth of the trees. Planting and ongoing management costs range from $1,200 to $7,000 per hectare (usually on the lower end).[48] Including silviculture and harvesting costs, a landowner may earn, for example, a return equivalent to approximately $400 per hectare per year in the East Coast[49] (excluding carbon revenue). However, the overall revenue depends heavily on factors such as log price, site access and distance to port or processor. Other exotic species also planted in commercial forests include Douglas fir, redwoods, macrocarpa or eucalypts. There are potential benefits to diversifying commercially planted tree species, including increasing the sector's resilience to wildfire, pests and pathogens,[50] as well as to volatile international markets. Owners of some existing commercial forest and some Iwi/Māori-collectives, have expressed an interest in converting exotic forests to native species following harvest, while others are actively managing their exotic forests.[51]

[46] Average based on data from the GHG Inventory, post-1989 planted forests (Ministry for the Environment, 2021b, pp. 57–58).
[47] Estimate includes HWPs. Without factoring in these, the long term average carbon stock is 517 tCO_2 at 17.5 years (Wakelin, Paul, et al., 2020, p. 11).
[48] Based on data for the ENZ model used by the Commission, establishment costs vary with region and quintile for structural regime; 28 years, 833 initial stocking, thinning to waste to 500 stems at age 7. Includes new land planting, not regeneration at thinning and moderate walk hindrance. Weed control costs are included but fencing costs are highly variable and site specific so are not included (Peter Hall, Scion, Pers. Comms.).
[49] Figures based on East Coast case study, structural regime, assuming log price of $115 per m^3, costings and volume assumptions from (Pizzirani et al., 2019) and discount rate of 6%.
[50] Because different species and sites are more or less susceptible to these threats.
[51] For example (Lake Taupō Forest Trust, 2020; Te Runanganui o Ngati Porou, 2018)

Option	Opportunities and challenges
	Alternative models for exotic forests. Some exotic forests are established with no intention of harvest.[52, 53] An unharvested planted forest, for example, could remove about 2,800 tCO_2 per hectare over 80 years.[54] However, over time the carbon stored could be released back into the atmosphere as trees eventually die. See *section 9.2.3 Risks and limits to removals from forests*. In theory, if these forests are actively managed, some exotic species could act as a **nurse crop** and accelerate the establishment of native forests.[55] This approach could achieve quick and early carbon removals together with the long-term ecological benefits of native forests. This process could take between 100 and 300 years, depending on factors such as climate, pest control, forest management, soils and seed sources. Radiata pine is known to survive up to 150 years when planted as single or a few trees.[56] Exotic forests could be managed in shorter rotations, longer rotations (e.g. 60 years)[57] or with alternative forest management techniques such as small-coupe clear-felling or continuous cover forests[58] (see *section 9.2.2 Forest management alternatives*). Some existing forests could also be retired from production.[59, 60]
Native forests	Native forests have slower growth rates compared to exotics, and therefore also slower carbon dioxide removals. Native forests can provide an enduring carbon sink for Aotearoa across several generations. Amongst the most important co-benefits of multi-species native forests are high biodiversity as well as cultural, recreational and spiritual benefits.[61] From an economic perspective, native harvesting is currently a niche market although some programmes are exploring how to improve economic gains.[62] Amongst the key challenges of native forests as mitigation options is their susceptibility to browsers and pests and the high planting and establishment costs.

[52] (NZ Carbon Farming, 2019)
[53] Some of these forests have been incorrectly called 'plant and leave'. Forests require ongoing management to maintain the health of the ecosystem, and in the case of 'carbon forests', to secure carbon stocks that are enduring.
[54] Extrapolated based on data from the GHG Inventory, post 1989 planted forests (Ministry for the Environment, 2021b, pp. 57–58)
[55] (Brockerhoff et al., 2003)
[56] (Woollons & Manley, 2012)
[57] Based on data of permanent sample plots over 50 years in Aotearoa, a study found that growing radiata pine on a rotation of 60 years is feasible, and it may be possible to use much longer rotations (Woollons & Manley, 2012).
[58] (Amishev et al., 2014)
[59] (Phillips et al., 2015)
[60] (Amishev et al., 2014)
[61] (Department of Conservation, 2020)
[62] For example, a project in Northland found that there are 'sustainable and viable business opportunities based on sustainable and ecological management of farm-based naturally regenerating tōtara' (Dunningham et al., 2020).

Option	Opportunities and challenges
	A key co-benefit of native forests is their high biodiversity value as they provide unique habitat for a large range of plants, animals and fungi.[63] In te ao Māori, there are cultural benefits associated with native forests which include mahi toi (artistic pursuits). For example, Whakairo (carving), tukutuku (meeting house panels), raranga (weaving), rongoa (medicine), kaitiakitanga (preservation of species), toi rakau (making traditional weapons), whakatuu raakau (weapon skill) and associated skills and cultural practices . On some leased land that has been returned to Māori (e.g. Ngati Tuwharetoa ki Kawerau), Māori are planting native forests for cultural reasons. There are some Iwi and hapū managing their native forests,[64] as well as small tourism businesses which use buried Kauri, highlighting the value (commercial and traditional) in working with native timbers.[65] Native forests continue to sequester carbon for hundreds of years, eventually reaching a steady state of around 920 tCO_2 per hectare.[66] There is limited information on native forests' carbon dioxide removal rates. The NZ ETS lookup tables have one value covering native forests, which indicate 323 tCO_2 is removed after 50 years.[67] When the planted forest area is larger than 100 hectares and registered for the NZ ETS, forest managers are required to do field measurements so that the actual tree growth is registered. Under certain circumstances, for example using species such as Kauri, native planted forests remove carbon dioxide at greater rates than the values from the NZ ETS look-up table.[68] Harvest rotations for native species could be considerably longer than for exotic forests and could result in lower environmental impacts from harvesting. Native forests managed on a continuous cover management approach could be considered an enduring carbon sink. The longer rotations also mean there is a long delay before earning timber income. Profits vary substantially, depending on factors such as location, species, carbon income and other potential income streams (e.g. from honey, eco-tourism, medicines). However, there are not currently well-developed markets and processing capacity for native timbers. In addition,

[63] (Ausseil et al., 2011)

[64] (Ngati Hine Forestry Trust, 2019)

[65] (Ka-Uri Unearthed, 2019)

[66] Indicative value for natural forests, these are mainly native species but include some naturalised exotic species, such as wilding conifers (Ministry for the Environment, 2021a, p. 266).

[67] A single default lookup table applies for all native forest species across all regions, although the amount of carbon sequestered by different types of native forest in different regions is likely to vary considerably. The current lookup table is based on regenerating indigenous shrublands (mainly mānuka and kānuka) (Ministry for Primary Industries, 2017a).

[68] For example, measurements of a stand of 69-year-old Kauri in Taranaki show that it sequesters about 19 tCO_2 per hectare each year, on average. The stand is estimated to be able to store about 1,300 tCO_2 per hectare when mature (Kimberley et al., 2014, p. 5).

Option	Opportunities and challenges
	native forests face additional regulations with respect to sustainable forest management. Establishing new native forests can be done either through reversion, planting and other methods (e.g. enrichment, nurse crops). **Reversion** is achieved by setting up the conditions to revert into native forest, removing pressures on young seedlings to enable a native forest to re-establish. If local seed sources are available and the climate and site fertility are favourable, the forest may naturally grow (or revert).[69] Costs vary widely depending on factors such as site, desired density and survival rates. Establishing natives through reversion is a cost-effective option and may include an up-front cost of around $1,100 per hectare for fencing,[70] and ongoing annual costs of around $500 per hectare for pest and weed control. In less productive farmland, species like mānuka and kānuka are usually the first to thrive. They are followed by other species like rimu after a few decades.[71] **Planting** establishment costs are around $6,600 per hectare[72] and can be as high as $20,000 to $50,000 per hectare.[73] Fencing and ongoing pest control are required to protect the new forests. If new native forests are selectively harvested, there would also be infrastructure costs such as roading and periodic thinning and/or pruning. **Enrichment** involves planting of desirable species into secondary, exotic or degraded forest.[74] Enrichment costs will depend on various factors such as the number of seedlings to be planted, method of planting and quality of the site. Access to native seedlings is a constraint to scaling up native forests. A recent survey of native tree nurseries[75] notes their production capacity; there can be a lead time of 2-4 years for accessing native seedlings. Native tree seedlings production in 2019 was 10.6 million plants and is estimated to be able to grow by 7.5% per year to 20 million by 2027. However, scaling up requires planning and cooperation across government, industry and the public. Mature native trees and shrubs are also particularly vulnerable to introduced pests, especially browsing mammals like possums, deer and goats. The presence of these animals can affect the composition of the forest, rates of regeneration and carbon sequestration,[76] and some species populations

[69] For example, tōtara regeneration in Northland (Tōtara Industry Pilot, 2019).
[70] Based on estimates from conservation covenants (Scrimgeour et al., 2017), similar to the national average of around $8/m; estimates vary with slope and region from $2.0/m to $20.0/m. (Ministry for Primary Industries, 2017b)
[71] (Wotton & McAlpine, 2014)
[72] (Bergen & Gea, 2007; Pizzirani et al., 2019)
[73] Adele Fitzpatrick, Project Crimson, Pers. Comms.
[74] (A. Forbes, 2021a)
[75] (New Zealand Plant Producers Incorporated (NZPPI), 2019)
[76] (Anderegg et al., 2020)

Option	Opportunities and challenges
	have been rising over the past decade.[77] Predators like rats, stoats and cats can also affect populations of native birds, bats, lizards and insects, which in turn can hamper the dispersal of native seeds. They can cause local or total extinction. The survival of many native animals also depends on effective pest control.[78] Expanding native forests on farms would result in a loss of grazing land, and potentially loss of other on-farm functions such as places to put animals to avoid pugging. However, there would also be a reduction in the amount of time spent keeping this pasture free of scrub.[79] **Nurse crops.** There is emerging evidence of native forests able to revert under pine canopy gaps so existing pine forests could transition to native forests.[80] Facilitating this process would require adequate forest management, based on ecology, and addressing the threats to regeneration and forest succession, at forest stand and landscape scales.[81] (See also *Exotic forests* at the top of this Table). See also *9.6. Appendix. New native forests: Scale of potential investment.*
Avoiding deforestation	Deforestation is cutting down a forest and converting the land to a non-forest activity such as pastoral agriculture. This leads to a carbon dioxide emissions equivalent to that held in the forest (above and below ground) and loss of ecosystem services. This is partially offset by a small gain in soil carbon if the land is converted to pasture. The 'glut' of forests planted in the 1990s will be due for harvest in the mid-2020s, which is a natural decision point for replanting or converting to a different land use. Many of these forests are smaller and are also not in the NZ ETS, which means they are not subject to a 'deforestation liability'. This could lead to a significant amount of deforestation over the coming decades. The deforestation emissions would be reflected in our emissions budgets and in accounting for our international targets, so could make it more difficult to reach those budgets and targets. In 2019, the net emissions from deforestation were 2.9 $MtCO_2$.[82] Most of the deforestation area in 2019 is pre-1990 planted forests.[83]
Increasing carbon stocks in planted forests	Improving forest genetics and forest management techniques could lead to higher wood density and volume. This would lead to an increase in carbon removals and storage per hectare. Current genetics programmes for radiata pine focus on breeding traits such as straightness, speed of growth, wood quality and disease resistance.[84]

[77] (Department of Conservation, 2021b)
[78] (Parliamentary Commissioner for the Environment, 2017)
[79] (Parliamentary Commissioner for the Environment, 2016)
[80] (Forbes et al., 2015, 2019, 2020)
[81] (Forbes, 2021)
[82](Ministry for the Environment, 2021a, p. 463).
[83] (Ministry for the Environment, 2021a, p. 474).
[84] (Radiata Pine Breeding Company, 2020; Scion, 2020)

Option	Opportunities and challenges
	Forest management changes in the last 20 years have increased the stocking rates and volumes. While the effects of these combined improvements have not been formally quantified, experts estimate an increase of wood volume in the planted forests of 15% by 2030,[85] possibly doubling productivity by 2050.[86] These estimates are likely optimistic as forest owners may harvest earlier as a result of more rapid growth. Current NZ ETS rules mean that these increases in carbon stocks may be recognised in forests established after 1989, but not those established prior to 1990. *Chapter 3: How to measure progress* details the conditions under which this increase in carbon stock could contribute towards emissions budgets.
Increasing carbon stocks in natural forests	Improved management of around 7.8 million hectares of natural forest in Aotearoa could increase the amount of carbon stored in those forests. Pests such as deer, possums and goats browse on foliage, seedlings and saplings, altering the composition of a forest. Ungulates such as goats and deer have increased significantly over the last decade.[87] Urgent and ongoing pest management is required to maintain the integrity of forests and the carbon stored in them. Controlling these pests could help to increase carbon stocks while protecting indigenous biodiversity.[88] If such pests are not adequately controlled, then there may be long-term declines in the carbon already stored in mature forests.[89] Depending on the pest, control can consist of shooting, trapping and poisoning. However, studies have shown that it is difficult to suppress these pests to low enough levels, over large enough areas, and for long enough to see a response.[90] Carrying out more predator control, fencing out grazing and browsing animals and preventing fires in regenerating and native forests can result in more native birds, more tree growth and prevent forest decline in the long term.[91] Carbon stocks in many of the natural forests are gradually increasing as the tall tree species that were milled over recent centuries regenerate. Accurately attributing changes that are due to management is not currently possible. Many of the effects are realised over decades or centuries and distinguishing the size of the change from natural changes in the existing forest is extremely difficult.[92] For this reason, we do not include changes in

[85] Heidi Dungey, Scion, Pers. Comms.
[86] Timberlands expects to double the productivity of Kaingaroa forests in the Central North Island by 2050 (Ellegard, 2020)
[87] Based on data from public conservation lands (Department of Conservation, 2021a)
[88] (Carswell et al., 2015; Richardson et al., 2014; Wright et al., 2012)
[89] The effects of wild animal control on carbon stocks could be measurable at the centennial timescale. Current studies have been mainly conducted at the decadal timescale. (Carswell et al., 2015)
[90] (Nugent et al., 2010)
[91] (Carswell et al., 2015)
[92] (Peltzer et al., 2010)

Option	Opportunities and challenges
	natural carbon stocks from forest management changes in our modelling or accounting towards emissions budgets. For more information, see *Chapter 3: How to measure progress.*
Increasing carbon storage in forest products	Some of the carbon stored in forests is then stored in the products made with the timber upon harvest. HWPs in Aotearoa are an important pool of carbon stocks in our GHG Inventory.[93] There are three ways to increase the carbon stored in HWPs: 1) Increasing the amount of timber going into products (e.g. through new forests and increasing yields of existing forests) 2) Shifting the product mix to more long-lived products 3) Making products last longer through, for example, recycling or circular economy approaches (See *Chapter 8: Reducing emissions from waste*). We focus on the second point in this section. Around 60% of the annual harvest is exported overseas as raw materials (logs, wood chips or pulp) and converted into short-lived HWPs such as pulp, paper and packaging materials, which decay relatively quickly.[94] Of the remaining harvest that stays in Aotearoa, around 77% of domestic processing goes into long-lived HWPs, such as houses.[95] Significant investment in domestic processing capacity would be required to substantively increase the volume of timber going to long-lived products. Investing in domestic processing facilities could result in a best-case scenario up to additional removals of 31.3 $MtCO_2$ between 2021-2050.[96] Export logs from exotic forests in Aotearoa have a range of half-lives, from 2.5 to 6 years in the top three export countries.[97] It is likely that timber harvested from native planted forests would go into long-lived products, for example, the timber in whare tipuna (meeting houses), some of which has been there for centuries. Further information on the accounting for HWPs is included in *Chapter 3: How to measure progress.*

9.2.3 Risks and limits to removals from forests

A heavy reliance on forests to reach net emissions targets poses challenges, as continuous levels of afforestation would be needed to maintain similar levels of mitigation year on year. Over time, the area suitable for new forest establishment would decrease and the newly planted forests would

93 (Wakelin, Searles, et al., 2020)
94 (Manley & Evison, 2017)
95 (Te Uru Rākau, 2018)
96 (Scion, 2018)
97 Overall weighted half-lives for all Aotearoa export logs in China, South Korea and India was estimated as 6.6, 18 and 2.5 years respectively. (Wakelin, Searles, et al., 2020, p. 6)

reach their long-term average carbon store and no longer contribute towards targets. There is also an ongoing risk that the carbon stored in forests could be re-released back into the atmosphere if forests are destroyed or damaged.[98] If the forest is not replaced, this results in a long-term increase of carbon dioxide back into the atmosphere. Current and future decision makers in Aotearoa could decide to change land use away from forests, in which case the carbon stored would be re-emitted.

Natural hazards such as wind, wildfire or pests can also destroy established forests and these are expected to increase as the climate changes.[99] Recent international examples show how vulnerable some forests can be to these kinds of threats and the potential climate impacts related to the large-scale destruction of forests. The bushfires in Australia in the summer of 2019/2020, for example, are estimated to have approximately doubled Australia's emissions for 2019.[100] In Canada, an outbreak of Mountain Pine Beetle in the early 2000s destroyed hundreds of thousands of square kilometres of forest in British Columbia, and by 2020, was expected to have led to the release of 270 Mt of carbon into the atmosphere.[101]

Increased air temperature and humidity is likely to increase the intensity and irregularity of rainfall, while winter wind speeds are also projected to rise. This would likely lead to more flooding and higher rates of windfall in both native and exotic production forests.[102] Some areas are expected to experience more droughts, which could also lead to increased forest losses. A synthesis study found productivity gains for radiata pine from the direct effects of climate change that ranged from relatively minor to substantial depending on the species' response to increasing carbon dioxide.[103]

It has been estimated that as air temperatures rise over time, the number of days with very high and extreme fire danger at forested sites across Aotearoa would increase on average by 71% by 2040.[104] Climate projections show insect populations and damage are likely to increase with warmer temperatures, and there has already been some damage from two current needle cast diseases in production forests. The native forests of Aotearoa are currently under threat from two pathogens, kauri dieback and myrtle rust, both of which pose significant threats to the survival of many species. There is a range of susceptibility to fire risks across native trees and shrubs.[105]

The New Zealand Climate Change Risk Assessment[106] concluded that climate change will have long-term impacts on the integrity and stability of forest ecosystems and species in Aotearoa. The evidence on the risks on tree physiology and broad-scale studies is, however, limited. Risks for both native and planted forests (the latter as part of land-based production systems) were considered to be 'moderate' by 2050 and to be 'major' by 2100. Important knowledge gaps remain in terms of the speed of impacts, geographic variation and the susceptibility of ecosystems and species.

Major natural events such as windthrow and wildfire release carbon into the atmosphere, however there are provisions within the international accounting rules that mean these emissions are not

[98] (Anderegg et al., 2020)
[99] (Reisinger et al., 2014)
[100] (Global Fire Database, 2020)
[101] (Kurtz et al., 2008)
[102] (Parliamentary Commissioner for the Environment, 2019)
[103] These productivity gains across New Zealand averaged 19% by 2040 and 37% by 2090 (Watt et al., 2019)
[104] (Watt et al., 2019)
[105] (Wyse et al., 2016)
[106] (Ministry for the Environment, 2020b)

always counted towards emissions reduction targets. These rules require the forests to be re-established and the carbon re-sequestered. This is discussed further in *Chapter 3: How to measure progress.*

Forest management practices consider the risks outlined above through a portfolio diversification approach[107] of alternatives suited to the site conditions and future climate, including the use of silvicultural techniques such as shorter rotations, mixed species, diverse age classes and continuous cover forestry.

9.2.4 Land suitable for forestry

There is a large amount of land across Aotearoa which could be suitable for afforestation. For example, in 2019 Te Uru Rākau estimated that up to 3.3 million hectares of non-forest land (typically low-producing pasture) could be suitable for afforestation.[108] To put this in context, the Productivity Commission estimated that between 1.3 to 2.8 million hectares of land planted in forests could be required to achieve net zero all gases by 2050.[109]

In practice, not all of this land is suitable for planting commercial forests. For example, steep slopes and distance from ports and processing sites can make harvesting difficult or uneconomic in some places. Resource Management Act (1991) legislation prevents commercial forestry activities on some steep slopes to avoid environmental impacts such as erosion and flooding.[110] For erosion prone land, establishing permanent forest or actively reverting land to native forest is likely to be a more feasible option. There could be 1.2 to 1.4 million hectares of highly erodible land in Aotearoa suitable for forestry, although these estimates are preliminary.[111]

The relative profitability of different land uses also affects how a piece of land is used. This changes over time depending on market forces and other factors.

In terms of land suitable for new native forests, Manaaki Whenua estimates around 740,000 hectares of private land could naturally revert (i.e. without planting), if pests are managed. This estimate includes areas that are not classed as forests, in land parcels of over 5 hectares that have at least 60% probability of regenerating into forest land within 30 years in land-use class 6, 7 and 8. The estimate excludes areas suitable for commercially-grown exotic forests, ecologically sensitive areas, extreme slopes and areas with environmental factors that limit tree growth. This estimate includes 260,000 hectares in the North Island, and 480,000 hectares in the South Island. [112]

Landowners base decisions about what to do with their land on many factors. Some landowners choose not to plant trees even if they are the most profitable option. Other landowners do plant

[107] (West et al., 2021)
[108] Te Uru Rākau estimations cited in (Manley, 2019, p. 33)
[109] (New Zealand Productivity Commission, 2018)
[110] (Ministry for Primary Industries, 2020a)
[111] (Mason & Morgenroth, 2017; Ministry for Primary Industries, 2018; Stats NZ, 2019)
[112] Manaaki Whenua recommends that the most likely areas that could regenerate (P> 0.8) should use natural regeneration, while other areas may require planting. The map uses national scale data only so will not be accurate for any individual land-holding or for small land areas. (The Aotearoa Circle, 2020). The specific area estimates for P>0.8 are not readily available.

trees for a variety of reasons, often not for profit.[113] The availability of land for forestry is ultimately a landowner's decision, however this can be influenced by policies.

9.2.5 Small scale afforestation and mosaic landscapes

There are many small pockets of land across the country which may be suited to relatively small-scale afforestation, by setting up the conditions to revert into native forest[114] or through planting. On some farms, trees may be able to be integrated into the farming system, for example, in the form of agroforestry or silvopastoral systems. Forests on farms also provide other benefits such as animal shelter, biodiversity, erosion control and water quality.

However, not all carbon removals by small scale planting are currently recognised in international and/or domestic accounting. There is work underway by Government and industry to assess the potential to measure and account for carbon sequestration of on-farm vegetation.

When forests are established interspersed with other land uses, these can lead to a 'mosaic' or interwoven type landscape.[115] A mosaic landscape would look different based on what is biophysically suitable, financially sustainable, environmentally desirable and socially acceptable, and this would differ at farm, catchment and regional levels.

Establishment of new forests can be targeted at locations that are less suited for livestock, but also play a role in producing diverse silvopastoral productive landscapes. Farmers already plant trees on their land for many reasons, including riparian plantings along waterways and to create shelterbelts. There is also a proportion of land across farms that is not very productive for livestock farming.

Estimates of this less productive land vary. Research for the Biological Emissions Reference Group[116] modelled the effect of planting forests on the most marginal 3% of a farm,[117] but made no assumption of how or whether this could be scaled up nationally. In the Cabinet paper for the Billion Trees Programme, Ministry for Primary Industries identifies about 4 million hectares of lower producing farmland that could potentially be planted.[118] Beef + Lamb New Zealand estimated that exotic production forestry is likely to be more profitable, on an annuity basis, than (roughly) the bottom 30% of hill country farms and could enhance their overall profitability.[119] A recent study found that, based on net present value analysis, 56% of the low-productivity non-dairy grasslands in the country are likely to financially benefit from afforestation.[120]

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[113] (Manaaki Whenua Landcare Research, 2020)
[114] (Schnepf & Sullivan, 2019)
[115] (Hall, 2018)
[116] (BERG, 2018, p. 11)
[117] (Reisinger et al., 2017, p. 29)
[118] (Ministry for Primary Industries, 2018, p. 2)
[119] (Reisinger et al., 2017, p. 50)
[120] (West et al., 2020)

Urban trees, forests and greenspaces can also be part of a mosaic landscape. They also remove carbon from the atmosphere and have important co-benefits,[121,122] including mitigating the heat island effect[123] and health benefits[124]. Community based urban greening programmes have additional benefits promoting civic engagement, social interaction[125] and climate change adaptation[126]. The additional carbon dioxide removed by small areas of forest and non-forest vegetation on farms and in urban green spaces is not currently recognised in target accounting, although it is in the GHG Inventory.[127] However, ongoing technology developments[128] may make it more possible to robustly estimate emissions from these areas in future.

New forests on Crown land

There may also be scope for some afforestation on government-owned land. Establishing new forests on Crown land could provide a carbon sink. The Department of Conservation estimated that 59,000 hectares of Crown land, including the conservation estate, land held by the Ministry of Defence and land held by the New Zealand Transport Agency, would be suitable for afforestation. About 29,000 hectares of these would be blocks of 50 hectares or more in size.[129]

9.3 Soil carbon

Aotearoa soils are of relatively high carbon content due to the temperate climate, the comparatively short time during which it has been under cultivation, and the fact that most of it is covered in permanent pasture.[130,131] As such, there may be less potential in Aotearoa to sequester additional soil carbon compared to other parts of the world where soil carbon loss has been greater. There could be a challenge to retain existing soil carbon stocks into the future.

While changes in soil carbon due to land-use change (e.g. pasture to forest or vice versa) are well known, it is difficult to ascertain the impact of management on soil carbon. Current evidence in Aotearoa suggests that soil carbon stocks were lower under irrigated than adjacent dryland

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[121] In most cases the benefits of urban trees outweigh the costs. The most studied benefits to people include shading, air quality, and carbon regulation, while the less studied benefits, e.g. aesthetic, amenity, and shading benefits, may be of greater value. (Song et al., 2018)
[122] Benefits reviewed by the IPCC include: Absorbing rainfall and moderating high temperatures, provide shading, evaporative cooling and rainwater interception, and storage and infiltration services for cities (Revi et al., 2014, p. 574).
[123] (Frantzeskaki et al., 2019)
[124] Exposure to trees is associated with multiple health benefits but the effects of trees vary by person and may not always be beneficial, such as the potential for tree pollen to exacerbate allergies (Wolf et al., 2020).
[125] (Wolf, 2017)
[126] (Egerer et al., 2021)
[127] Urban forests and green spaces are classified as part of 'Settlements' in the GHG Inventory. Settlements in Aotearoa are only 0.9% of land and they are not considered a 'key category' in the GHG Inventory, hence not prioritised for improvement.(Ministry for the Environment, 2021a, pp. 287–288).
[128] For example, the tool i-Tree that measures different values of trees has been applied in 131 countries, including Australia, United Kingdom, United States and Canada (Nowak et al., 2018).
[129] Desktop estimations only that require ground-truthing (Department of Conservation, 2017). The Department of Conservation asked that this estimate should be caveated and noted that the purpose of Public Conservation Land is incompatible with exotic forestry (sub. DR370 to Productivity Commission) (New Zealand Productivity Commission, 2018).
[130] (Pastoral Greenhouse Gas Research Consortium, 2015)
[131] (The Nature Conservancy et al., 2020)

pastures.[132] There is some evidence that fertiliser inputs to tussock grasslands increased carbon stock.[133] Occasional pasture renewal is unlikely to greatly affect soil carbon stocks. This contrasted with general losses of carbon due to frequent and repeated cultivation. There is no evidence that fertiliser application rate influenced soil carbon stocks.[134] Changes in soil carbon occur over long time periods. The science and measurement of soil carbon is still developing and long-term monitoring programmes have been established in Aotearoa.[135] There is little systematic data on practices that could increase soil carbon stocks in Aotearoa such as cover crops, no-till or reduced till, biochar, full inversion tilling and peatland restoration (Table 9.2). For more information see *Chapter 7: Reducing emissions from agriculture*.

Table 9.2: Options for increasing carbon stocks through soils

Option	Opportunities and challenges
Cover crops	Cover crops provide land cover in between cropping cycles to protect soils from erosion, mitigate nutrient losses and provide biologically fixed nitrogen. Cover crops can store soil carbon and potentially reduce soil nitrous oxide emissions, although further research is needed to fully attribute this effect.[136] An international meta-analysis estimated the average emissions reduction potential of cover cropping by increasing soil carbon in cropping systems over 54 years at 1.17 ± 0.29 tCO_2e per hectare per year.[137]
No-till or reduced till	No-till or reduced-till approaches avoid soil disturbance and associated carbon loss by ploughing. Reducing tillage can lead to increased organic matter accumulation (including carbon) in the undisturbed topsoil. The evidence for this practice is mixed. In some cases, soil carbon increases at shallow depths were offset by decreases at deeper levels. The increase in soil carbon stock can be lost as farmers alternate between tilling and not tilling over several years.[138] As most of agricultural land in Aotearoa is in long term-pasture, the overall potential to store carbon would be more limited.[139] Switching to no-till approaches would likely incur capital costs for new machinery such as direct seed drills.[140] Specific costs/capital requirements would likely vary by system type.
Biochar	Biochar is a high carbon, fine grained product created through pyrolysis[141] when biomass is burnt in the absence of oxygen. Depending on the biochar and soil properties, applying biochar to soils can improve soil physical, chemical or biological properties, increase and stabilise soil organic carbon stocks and reduce

[132] (Mudge et al., 2017)
[133] (Schipper et al. 2017)
[134] Ibid.
[135] (NZAGRC, 2019)
[136] (Basche et al., 2014)
[137] Estimates for mean soil depth=22 cm (Poeplau & Don, 2015)
[138] (Griscom et al., 2017; Powlson et al., 2014)
[139] (Baker, 2016)
[140] (Saskatchewan Soil Conservation Association, 2020)
[141] Pyrolysis is the thermal decomposition of materials at elevated temperatures in an inert atmosphere. It involves a change of chemical composition.

Option	Opportunities and challenges
	greenhouse gas emissions.[142] Biochar can be retained in the soil for at least several hundred years. [143] A recent review found that further research would be needed to better understand the potential of applying biochar to soils in temperate climates similar to Aotearoa.[144] The potential of emissions reductions from biochar application depends on the production of biochar, which in turn is dependent on the amount of biomass available to produce it. Our analysis indicates that biochar production could avoid approximately 0.73 $MtCO_2e$ of waste emissions[145] or 0.32 $MtCO_2e$ from avoided landfill emissions.[146,147] The estimated cost of biochar production is expected to be in the range of $300 - $800 per tonne.[148]
Full inversion tillage (FIT)	FIT is a technique that transfers carbon-rich topsoil into the subsoil[149] (potentially slowing its decomposition) and exposes the inverted, carbon unsaturated subsoil to higher inputs from the new pasture. FIT remains relatively unproven in Aotearoa and elsewhere. A recent trial in the Manawatu found FIT to successfully transfer soil organic content below 10 cm. This showed the potential to reduce peak nitrous oxide emissions and maintain pasture production.[150] A model estimated that an additional 3 Mt of carbon could be stored over a 30-year period in high producing grassland soils following a 'one-off' pasture renewal with FIT.[151] This number ought to be treated with caution as such potential is yet to be demonstrated in practice.
Peatland and wetlands protection and restoration	Peatland soils hold large pools of carbon, accumulated over many centuries. When peat soils are drained for agriculture, they become a source of greenhouse gas emissions and remain one as long as the land remains drained.[152] In 2019, they accounted for approximately 1.64 $MtCO_2$.[153] This makes them one of the major sources of land emissions currently outside of target accounting. For more information on the land emissions accounting see *Chapter 3: How to measure progress*.

142 (Hedley et al., 2020)
143 (Spokas, 2010)
144 (Hedley et al., 2020)
145 Organic components of landfill and farm fill waste in Aotearoa account for 2.9 Mt of solid waste, or 35% of the total, but account for almost all waste emissions. This estimate assumes that 20% of this was converted into biochar via pyrolysis without any fugitive emissions (0.2*3.65 $MtCO_2e$). The total solid waste emissions are for 2018 from the GHG Inventory.
146 Griscom et al. (2017) estimate biochar carbon sequestration: 0.18 tC/t dm (dry matter). Taking 20% the dry biological waste (wood, garden and paper (0.2*1.29 Mt=0.258) from landfills and assuming a 75% biochar carbon content (biochar tends to be 70-80% carbon).
147 (1.29/2.9 Mt)*3.65 $MtCO_2e$*0.2=0.32 $MtCO_2e$
148 This includes the initial plant capital and a 20 year operating life. See: (Jones & Camps, 2019)
149 FIT has shown more soil organic carbon than no-till at 21-35 cm soil depth.(Angers & Eriksen-Hamel, 2008)
150 (Pereira et al., 2019)
151 The estimate assumes 10% farmer adoption (i.e. 367,000 ha, or 6% of New Zealand high producing grass) and 10% annual pasture renewal. See (Lawrence-Smith et al., 2015)
152 (Meduna, 2017)
153 Estimations based on emissions from organic soils on grassland and cropland (Ministry for the Environment, 2021a)

Option	Opportunities and challenges
	Avoiding further draining or destruction of the few remaining peatlands and wetlands would avoid emissions in Aotearoa. Restoring drained peat soils and wetlands (including on farms) could potentially make a modest contribution but further research is needed to quantify this.[154] Peat and wetland restoration costs include the costs of native species planting and fencing, and vary by region.[155] Maintaining and restoring wetlands also has cultural benefits. For example, many Māori have strong historic and cultural links with wetlands, which are taonga that could be enhanced through their restoration. They can be important habitats for native species and sources of traditional building and weaving materials, medicines and food.[156]

9.4 Carbon capture and storage

There is increasing international interest in the use of CCS to meet climate change targets and obligations. For example, most of the pathways the Intergovernmental Panel on Climate Change (IPCC) modelled with no or limited overshoot of the 1.5°C target relied on large-scale deployment of emissions removal technologies after 2050. The pathways which assume slower reductions in gross emissions from fossil fuel use require removals to scale up to around a third of current global carbon dioxide emissions levels by 2050. There is significant risk that the scale of CCS technologies required in some of the IPCC's modelled pathways may not be feasible. Globally, there are 21 facilities in operation, three under construction and 35 in various stages of development.[157] Most of these facilities are associated with coal power generation or oil and gas production.

CCS and CCS-based emissions removal options are relatively expensive, emerging technologies with highly variable, site-specific costs tailored to the region's geology. The costs of CCS are influenced by several factors, including concentration of carbon dioxide in the emissions stream, type of capture technology, transport distance to the storage site, presence of existing well and pipeline infrastructure and the energy demand of the process.[158]

In Aotearoa, CCS technology has not progressed beyond the concept and research stage. This is because forestry is currently a lower-cost emissions removal option and because zero- to low-emissions substitutes for fossil fuel combustion for energy are increasingly economic at current policy settings. For fossil fuel use as a feedstock or reductant, zero- to low-emissions alternatives to achieve gross emissions reduction are being investigated domestically and internationally. As such, interest in CCS has been limited. It is unlikely it would be required to meet our climate change targets and obligations. However, it may play a role in the latter half of the century to maintain net

[154] (Burrows et al., 2018)
[155] For example, in a plan for wetland restoration near the Ōtākaro Avon river, capital costs ranged between $20,000 and $100,000/ha (Regenerate Christchurch, 2018)
[156] (Harmsworth, 2020)
[157] (Global CCS Institute, 2020)
[158] There are additional costs associated with reservoir mapping, injection, well operation and ongoing monitoring and compliance activities.

zero emissions in a 1.5°C compatible pathway and to address residual emissions from hard to abate sectors.

9.4.1 Options for increasing carbon removals through emissions capture

For sectors with hard to abate emissions, such as cement and lime manufacturing, geothermal power generation and ongoing nitrous oxide emissions from agriculture, CCS might be an option in the latter half of the century to maintain net zero emissions in Aotearoa.

Post-combustion carbon capture technology can 'bolt on' to a conventional industrial plant to capture up to 90% of the emissions stream. Reinjection of fugitive emissions from geothermal power generation and oil and natural gas extraction activities back into the producing field or a nearby storage location is a mature and technically feasible emissions removal option that could be deployed in Aotearoa.

Depleted or producing oil and gas fields in the Taranaki region may offer significant storage potential. For example, a 2016 study[159] estimated the total storage potential to be roughly 15,000 MtCO_2. The achievable storage potential would require detailed field assessments but is likely to be significantly less. The primary advantage of these fields over other potential storage sites is that they are well understood geologically and have existing infrastructure which may be adapted for CCS. Given the location near an active plate margin, additional research and analysis would be needed to fully understand and assess the feasibility for permanent storage and risk of reversal from natural disasters such as earthquakes.[160] Additional research would also be required to better understand the potential for induced seismicity and interactions with other subsurface activities.

There are a range of existing regulatory mechanisms and carbon accounting rules which do not currently incentivise the development of CCS. They do not fully account for the environmental, health and safety, access to land and mineral and property rights associated with the process. Long-term regulatory supervision including post-operation and procedures and assessment criteria for permits would also need to be established. There may also be a perception that CCS is merely a means to prolonging the emissions stemming from fossil fuel production activities and fossil fuel combustion for energy, which would be in conflict with ambitions to reduce gross emissions.

CCS and other CCS-based emissions removals options require consideration around the potential value and role of land use in climate change. Similar to other infrastructure or plant developments, assessment of ecological and environmental impacts would be required to ensure alignment with broader national government or community objectives. Particularly for bioenergy with CCS, increased competition for land and resources may impact the ability for sectors to decarbonise through the use of biofuels, and may remove land from food production. There may also be additional considerations in order to fulfil obligations under Te Tiriti o Waitangi/The Treaty of Waitangi, including land and water (taonga) use and allocation, kaitiakitanga and traditional hunting and fishing grounds.

CCS applications can leverage different emissions capture approaches and technologies. These approaches are discussed briefly in Table 9.3. While there is increased international interest in these

[159] (Field, 2016)
[160] (Field, 2016)

approaches, there remains considerable uncertainty as to their potential achievable contribution to Aotearoa reaching net zero emissions in practice.[161]

Table 9.3: Options for increasing carbon removals through emissions capture

Option	Opportunities and challenges
Reinjection of geothermal gases and other fugitive emissions	Reinjection has potential to reduce fugitive emissions from geothermal power generation and oil and natural gas extraction. Geothermal fluid contains mostly carbon dioxide with small volumes of methane and hydrogen sulphide. During operation of a geothermal power plant some of the gases can become separated from the geothermal fluid as a result of changes in temperature and pressure when the fluid is extracted. The gases are released to the atmosphere as a part of the power generation process.[162] It may be possible to reinject some or all of the gases from geothermal power generation and oil and natural gas extraction sites back into the producing field or reservoir or a nearby storage location. The economics and technology for emissions capture and reinjection would depend on the composition of the gases released, the pressure of the gas at the outlet or wells and the volume of gases released. The economics of this option may also be influenced by the potential need to site new suitable reinjection wells and increase field monitoring and management activities. Potential alteration of, or interaction with, the chemistry of producing reservoirs may also impact the economics and technology used for reinjection of gases. Reinjection technologies and practices are a deployable emissions reduction option in Aotearoa.
Bioenergy with carbon capture and storage (BECCS)	BECCS is the combination of two capture options: increased biological uptake through forests and plants (biomass) and engineered direct emissions capture. The biomass is harvested, processed into a solid or liquid fuel and then combusted to generate heat or power. The emissions from combustion or processing activities are captured through post-combustion carbon capture technology and then compressed, transported, injected and stored. BECCS is an emissions removal option which could provide net negative emissions. In order to be considered net negative, the emissions associated with production and combustion (or processing) of biomass, emissions capture and transport cannot exceed the amount of emissions removed through biological uptake.[163] The biomass must also originate

[161] (IEA, 2020a)
[162] (New Zealand Geothermal Association, 2019)
[163] (Fajardy & Köberle, 2019)

Option	Opportunities and challenges
	from sustainably managed forests in order to be considered carbon neutral.[164] Biomass is a key emissions reduction opportunity across industry and transport. Increasing competition for biomass and land through BECCS may increase prices and limit availability. This could constrain the uptake of biomass to displace fossil fuels for combustion for energy. Clear government signals and coordination are required to prioritise the resource for its most valuable end uses across the economy, in terms of displacing emissions. Doing so in a coherent and planned manner may lessen some of the effects of competition.[165] Deployment of BECCS may be further limited by competition for land, potential impacts on water, biodiversity, soil health and social equity (particularly in rural communities).[166] Deploying BECCS as part of a suite of measures could lessen some of these potential impacts.[167] While there is increasing international interest and development of CCS applications, BECCS is a relatively expensive and emerging technology. Deployment of BECCS would be dependent on the coordination of multiple areas of the economy, such as forestry, industry, communities and government. Given the relatively dispersed nature of large point sources of emissions and bioenergy resources in Aotearoa, cross-sectoral collaboration would be critical to establish the shared infrastructure and investment required to deploy BECCS. An alternative approach to emissions removal through increased biological uptake is through increased use of durable, engineered wood products in the built environment. The duration of emissions removal would be limited to the life of the building. See also *Chapter 5: Reducing emissions from energy and industry.*
Direct air capture with carbon capture and storage (DACCS)	Direct air capture is the direct engineered capture of carbon from the atmosphere. It involves passively or actively passing large volumes of air over a liquid or solid compound to adsorb (chemically bond) carbon dioxide from the atmosphere. The carbon dioxide is then separated and regenerated with heat, water or both and released in a more concentrated form.[168,169] Once released, the emissions are captured, compressed, transported, injected and stored. DACCS requires a large volume of air flow for a relatively small amount of carbon dioxide capture. Different technologies can be used for direct air

[164] Woody biomass is considered carbon neutral as the carbon dioxide released during combustion is equivalent to the amount absorbed by the tree during growth. If the wood originates from sustainably managed forests, then this is a renewable energy source.
[165] (Committee on Climate Change, 2018)
[166] (Fajardy & Köberle, 2019)
[167] (The Royal Society & Royal Academy of Engineering, 2018, p. 8)
[168] (The Royal Society & Royal Academy of Engineering, 2018, p. 59)
[169] (IEA, 2020b)

Option	Opportunities and challenges
	capture and adsorption, but the processes all have high energy or heat and water requirements[170] which may be supplied from renewable sources or waste heat depending on project design and location. As with other CCS-based emissions removal options, DACCS has implications on resource use. Globally, DACCS is a developing technology with a limited number of pilot projects. Costs are highly variable but generally expensive.
Carbon capture and utilisation (CCU)	As an alternative to storage, the captured carbon dioxide can be used in other industrial processes or products. There are three main categories of carbon dioxide-based products: fuels, chemicals and building materials. Conventional use of captured carbon dioxide includes production of carbonated beverages and to enhance photosynthesis in hot houses. An emerging application is the production of low-carbon concrete. Carbon dioxide can be added and absorbed into concrete during the curing process. This may reduce the amount of cement required to produce equivalent-strength concrete with the benefits of improved durability.[171] However, this may affect the curing time of concrete which can have economic impacts on the end user that could outweigh the emissions reduction benefits and limit uptake. Uptake may also be limited by perceptions of risk in using new products, differences in cost between products and limitations within Standards New Zealand building standards regarding blended cement and concrete products. Another potential application of CCU is in the production of petrochemicals (urea and methanol) and electrofuels (e-fuels or synthetic fuels) where a pure carbon dioxide source can be used in conjunction with green hydrogen. The carbon dioxide source could be supplied from the Kapuni Gas Treatment Plant where it is stripped out from the natural gas during processing. The gas from the Kapuni gas field contains a concentration of about 44% carbon dioxide. The extent to which CCU removes emissions is highly dependent on the source of the emissions stream, the category of carbon dioxide-based product it is used in and the lifetime of the product. The deployment of CCU is also dependent on uptake of carbon capture to provide a long-term supply of carbon dioxide to produce carbon dioxide-based products. Globally, CCU is an emerging technology with a limited number of pilot projects. Costs are highly variable but generally expensive. See also *Chapter 5: Reducing emissions from energy and industry* and *Chapter 6: Reducing emissions from transport, buildings and urban form.*

[170] (IEA, 2020b)
[171] (Energy Transitions Commission, 2020)

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9.6 Appendix – New native forests: Scale of potential investment

In our demonstration path, about 286,000 hectares of native afforestation are established during the emissions budget period 2022-2035. The costs of native afforestation are highly uncertain and are likely to vary regionally and depend of different factors. Specific sub-catchment analysis is required to better estimate costs of establishment, maintenance and potential co-benefits.

We estimated the level of potential investment required for alternatives using different proportions of native forest establishment methods: reversion and planting. Among key assumptions used are deer fencing costs for the reversion option, two estimates for planting ($20,000/ha and $50,000/ha) and ongoing pest control costs. We have used conservative planting costs to factor in the likelihood that some plantings will not survive. The potential revenue from other sources such as timber harvesting, mānuka honey and other non-wood forest products and services are not included in these estimations.

The results in Appendix Table 9.1 are indicative of a range of possible costing alternatives at national level and range from -$5.3 to -$15.4 billion for the emissions budget period 2022-2035. The costs of seedlings and hence planting are expected to reduce over time, with economies of scale, new production technologies and as broader pest management takes effect.

Appendix Table 9.1: New native forests – Scale of potential investment

Establishment method	Year 1 capital expenditure (Weighted average) (NZ$/ha)	NPV 3% discount, 120 years (NZ$/ha)	Total for emissions budget period 2022-2035 (billion NZ$)
80R/20P	-6,946	-18,416	-5.3
80R/20PH	-12,946	-24,241	-6.9
50R/50P	-11,841	-24,499	-7.0
50R/50PH	-26,841	-39,062	-11.2
80P/20R	-16,736	-30,583	-8.7
80PH/20R	-40,736	-53,884	-15.4

R=Reversion, P=Initial planting cost: NZ$20,000/ha, PH: Initial planting cost: NZ$50,000/ha.
NPV=Net Present Value

Including modelled emissions values

One of the main limitations of the analysis is lack of information on the yields and costs for planting native forests and reversion of native forests in Aotearoa. We estimated the national net benefit (as opposed to the private NZ ETS benefit) by considering the post-1989 natural forests yield table in the GHG Inventory. We found positive net present value (NPV) results using the modelled emissions values in our demonstration path, ranging from $2.3 to $12.5 billion for the emissions budget period 2022-2035 (Appendix Table 9.2). Reversion dominant alternatives may result in higher net benefits than planting dominant alternatives, however these numbers are only indicative as growing yields can vary based on species, site and forest management system applied.

Appendix Table 9.2: Indicative estimates including modelled emissions values

Establishment method	NPV 3% discount, 120 years, including CO_2 yields* and modelled emissions value** (NZ$/ha)	Total for emissions budget period 2022-2035 (billion NZ$)	Years to positive NPV
80R/20P	43,624	12.5	13
80R/20PH	37,799	10.8	19
50R/50P	37,540	10.7	18
50R/50PH	22,977	6.6	40
80P/20R	31,457	9.0	24
80PH/20R	8,156	2.3	72

R=Reversion, P=Initial planting cost: NZ$20,000/ha, PH: Initial planting cost: NZ$50,000/ha.
*Based on Post-1989 natural forest yield table (Ministry for the Environment, 2021b, p. 52).
**Modelled emissions values of tCO_2e vary from 52 to 523 $/$tCO_2$-e during the period of analysis.