Offsetting livestock methane with trees

Balancing warming from ruminant methane emissions with cooling from carbon sequestration by forestry

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Executive Summary

This report examines the potential for forestry sinks to offset the temperature effects associated with methane emissions from livestock. The report aims to balance step changes in radiative forcing from land sector sinks and sources, to equalise the associated temperature effects.

The core experiment compares the warming effects of a step change in ongoing methane emissions with the ability of forest sinks to offset this change. To investigate this, we use a simple climate model (FAIR) and an innovative greenhouse gas metric (GWP*) to impose a step change increase in ongoing methane emissions (from a constant base), representing a step change in the size of a herd of livestock. Methods to offset the short and long-lived warming effects of the step change increase in ongoing methane emissions by planting forests are explored. Incremental step changes in herd size are assessed for dairy cows, beef cattle, sheep and deer.

The main scenario offsets the warming from livestock methane by planting a pine plantation forest. A new pine plantation forest sequesters carbon from the atmosphere during the initial growth period prior to harvest. After the first harvest, a small fraction of the carbon remains sequestered as harvested wood products and other sinks, while a high fraction is returned to the atmosphere. The next rotation repeats this cycle. The time-average of carbon sequestration from a pine plantation forest is well-matched to the radiative forcing associated with a step change in ongoing methane emissions – a steep early change, followed by a more gradual adjustment over time. This is why approaches that compare the temperature effects of planting forests with step changes in ongoing livestock methane emissions represent a promising avenue for high-integrity environmental policy. This is true for both exotic and native species, though the exact area required over time depends on a number of factors, including growth rates and management practices.

In the simple illustrative scenario below, our main results are that, on average, planting 0.63 ha of pine plantation forest has a roughly equal but opposite temperature effect to increasing the size of a herd of dairy cows by one animal. Equivalently, keeping the size of a herd of dairy cows constant and planting 0.63 ha of pine plantation forest has a roughly equivalent temperature effect to decreasing the size of the herd by one animal. The equivalent areas required for beef cattle, sheep and deer are 0.40 ha head^{-1}, 0.08 ha head^{-1} and 0.16 ha head^{-1} respectively. The area of forest required varies regionally and depends on the tree species and forest management regime.

1. Introduction

Anthropogenic emissions of greenhouse gases (GHGs) increase GHG concentrations and result in warming. Correspondingly, reductions in the concentration of GHGs produce cooling. Oceans, forests and other ecosystems can emit or remove carbon dioxide (CO_2) from the atmosphere, and represent important aspects of the global carbon cycle. Carbon dioxide emissions and removals from forests already play a significant role in the climate change mitigation policies of many countries, including New Zealand.

The climate response to any step change increase in radiative forcing involves a rapid early response, followed by a long thermal adjustment, irrespective of whether the change in radiative forcing results from a one-off pulse emission of a long-lived GHG or a step change in ongoing emissions of a short-lived GHG. This thermal adjustment process is gradual, concave, and lasts several hundred years (e.g. Houghton et al., 1990, Collins et al., 2013). As the planet warms in response to the step change in radiative forcing, heat energy is absorbed by the climate system, primarily in the ocean. Gradually the system approaches a new, warmer equilibrium (Forster et al., 2021).

In a growing forest, there is a net transfer of carbon dioxide from the atmosphere to the land surface, an associated reduction in atmospheric carbon dioxide concentrations and, equivalently, a cooling compared to what would be the case if the forest had not grown.[1] If the forest is not harvested and is allowed to reach maturity, this effect reaches a limit as the amount of carbon the forest emits becomes approximately in balance with the amount of carbon it sequesters. At this point the forest is no longer gaining mass and no longer has any additional cooling effect (but nevertheless remains an important store of carbon). The dynamics of carbon sequestration tend to be sigmoid – with a slow start, acceleration towards some maximum annual rate of sequestration, then a diminishing annual sequestration beyond that, up to some asymptote when the system has reached the maximum anticipated carbon stock.

The situation is different for a plantation forest. If a plantation forest is roughly defined[2] as a forest deliberately established for commercial purposes, that has been planted and has been or will be harvested and replanted, then the emissions, concentration and warming dynamics are as follows: the forest sequesters carbon from the atmosphere in the first growth phase; when trees are removed, by harvest, clearing, or burning, then a significant fraction of the carbon dioxide sequestered during the growth phase is re-introduced into the atmosphere and will warm the planet; subsequent growth and felling phases repeat the process, such that the time-average of the carbon stored in the forest is a fairly steep early rise, followed by a series of periodic peaks and troughs superposed on a small upward trend. The time-averaged carbon sequestration dynamics tend to be concave after the first few years. The plantation forest's time-average dynamics have slightly different characteristics from an unharvested forest but both sequester carbon over time, up to some eventual limit.

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[1] Extensive deforestation in the past released significant quantities of carbon dioxide into the atmosphere, which continues to have a warming effect. Planting new forests has a relative cooling effect in the sense that it returns some of this carbon back to the biosphere and undoes some of the warming caused by past deforestation.

[2] Following Section 1.3 of the Resource Management Act, for instance.

In this report, we examine the possibility of using sequestration of carbon dioxide by pine plantation forests to offset the warming associated with a step change in ongoing livestock methane (CH_4) emissions. Per molecule, methane has a stronger radiative forcing than carbon dioxide but it is short-lived in the atmosphere.[3] The warming caused by a pulse emission of carbon dioxide is similar to the warming caused by a step change increase in ongoing methane emissions. As a result, a pulse sequestration of carbon dioxide – which is, in effect, what a fixed forestry block achieves, albeit over the course of several decades – can be used to offset either a pulse of carbon dioxide emissions or a step change increase in ongoing annual emissions of biogenic methane. The physical relationship is the same in the case where the herd size is held constant, and forest sequestration of carbon dioxide is used to mimic the cooling effect of reducing the herd size by one cow.

Different greenhouse gases have different atmospheric lifetimes, and hence their effects on the climate differ. According to the Intergovernmental Panel on Climate Change (IPCC), the lifetime of methane in the atmosphere is around 9 years.[4] Nitrous oxide has a lifetime of around 116 years (Canadell et al., 2021). The residence time of carbon dioxide is not characterised by a single timescale, but since some 30-40% of a kilogram emitted today remains in the atmosphere for more than a thousand years, it can be treated as a permanent pollutant.

From the atmosphere's perspective, a step change increase in ongoing methane emissions acts quite a lot like the opposite of a new plantation forest – there is an early rapid increase in warming, followed by a long tail in which there is declining warming year on year. This is in contrast with ongoing fossil carbon dioxide emissions, for which warming increases more or less linearly in proportion to cumulative emissions, and nitrous oxide (N_2O), which is a hybrid case. These differences are illustrated in the next section.

Of course, there are actions that farmers can take to reduce gross livestock methane emissions. These range from changing farm systems and practices to reducing stock numbers and land use change. The suitability of on-farm actions will vary from farm to farm. Some changes to farm management practices can be cost-saving, which means farm managers are likely to want to explore those options first before considering plantation forest investments as additional warming offset strategies. Besides, at the time of writing no policy mechanisms exist to base multi-gas climate policy on contributions to warming.[5]

It should be noted that afforestation also has non-carbon climate impacts, such as changes in albedo as land is repurposed from one use to another (Bright et al., 2105, Kirschbaum et al., 2011). This report does not discuss the incorporation of non-carbon effects, but we note that this could be done as part of policy design in future.

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[3] Globally we emit more than a hundred times as much carbon dioxide as methane (by mass). In New Zealand our carbon dioxide emissions by mass are merely 20 times our methane emissions.

[4] Atmospheric residence time expresses the average amount of time a molecule spends in the atmosphere. For methane, this is around 9 years. Methane follows a more or less exponential decay curve, with most methane being removed from the atmosphere by reaction with hydroxyl radicals.

[5] This may surprise some readers. Part of the reason is an inertial reliance on notions of CO_2-equivalence developed in the early 1990s. CO_2-e emissions cannot robustly fit into a warming based framework where short-lived gases are involved.

2. Emissions sources: approximating the warming per cow

In the experiment below, we consider the warming effect on the climate of a step change increase in annual methane emissions of 1 $ktCH_4$ (0.001 $MtCH_4$). We use a simple climate model called the Finite Amplitude Impulse Response (FAIR) model (Smith et al., 2018) to simulate the effect of a step change increase in methane emissions on global methane concentrations, radiative forcing and temperature. In the numerical experiment, the step change is imposed upon the RCP4.5 global scenario, with the unaltered scenario then subtracted from the result to reveal the impact of the additional step change in methane emissions. This is broadly consistent with the approach taken in other NZ-specific studies, such as Reisinger, 2018. The experiment is repeated using cumulative GWP20, cumulative GWP100 and cumulative GWP* emissions. To move from cumulative emissions to warming, we follow the approach in Cain et al., 2019, which involves multiplying cumulative emissions by a form of the transient climate response to cumulative emissions (TCRE), 1.8 K TtC^{-1} (equivalently 0.49 K $TtCO_2^{-1}$).

The temperature effect, as simulated by FAIR, of a step change increase in ongoing methane emissions of 1 $ktCH_4$ is shown in Figure 1 as the solid red line. Methane has a strong warming effect over its short atmospheric lifetime, then decays into carbon dioxide, tropospheric ozone and stratospheric water vapour, which also cause warming. However, in the case of biogenic methane, the carbon dioxide molecule is part of a closed loop – it was removed from the atmosphere, fixed to organic matter via photosynthesis, ingested, then released back to the atmosphere as methane by the ruminant. This does not increase the overall amount of carbon dioxide in the atmosphere.[6] The other products associated with methane oxidation – tropospheric ozone and stratospheric water vapour – are also greenhouse gases but are short-lived, with lifetimes of a few weeks (Stevenson et al., 2006) and several years (Ehhalt et al., 2004) respectively. None of the daughter products of methane give rise to long-lived climate forcings, so biogenic methane emissions leave no permanent record on atmospheric chemistry. Rather, their climate impacts largely follow the trajectory of annual methane emissions (Lynch et al., 2021).

Step changes in forcing lead to a long-lasting warming effect because any step change in forcing leads to the same response: rapid early adjustment, followed by an extended period of gradual temperature stabilization (e.g., Houghton, 1990). This is the cause of the concavity of the red line in Figure 1 and is why it takes a long time for the climate to come into equilibrium with adjustments to forcing (e.g., Collins et al., 2013). It is also why constant emissions of methane in New Zealand would lead to increasing but ever-diminishing additional warming above the current level, and the total amount of warming caused would eventually stabilise (e.g. Reisinger, 2018). In that event, warming would continue to rise for several decades because from a climate perspective, the increases in methane are recent enough that the climate is still equilibrating to the perturbation we have already made. This will also be the case for any country in which methane emissions peaked within the last 70 or so years, and remain near the peak level. The magnitude of this ever-diminishing increase in additional warming depends on several factors such as how close current emissions are to peak emissions and how close to equilibrium the climate response is. Whether this additional warming is significant in a policy sense depends on social judgements and priorities.[7]

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[6] This is not the case for fossil methane: fossil sources always add new carbon dioxide to the atmosphere, worsening climate change.

[7] A previous PCE report (Reisinger, 2018) was dedicated largely to this issue, while the UK's Climate Change Commission dealt with it in a single footnote: "A slow decline of methane emissions is in fact required to

By design, the GWP* metric closely aligns cumulative emissions to the actual warming as shown by Figure 1, which shows the effect of estimating warming by using cumulative GWP* emissions (solid black line), cumulative GWP100 emissions (dashed blue line) and cumulative GWP20 emissions (dashed green line). Cumulative GWP* approximates the temperature response well, though with mild overestimates in the 15-25 year timescale, and in the long run (>200 years).[8] By far the worst fit is cumulative GWP20 emissions, followed by cumulative GWP100 emissions, both of which give linear responses to a step change in ongoing methane emissions, whereas the climate system response does not.[9] This is consistent with the recent IPCC Working Group I Report on the Physical Science Basis of climate change, specifically Chapter 7.6, and Figure 7.22 (Forster et al., 2021).

The numerical experiment was based on a step change increase of 1 ktCH_4 to provide a signal that is amenable to calculation in a climate model. In the experiment we modelled the methane-induced warming directly (using FAIR) and scaled the metric-based cumulative emissions by the TCRE to obtain metric-based warming.[10] Results can be scaled using the data in Table 1. 1 ktCH_4 is equivalent to the annual methane emissions of: 10,560 dairy cows; 16,442 beef cattle; 81,300 sheep; or 42,194 deer. So making a step change increase of 1ktCH_4 is equivalent to adding 81,300 sheep (etc.) to a herd and then maintaining that larger herd indefinitely.

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produce a constant level of warming, due to the slow thermal adjustment of the climate system. However, this rate of decline is on the order of <1% per year and can be approximated by constant emissions."

[8] Consequently, net zero emissions targets based on GWP* are likely to lead to cooling on multi-centennial timescales.

[9] It should, however, be noted that neither GWP100 nor GWP20 were designed to be used in this way, and although there are precedents for using cumulative GWP100 emissions in a policy framework, GWP20 has not been used this way.

[10] Scaling cumulative carbon dioxide emissions by the TCRE provides a good approximation of warming from carbon dioxide emissions, because warming is close to linear in cumulative emissions. See Cain et al. (2019) for instance.

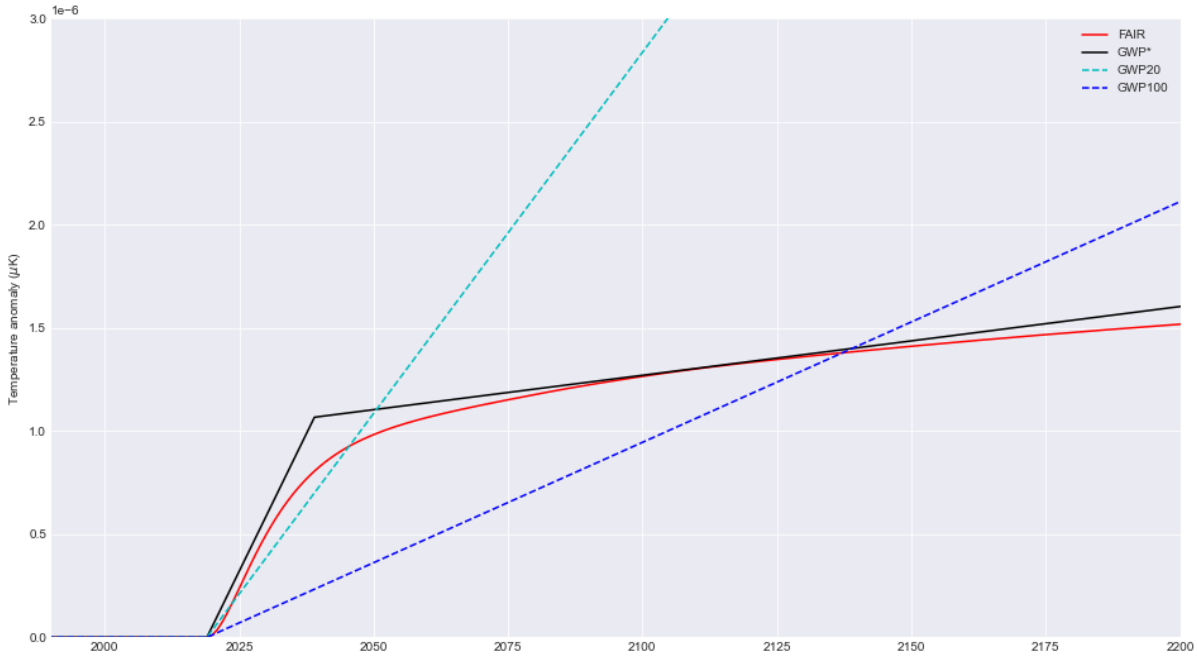

Figure 1. Climate response to a step change increase in ongoing methane emissions of 1 ktCH_4 in 2021 as estimated by the FAIR climate model (solid red line), and cumulative GWP20 (dashed green line), GWP100 (dashed blue line) and GWP (solid black line) emissions.*

GWP* approximates the temperature response to a step change in ongoing methane emissions via two simple approximations. The first component represents the initial steep but short-lived warming (or relative cooling) that arises from an increase (or decrease) in ongoing methane emissions. The second reflects the gradual longer-lived warming (or relative cooling) that arises from slow equilibration of the climate system to the earlier step change in forcing. For methane, these two terms are driven by the rate of change of annual emissions ($\Delta E_{CH_4}/\Delta t$) and the annual emissions (E_{CH_4}) terms, respectively, in the following equation:

$$E_{CO_2we} = \left[0.75 \times H \times GWP_H \times \frac{\Delta E_{CH_4}}{\Delta t}\right] + \left[0.25 \times GWP_H \times E_{CH_4}\right]$$

where

$E_{CO2we} =$ Annual GWP* emissions (in tonnes of carbon dioxide warming-equivalent, tCO_2-we)

$H =$ Time horizon for the conventional global warming potential (100 years)

$GWP_H =$ Global warming potential over time horizon H. For this experiment, the 100-year GWP for methane without climate-carbon feedbacks from the IPCC fifth assessment report was used, which is 28 (Myhre et al., 2013).

$\Delta t =$ Time horizon for the rate of change of annual emissions (20 years)

$E_{CH_4} =$ Annual methane emissions (in tCH_4 per year)

This relationship gives the warming-equivalent emissions (Cain et al, 2019) consistent with a cumulative emissions or carbon budget framework for a short-lived gas (in this case methane). A more detailed discussion can be found in Cain et al., 2019, with some recent updates in Smith et al., 2021.

The actual climate response to a step change in radiative forcing is an exponential asymptote towards an equilibrium value, and a two-step linear equation does not capture that perfectly. However, in general the climate response to time-varying changes in forcing is not as simple as an exponential. The GWP* equation provides a reasonably accurate approximation of the actual warming response; far more accurate than either cumulative or annual GWP emissions (Forster et al., 2021). In this analysis we use a GWP*-based approximation of the warming response to the step change in ongoing methane emissions associated with the addition or subtraction of a ruminant from a herd. Further analyses investigating a model-based assessment of warming are planned.

On the forestry side of the experiment, we consider the planting of new forests to offset the warming on the emissions side of the experiment.

3. Offsetting methane with trees

In this section we find a balance between the warming effect of a step change increase in ongoing methane emissions and the cooling effect of sequestering carbon by planting a new forest. In these experiments we present conservative solutions that ensure the net temperature effect is always cooling or no change in temperature from the outset,[11] instead of allowing net warming initially and then reducing this in later periods. For the plantation forest option, we rely on thoroughly researched *Pinus radiata* which is remarkably resilient, fast-growing, and responds favourably to planting on former livestock pasture.

The scenario we consider is where a pine plantation forest is used to mimic the relative cooling effects of removing a ruminant from a herd or, equivalently, to offset the warming effect of adding a ruminant to a herd. The “exchange rate” between trees and ruminants is likely to be the same in either case.

We use New Zealand average values for exotic forest sequestration rates based on the National Forest Inventory developed for international reporting for the Kyoto Protocol and UNFCCC greenhouse gas inventory reporting (Beets et al., 2010; Paul et al., 2019). The average values from the National Forest Inventory are heavily skewed towards *P. radiata* to the extent that they can be assumed to represent the national area average sequestration rates for this species. We assume onsite planting of *P. radiata* in a thinning and pruning regime to match industry best practice and alternative income options. In our primary scenario trees are harvested at the end of the rotation and replanted. As averages values are used throughout the report, interpretation of these results should be used in a qualitative sense and will vary to a large degree depending on site, location, silviculture, genotype etc.

Typically, one hectare of *P. radiata* is planted at around 1,000 stems ha^{-1} and thinned several times to reduce stocking densities to provide unknotted timber initially and enhance the quality and size of the final trees. In the most recent values for stocking and sequestration, Paul et al. (2019) calculate average stocking in post-1989 planted forests were 587 stems ha^{-1}.

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[11] In other words, the net temperature effect relative to the baseline is always less than or equal to zero; at no point does it result in net warming.

In the following scenario, we consider planting a fixed area with trees. The example shows how a finite area of fixed size can be used to offset or mimic the temperature effect associated with a step change in the flow of methane emissions from ruminants. There is an important conceptual distinction here between how forests can offset the warming associated with biogenic methane and that associated with fossil carbon dioxide. A forest of fixed size, because it sequesters carbon dioxide up to some limit, can be used to offset the warming associated with a pulse emission of carbon dioxide. This is because the amount of carbon dioxide released in the pulse is of finite size, and so is the amount of carbon dioxide sequestered by the forest. However, an indefinite flow of carbon dioxide cannot be offset by any forest of fixed size, because the warming caused by an indefinitely persisting flow of carbon dioxide is not of finite size – it grows every year, indefinitely. To offset the warming associated with an indefinite flow of carbon dioxide emissions would require an indefinitely growing area of forest. However, because the warming effects of an on-going flow of methane results in a fixed amount of warming – as does a pulse emission of carbon dioxide – a fixed-area forest can offset the near-constant warming associated with an ongoing source of methane emissions, such as a herd of sheep or cattle.

3.1 Main scenario: Pine plantation forest

This scenario accounts for multiple harvests and planting rotations of an average New Zealand exotic pine plantation, accounting for the carbon fluxes in the soil, harvest residues and harvested wood products. The warming pattern associated with additional ruminants closely mirrors the time-averaged time-series of cooling associated with the establishment of a new plantation forest and its subsequent rotations (Figure 2).

We use the idealisation that a ruminant emits a steady rate of methane at the national average for the ruminant in question. This is converted into carbon dioxide warming equivalent (CO_2-we) units via GWP* as shown in brown in Figure 3. The initial 20-year CO_2-we rate is 1.28×10^{-5} $MtCO_2$-we which then drops to 8×10^{-7} $MtCO_2$-we. The *P. radiata* (light green) is stocked at 1,000 stems ha^{-1} and grows rapidly.

The plantation forest as dictated by international carbon reporting standards surrenders a small amount of biomass carbon initially as the site is cleared for planting. A certain amount is regained upon planting. Soil carbon is also lost when converting land use from pasture to forest – nominally at a constant rate over 20-years. Note that the ETS does not include those losses, but we follow national accounting sequestration here which does. During growth, deadwood litter and fine litter reach their maximum values around 11-years (Paul et al., 2019) which result in the increased surrendering of biomass from the site and rates dip before equilibrating.

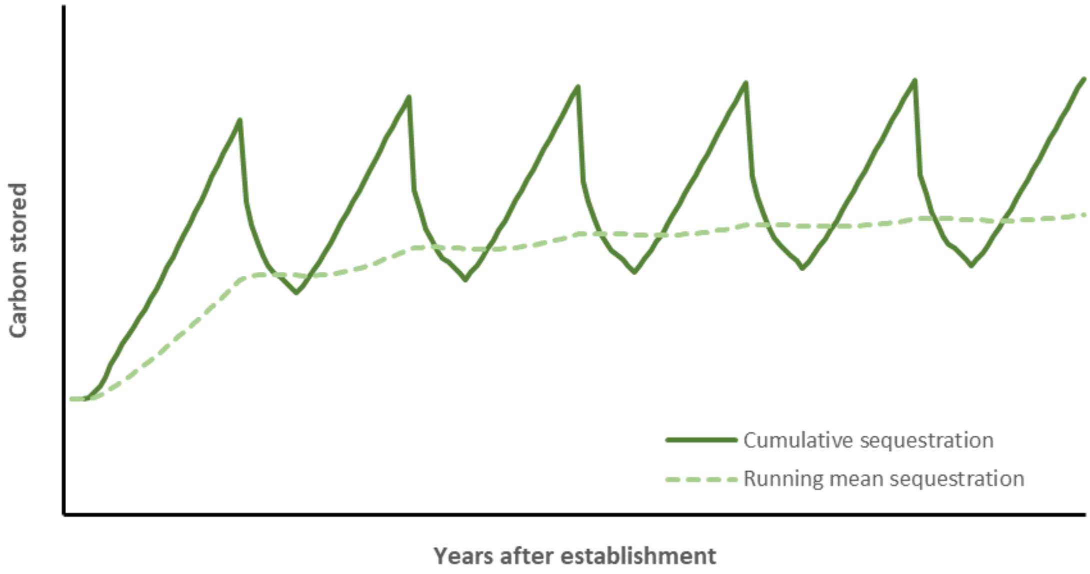

Figure 2. Illustration of the long term plantation cumulative sequestration over many 30 year rotations of harvest and replanting, creating the characteristic 'sawtooth'. The dashed line shows the running mean sequestration (which the ETS now uses for example).

The area of plantation forest required somewhat depends on how carbon dioxide sequestration is averaged over the rotations. A pragmatic solution is to use the actual sequestration up to the harvest of the first rotation, after which we use the decadal mean sequestration. Qualitatively, this sequestration curve represents a mirror image of the warming associated with additional ruminant emissions sources associated with herd expansion.

4. Results

At the simplest level of warming-equivalence, to offset the increase in warming associated with increasing the size of a herd of dairy cows, around 0.63 ha cow^{-1} of pine plantation forest should be planted. This figure accounts for land stocked initially at around 1,000 stems per hectare, thinned and pruned as required, with a final stocking of ~350 trees, harvested at around year 30 for wood products, and replanted thereafter. Subsequent cycles of planting, growth, and harvesting are shown as the saw-tooth pattern in Figure 2 and Figure 3. Averaged over time, this level of planting shows a small net cooling effect (the blue band in Figure 3). In this case four of the six averaging methods were tested to have no net warming effect, and the remainder of the cooling signal could potentially be used to claim carbon credits or to offset other onsite emissions. The two methods that initially give net warming for a time are the running mean from year-zero to year-*n* and the right-aligned rolling 30-year mean. These methods may be the strictest method in terms of robustness as they use only past emissions and no future data. All the other averages use future emission values to some extent (like the revised ETS averaging approach).

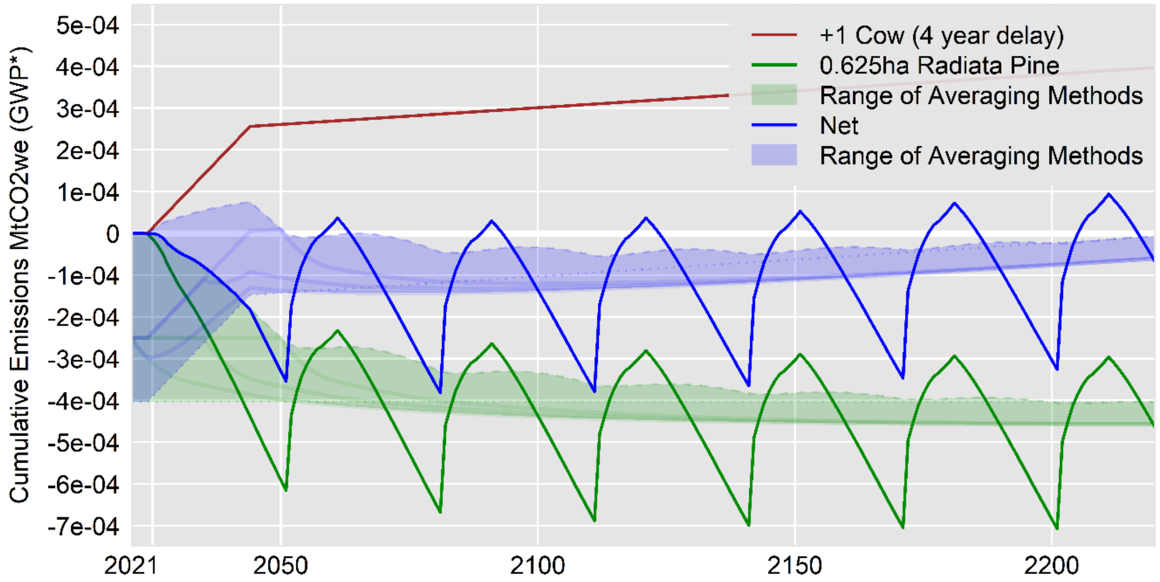

Figure 3. P. radiata plantation forest planted to offset an increase in herd size by one cow. This preliminary analysis uses GWP-based warming for the warming associated with the additional cow.*

The same exchange rate of 0.63 ha cow^{-1} can be used to achieve warming reductions equivalent to those resulting from the removal of dairy cows from a herd, and similar exchange rates can be obtained for other ruminants. If the goal for a farm with 100 dairy cattle is to reduce its livestock methane emissions by 35%, then it could achieve the same temperature effect by keeping its livestock methane emissions constant and planting $100 \times 0.35 \times 0.63 = 22$ ha of pine plantation forest. The goal could equally be achieved by a combination of gross emissions reductions and forest offsetting. Equivalent relationships can be constructed for other ruminants (Table 1).

Table 1: Ruminant emissions and average area of pine plantation forest required to offset or mimic the temperature effect of a step change in livestock numbers by livestock type

	Dairy cattle	Beef cattle	Deer	Sheep
Methane emissions [kgCH$_4$ head^{-1} yr^{-1}]	94.7	60.8	23.7	12.3
Average area of pine plantation forest per ruminant [ha head^{-1}]	0.63	0.40	0.16	0.08

These quantities can be used to construct the following equation, in which p is the area (hectares) of pine plantation forest required for planting, N is the herd size, q is the fractional emissions reduction required of the herd, and e_r is the average area of pine plantation forest required per ruminant from the table above:

$$p = Nqe_r$$

For example, if a sheep farm with 250 stock wanted to achieve the same temperature effect as a 20% step change decrease in its methane emissions by planting pine plantation forestry instead of reducing stock numbers, then it could arrange the planting of $p = 250 \times 0.2 \times 0.08 = 4$ ha of plantation pine forest. This would achieve the same temperature effect as a 20% reduction in stock numbers.

The equation can also be applied to herds at the national level. As of 2019 there were 6.26 million dairy cattle, 3.89 million beef cattle, 26.8 million sheep, and 810,000 deer being farmed in New Zealand (StatsNZ, 2021). To achieve the same temperature effect as a 24% decrease in livestock methane emissions from the national dairy herd would require $6{,}260{,}000 \times 0.24 \times 0.63 = 947{,}000$ ha of pine plantation forestry to be planted. The equivalent areas for the national sheep, beef cattle and deer herds would be 515,000 ha, 373,000 ha and 31,000 ha respectively. Reducing gross livestock methane emissions from each herd by 23% in addition to planting the areas of pine plantation forestry above would achieve the same temperature effect as a 47% decrease in livestock methane emissions from each national herd.

The method does not stipulate where the forest must be planted, or what type of land is converted to forestry. At the farm level, the trees could be planted on the same farm as the herd of livestock, or they could be planted by a different landowner elsewhere. At the national level, a significant proportion of new forest planting is likely to occur on sheep and beef land, which in turn is likely to reduce livestock numbers and further decrease methane emissions. The two effects are additive: warming reductions from declining stock numbers and cooling from the carbon sequestration associated with tree planting combine linearly.

Plantation pine is not the only option. Diversification of forestry regimes can mitigate future climate change risk (West et al., 2021). It is possible to use the differing sequestration characteristics of pine and native forests to match the warming associated with ruminant herds. One possibility would be to match the warming trajectory associated with a step change in herd size by planting a mix of pines and native tree species. The rapidly growing pines would be used to match the rapid initial temperature response to a step change in herd size, and the slower-growing native forest would correspond to the smaller, long-lived warming component. Although a mixed forest requires some management post-planting, the improved growth and health mean that the carbon sequestration of a mixed forest is potentially greater in the long term than a pine forest alone (Hollinger et al., 1993).

Adjusting the timing of planting can improve the match between ruminant warming and forest-based cooling. For example, to offset or mimic the temperature effect associated with a step change in the size of a dairy herd using a mixed forest, 0.34 ha cow^{-1} of pine could be planted around three years before the change in herd size, followed by 0.16 ha cow^{-1} of native forest planted around a decade after. These are average values; the details of the timing requirements are likely to vary significantly around the country, and would require further investigation if mixed forests were to be used to counter ruminant warming.

In the long run, the carbon sequestered by the pines in the mixed forest during the first two decades must remain stored within the forest (or an equivalent amount of carbon must be sequestered and stored elsewhere) to continue offsetting the ruminant-related warming for as long as methane emissions from the herd persist. This implies that if the pines are harvested or otherwise release their carbon to the atmosphere due to death, disease or extreme weather events, either the pines are replanted (if they do not seed a following generation) or additional natives are planted to take their place and compensate for the carbon released.

4.1. Scaling results for regional planting

The results here are based on the national forest inventory of forestry permanent sample plots (PSP), and as such are an area average. If we assume the PSP data represents national average values, then one can perform some simple scaling of the regional 300 index[12] growth rate via the relative percentages in Table 2.

Table 2. Regional average growth rates via the 300-index (Palmer et al), and their relative percentages compared to the New Zealand average values used in this report. One can calibrate the results in Table 1 to obtain approximate regional adjustments.

Region	**300 Index ($m^3\ ha^{-1}\ yr^{-1}$)**	**Relative %**
Auckland	27.4	100.0
Bay of Plenty	27.2	99.3
Canterbury	22.2	81.0
Gisborne	32.2	117.5
Hawke's Bay	31.3	114.2
Manawatū-Whanganui	28.3	103.3
Marlborough	26.8	97.8
Nelson	26.3	96.0
Northland	26.8	97.8
Otago	23.6	86.1
Southland	25.6	93.4
Taranaki	31.2	113.9
Tasman	25.8	94.2
Waikato	27.5	100.4
Wellington	27.6	100.7
West Coast	23.3	85.0
New Zealand	27.4	100.0

Thus if a pine plantation forest in Gisborne were used to offset the warming from an average additional dairy cow, then the area of forest required would be $\frac{0.63}{1.175} = 0.54$ ha head^{-1}, while if a pine plantation forest in Canterbury were used to offset the warming of an average additional dairy cow, then it might be expected to be around $\frac{0.63}{0.81} = 0.78$ ha head^{-1}. In other words, we expect regional variability in forest growth rates to be an important factor. If a scheme offsetting warming from ruminant methane with forestry were to be developed, care would have to be taken regarding both variations in ruminant emissions and regional variations in forest sequestration.

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[12] A measure of volume productivity for *Pinus radiata*. It is the mean annual volume increment in cubic metres per hectare of a 300 stem per hectare radiata pine stand at age 30 years.

5. Conclusions and possible implications for policy

This paper is a preliminary exploration of the relationship between ruminant emissions of methane, which elevate global average temperature, and carbon sequestration by forests, which reduces global average temperature. The paper shows that the temperature effect of a step change in herd size can be closely matched by the cooling associated with the establishment of a forest. If a dairy farm with a herd of fixed size were to mimic the effect on warming of a step change reduction in its stock numbers by planting a pine plantation forest, then the area of forest required would average out at around 0.63 ha head^{-1}.

Climate policy can encompass a number of goals, and among these are a range of temperature or warming goals or targets. Scientific tools, such as step-pulse emissions metrics, and scientific relationships such as those set out above can help create environmentally sound trade-offs, or clarify progress towards goals, but they do not determine the goals.

This is because normative questions cannot be answered by reference to facts alone. Choices regarding how to compare different emissions sources and sinks may bear on, but do not determine, the goals of climate policy. A range of warming and emissions targets could be, and have been, advanced, critiqued, and defended. The role of physical science in this conversation is to trace through the relationships between various scenarios and goals, rather than to set the goals or the scenarios.

At present, New Zealand has a target to reduce biogenic methane emissions by 24-47% from the 2017 level by 2050. This range would result in warming reductions of between 0.28-0.56 milli-Kelvin (mK) relative to the current level by 2050, peaking at 0.32-0.64 mK by 2070 if emissions are maintained at respective 2050 levels. Current levels of warming due to biogenic methane in New Zealand are around 1.48 mK, so the 24-47% emissions reduction target represents cuts of between 19% and 38% of current biogenic methane warming by 2050.[13] These levels of warming reduction could be achieved by a combination of methane emissions reductions, coupled with forest sequestration as set out above.[14] Policies based on the relationships described above could assist in achieving any specific warming reduction target associated with the commitment to reduce methane emissions by a specific level within the range 24-47% by 2050, whatever the specific target.

The relationships set out above provide a method through which to make trade-offs between biogenic methane mitigation and afforestation which is equivalent in warming to biogenic methane mitigation. As with other warming-based approaches to comparing biogenic methane to carbon dioxide, the scientific aspects are uncontentious. Because the warming associated with a flow emissions of biogenic methane and pulse emissions of carbon dioxide can both be offset by fixed-area forests, it is possible to develop scientifically sound land-based climate policies that are structured around the contributions forestry and herd size make to warming.

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[13] The level of warming from New Zealand's biogenic methane in this paper is a little greater than the 1.3 mK estimated in Reisinger, 2018, but well within the range of reasonable scientific uncertainty.

[14] The current intention is that carbon dioxide and nitrous oxide emissions will decline to net zero by 2050, so the warming reductions associated with biogenic methane are expected to be additional to the cessation of New Zealand's contribution to warming from these other, long-lived, gases.

While the idea of a warming-centred, land-based climate policy is attractive from a biophysical perspective, the following important caveats should be borne in mind:

- Local conditions matter, both in terms of ruminant methane production, and in terms of trees' ability to sequester carbon. Local details would need to be worked through to ensure environmentally sound outcomes.
- Forest sinks are vulnerable to fires and other disruptions (including policy reversals), which bring potential risks to stored carbon.
- A warming-centred policy is possible using CO_2e measurements, but only if the gases are treated separately, and are not compared on that basis.
- Care is needed in interpreting the results for herds established before the base year, particularly if the size of the herd steeply increased or decreased in the decades prior to the base year. The planting areas in Table 1 are independent of stock numbers and emissions trends before the base year, and do not offset warming from methane emitted before the base year. If an area of forest is planted to mimic the effect of a step change reduction in herd size in the base year, the result is a reduction in warming relative to a counterfactual baseline in which the herd size remained constant at the base year level and no forest were planted. Whether the herd's contribution to warming increases or decreases in absolute terms as a result of the forest planting will partly depend on trends in stock numbers and emissions before the base year, since these shape the counterfactual baseline. If used in a policy context, the choice of base year therefore matters because it can influence the warming outcomes of the policy in absolute terms, as well as the distributive effects for different sub-sectors. The year 2021 was used in this report for illustrative purposes.

There is considerable scope for flexibility in terms of exactly how forestry could be treated in a warming-based approach: while pine plantation forests match up well with changes in ruminant emissions, they are not the only possibility: depending on the role of other goals, such as biodiversity enhancement, there could be an important role for mixed exotic and native forests in matching the warming associated with ruminants in a land-based climate policy.

If a warming-centred land-based climate policy were developed, it could use the fact that a fixed area of plantation pine forest can mimic the relative cooling implied by a reduction in herd size or, equivalently, offset the new warming implied by expansion of a herd. From a temperature perspective, the two are well-matched. The two could be traded off within a land-sector emissions trading scheme, or paired within a levy and subsidy system.

A small-scale application of these ideas would be in on-farm management, where a single farm could offset warming from livestock by planting and managing additional trees on the farm. Policy could recognise and incentivise this sort of active management of the farm's contribution to climate change. Depending on the appetite for managing climate policy, such a scheme could also involve trading between farms. While opening up the possibility of substantial efficiency gains in terms of how land is used in a climate policy context, this would also require additional administration and oversight if pine plantations in one part of the country were used to offset warming in another.

If a farmer had 100 cows and was expected to reduce her ruminant methane emissions by 10% over 10 years, then she could achieve the same temperature effect by keeping the herd size constant and planting $100 \times 0.10 \times 0.63 = 6.3$ ha of plantation pine in one go, or she could plant $6.3 \div 10 = 0.63$ ha per annum for 10 years. That is, a multi-annual obligation to reduce warming could be dealt with either via a one-shot up-front investment (which would generate surplus warming reductions beyond the target rate in the short-term), or via an annual planting schedule designed to match the required multi-annual warming reductions requirement.[15]

The most expansive way of using these ideas would be as part of an international mitigation scheme. As with a national scheme, this would require additional bureaucracy – agreements around monitoring, reporting, verification, policy harmonisation, and so on. However, efficiency gains could also be very substantial, and such a scheme might provide a good exemplar of environmentally sound land-based climate policy. It is likely that any such scheme would be based on bilateral agreements (at least initially), rather than a formal multilateral trading mechanism under the United Nations Framework Convention on Climate Change (UNFCCC).

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[15] The scheme should not be designed to allow planting at rates that would imply actual warming reductions fall substantially behind the required warming reductions: e.g. deferring all planting until the final year of the programme (the decade over which the 10% reduction occurs, in this example) would not meet the warming reductions requirement.

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