Large greenhouse gas emissions from drained peatlands in New Zealand, and the climate mitigation potential of rewetting

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SUMMARY

Drained peatlands are a substantial contributor to global anthropogenic greenhouse gases despite the relatively small areas they occupy. In New Zealand, drained Organic Soils (former peatlands) under cropland and grazed grasslands disproportionately contribute to emissions, but outdated mapping and limited measurements result in large uncertainties. To progress our understanding of the magnitude of these emissions and potential for mitigation, we compiled existing measurements from New Zealand and default emission factors from the IPCC along with updated soil mapping to develop a comprehensive national assessment. Using the IPCC 2013 Wetland Supplement (WS), Tier 1 default emission factors, total CO_2 equivalent (CO_2e) drained Organic Soil emissions were 3.86 Mt yr^{-1}, equivalent to 6.5 % of the country's net emissions. This was similar to the estimate derived from the mean of New Zealand-specific annual CO_2e emissions (3.61 Mt yr^{-1}). However, there are insufficient measurements from which to develop robust Tier 2 emission factors, and the range of CO_2e estimates based on existing data (3.06–4.69 Mt yr^{-1}) reinforces the need for more distributed measurements. The estimated CO_2e contribution to national emissions increased to 6.34 Mt yr^{-1} (or 11 % of net emissions) when peaty-mineral soils were included in the calculations. Carbon-rich soils with a peaty surface horizon that do not meet the technical definition of Organic Soils are increasingly recognised as a potential source, but we have even less data quantifying their emissions to determine appropriate emission factors. We evaluated the potential for emissions mitigation through rewetting Organic Soils by running scenarios representing different areal rates of annual rewetting over the next ten years using WS default emission factors. Cumulative emissions avoided by rewetting 500–3000 hectares per year from 2026 until 2035 ranged from 0.53 to 1.25 Mt of CO_2e. Despite the barriers to practical implementation of peatland rewetting in New Zealand, the opportunity for emissions reductions is substantial. Further work is needed to refine emission factors, improve spatial activity data, and develop operational water table management capability to realise the potential in climate mitigation.

KEY WORDS: emission factors, LULUCF, Organic Soils, peaty-mineral soils, restiad peatlands

INTRODUCTION

Peatlands are wetlands that have accumulated dead organic matter at their surfaces due primarily to saturated conditions that limit decomposition (Clymo 1984, Belyea & Baird 2006). While they occupy a relatively small portion of the terrestrial surface (Xu *et al.* 2018), peatlands contain 25–30 % of all soil carbon globally (Blodau 2002, Yu *et al.* 2010). The slow but consistent accumulation of peatland organic matter has resulted in a net cooling effect over the last 10,000–20,000 years, overcoming the transient climate effects associated with methane (CH_4) emissions from peatlands (Frolking *et al.* 2006, Frolking & Roulet 2007).

Roughly 10 % of the global peatland area has been drained for agriculture, forestry or mining (Joosten 2009, Fluet-Chouinard *et al.* 2023), and the consequently degraded peatlands emit approximately 4 % of global anthropogenic emissions (Evans *et al.* 2021, UNEP 2022). Draining or lowering peatland water tables leads to an increase in net greenhouse gas (GHG) emissions as a greater portion of the organic matter is exposed to aerobic microbial decomposition (Evans *et al.* 2021). The resulting increasing rate of carbon dioxide (CO_2) losses is exacerbated by substantial nitrous oxide (N_2O) emissions (Leifeld 2018) due to mineralisation of the organic nitrogen in previously saturated peat (Leifeld & Menichetti 2018). While CH_4 emissions are generally lower from drained peatlands, the drainage ditches become hotspots (Schrier-Uijl *et al*. 2010). Standardised methods for estimating emissions of all three GHGs from drained Organic Soils within national inventories for reporting to the United Nations Framework Convention on Climate Change (UNFCCC) are described in the 2013 IPCC Wetlands Supplement (WS; IPCC 2014), which expanded on the original guidance (IPCC 2006) and incorporated more comprehensive data from international literature. In addition to land uses (Grassland, Cropland, Forest land) and climate zones, the WS further separates emission factors by drainage depth and nutrient status for a subset of land uses. The contribution of Organic Soils to global emissions associated with land use, land use change and forestry (LULUCF) is roughly 25 % (Tubiello *et al*. 2016).

In New Zealand, peatlands have been accumulating carbon for at least 14,000 years (Newnham *et al*. 1995, McGlone 2009, Ratcliffe *et al*. 2020a) despite mild temperatures and often negative summer water balances. The development and persistence of peatlands have been made possible in large part by key traits of the main peat-forming species *Empodisma robustum*, a perennial jointed wire rush (restiad) belonging to the botanical family Restionaceae (Wagstaff & Clarkson 2012). Stomatal sensitivity to elevated atmospheric vapour pressure deficit, and its dense canopy of mostly dead stem material that acts as a mulch, both serve to reduce evaporation (Campbell & Williamson 1997, Goodrich *et al*. 2015a, Speranskaya *et al*. 2024), allowing the negatively geotropic cluster roots to build peat over time (Agnew *et al*. 1993, Hodges & Rapson 2010). These peatlands are able to maintain their role as consistent annual carbon sinks during years with relatively severe summer droughts (Goodrich *et al*. 2017), and under pressure from adjacent land drainage that lowers the water table, provided *E. robustum* remains well-established (Campbell *et al*. 2014, Ratcliffe *et al.* 2020b).

Peatlands cover less than 1 % of the land area of mainland New Zealand (i.e., not including Stewart Island or the Chatham Islands) and roughly 80 % of that peatland area has been drained (Ausseil *et al.* 2011), largely for agricultural uses. Ongoing loss and conversion of peatlands is also reported, despite the regulations intended to avoid it (Robertson *et al.* 2019). Drainage and lowered water tables lead to ongoing subsidence (Pronger *et al.* 2014), which puts pressure on infrastructure and eventually causes some areas to become prohibitively expensive to manage (Pronger *et al.* 2022). Studies reporting CO_2 emissions from drained peatlands used for grazed pasture in New Zealand are in general agreement with the international literature, with annual CO_2-C losses ranging from 2.23 to 8.47 t ha^{-1} yr^{-1} (Schipper & McLeod 2002, Campbell *et al.* 2015, Campbell *et al.* 2021). There is growing recognition that these areas contribute disproportionately to the country's total emissions, yet the national inventory relies on default emission factors from the 2006 IPCC guidelines (IPCC 2006), under-estimating emissions occurring to date (MfE 2024).

Given that emissions from drained peatlands can be substantially reduced or halted by raising the water table (Zou *et al.* 2022) and potentially reversed by restoration (Nugent *et al.* 2018), these emissions also represent an opportunity for abatement (Günther *et al.* 2020). Although New Zealand's national inventory report includes CO_2 emissions from drained Organic Soils (i.e., former peatlands) within the LULUCF sector (MfE 2024), their contribution is somewhat opaque. This is partly because the emissions are embedded in broader land use categories, namely Grassland and Cropland, and therefore difficult to ascertain from the report. The LULUCF sector is an overall net sink in New Zealand because the contribution of Forest land carbon removals generally masks the emissions from drained Organic Soils. Associated N_2O emissions from management of Organic Soils are reported separately in the Agriculture sector and recognised as a key category (MfE 2024). The lack of visibility and the outdated information used to estimate greenhouse gas emissions, along with the separate reporting of gases between sectors, makes it difficult to appreciate the contribution of drained Organic Soils to national emissions and, therefore, to incentivise mitigation or restoration, a problem already identified in European Union countries (Barthelmes 2018). The contribution of human-induced peatland fires to CO_2 emissions is also absent from national reporting but can be substantial when fires occur (Pronger *et al.* 2024). In the last decade many countries have started to obtain better information on the contribution of drained peatlands to their national inventories (Tiemeyer *et al.* 2016, Aitova *et al.* 2023), prompting increasing understanding of the potential for rewetting and improved peatland management as a mitigation strategy.

To improve the estimate of current emissions from drained Organic Soils in New Zealand, we compiled the latest information on spatial extent, nutrient status and existing local emissions data to incorporate into the internationally accepted approaches outlined in the WS (IPCC 2014). We then used these national estimates to explore potential scenarios for climate mitigation through peatland rewetting.

METHODS

Extent of drained Organic Soils in New Zealand

For the purposes of reporting emissions in its national inventory report as a party to the Paris Agreement (United Nations 2015), New Zealand defines Organic Soils as having a minimum organic horizon depth of 30 cm, comprised of at least 18 % organic carbon, which must be present within the top 60 cm of the soil profile (Hewitt 2010, MfE 2024). For the current national inventory, New Zealand estimates Organic Soil area from spatial information contained in the Fundamental Soils Layer (FSL), resulting in roughly 1 % of the total land area at 258,748 ha (Dresser *et al.* 2012). Much of the FSL is derived from legacy soil surveys conducted between the 1940s and 1980s. An updated source of spatial information on New Zealand's soils, called S-map, is under development and includes refined delineation of Organic Soils. Soil mapping for some regions is still being updated, but where S-map coverage exists, the accuracy of Organic Soil boundaries has been improved over the FSL information currently used in the national inventory.

An updated map of Organic Soils for New Zealand was recently developed by Pronger *et al.* (2025). Their approach was to combine the two national-scale soil maps (FSL and S-map) to reflect the best available information on the spatial extent of Organic Soils. In practice, this means that S-map was used to derive Organic Soil extent wherever it was available, while FSL was used otherwise (Figure 1).

We also examined the potential effect of expanding the definition of Organic Soils by including areas covered by mineral soils with a peaty surface layer (< 30cm depth). These areas may be occupied by former drained Organic Soils where the organic surface layer has oxidised due to long-term drainage, or areas within the landscape sharing characteristic features that promote organic matter accumulation but where peatlands never fully developed. In either case, peaty-mineral soils are poorly drained, often requiring similar water table management to Organic Soils to facilitate productive use, and may exhibit similar biogeochemistry and resulting emissions (Kelliher *et al.* 2002). To obtain the area of peaty-mineral soils within each land use category, the same spatial layers used to derive Organic Soil areas (S-Map and FSL) were used to identify mineral soils with a subclassification indicating a peaty surface layer. We then added the area of peaty-mineral soils for each land use category to the Organic Soil area for separate emission calculations (Table 1). Land use information was taken from the 2020 Land use and Carbon Analysis System land use map (2020 LUCAS LUM v003; Harris *et al*. 2023).

In addition to the total area, the nutrient status of the original wetland ecosystems is required to estimate emissions using Tier 1 WS (IPCC 2014) methods (Table A1 in the Appendix) because of its effect on decomposition rates and subsequent emissions. Nutrient status of the peat is determined by the environment in which the peatland originally formed rather than subsequent anthropogenic nutrient inputs.

One approach to assigning an emission factor to a given area based on the nutrient status of drained Organic Soils is to use historical information on wetlands. Ombrotrophic bogs are low-nutrient ecosystems where the sole input of water and nutrients comes from rainfall or dry atmospheric deposition, whereas fens and swamps are influenced by surface and subsurface flows that supply external nutrients, while recognising that swamps may also have high mineral content in some settings (Johnson & Gerbeaux 2004). Therefore, information from historical wetland classifications can be used to disaggregate drained Organic Soil areas for the purpose of emissions scaling by assigning drained former bog areas as nutrient-poor and drained former fen and swamp areas as nutrient-rich. The historical extent of bogs in New Zealand was roughly 6.2 % (153,116 ha) of the total wetland area (2.5 Mha), while fens accounted for approximately 7.8 % (192,097 ha) and swamps (including both mineral and organic) for 60 % of wetlands (Ausseil *et al.* 2011).

Pronger *et al.* (2025) derived a nutrient status area map for New Zealand's drained Organic Soil, using an historical wetland layer and soil nutrient data from the New Zealand wetlands database with information on shallow soil carbon to nitrogen ratios for remnant intact wetlands. Their analysis showed that bogs can be differentiated from other wetland types based on a lower quartile C:N ratio cut off at 25:1. This is consistent with international literature showing higher emissions from drained nutrient-rich peat (Klemedtsson *et al.* 2005, Leifeld 2018, Minkkinen *et al.* 2020, Yao *et al.* 2022). Therefore, where land use required the distinction, we assigned nutrient-poor emission factors to any drained Organic Soil areas designated below this threshold (i.e., former bogs), and nutrient-rich emission factors to those above. For peaty-mineral soil areas outside the scope of the nutrient status mapping analysis (Pronger *et al.* 2025), we assigned emission factors according to the proportion of the total area of Organic Soils designated as nutrient-rich to nutrient-poor (52 % nutrient-poor and 48 % nutrient-rich).

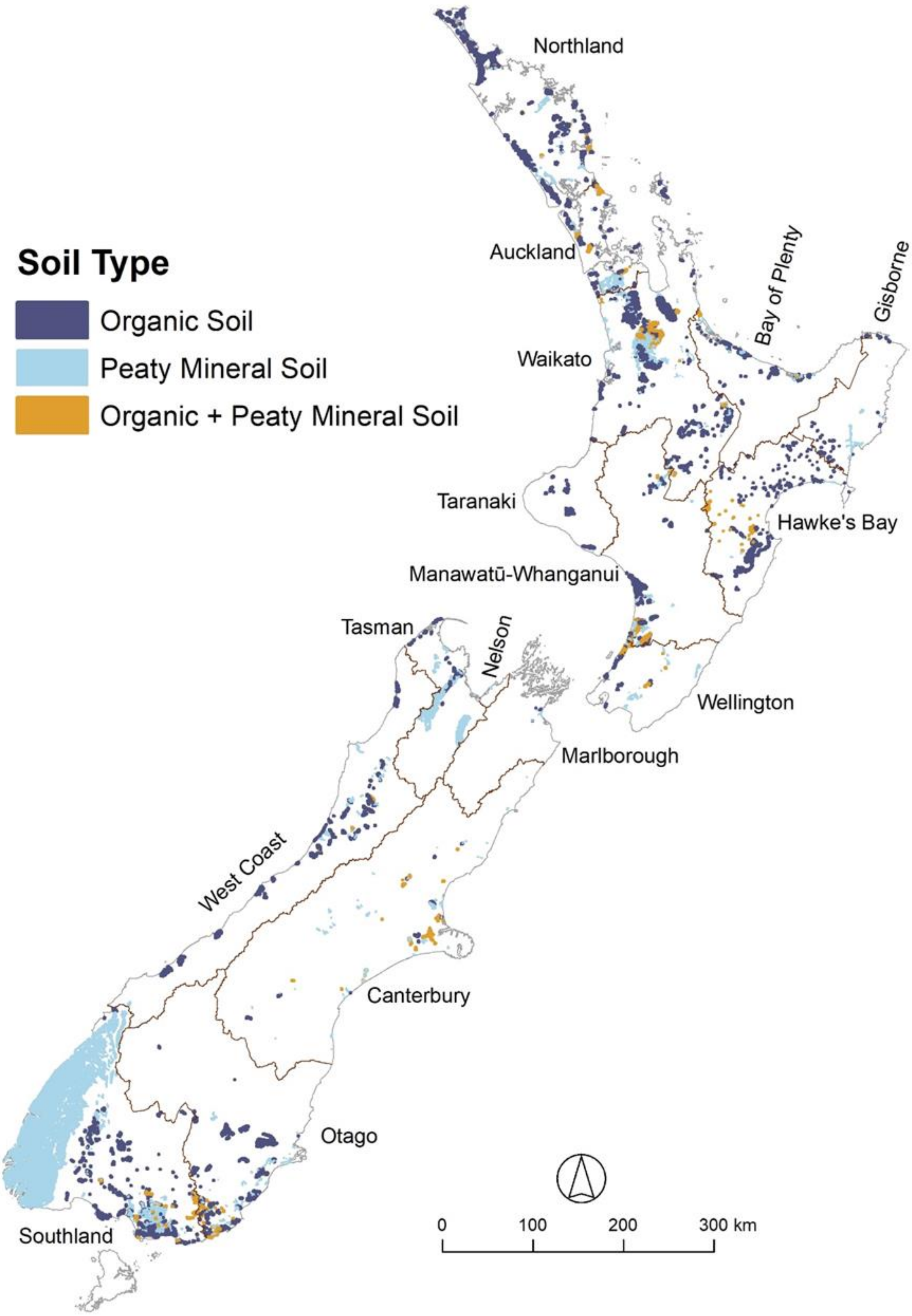

Figure 1. Current mapped extent of Organic Soils and peaty-mineral soils in New Zealand using spatial information from S-Map where available and the fundamental soils layer otherwise (Pronger *et al*. 2025). The area of Organic and peaty-mineral soils is visually exaggerated because soil mapping units, displayed spatially as polygons, can contain proportions of other soil types and line width has been increased so that smaller areas are visible on the map. Polygons contain 10– 100 % of the identified soil. Dark blue polygons are Organic Soils without peaty mineral soils, light blue polygons are peaty mineral soils without Organic Soils and orange polygons are a mixture of Organic Soils and peaty mineral soils that occur together in a soil map unit. The purpose of this map is to show the general distribution of Organic and peaty mineral soils across New Zealand.

Emissions from drained Organic Soils in New Zealand

IPCC Tier 1 emission factors

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006) provided Tier 1 default emission factors for Grassland, Cropland and Forest land based on the very limited international research available at the time. Currently, New Zealand utilises these defaults for estimating emissions from drained Organic Soils in its national inventory report (MfE 2024). The 2013 WS provided an improvement over the 2006 guidance by incorporating information from a much larger body of research. The 2013 WS Tier 1 default EFs are stratified by nutrient status in temperate climate zones (for Grassland and Cropland) and by drainage class (IPCC 2014). Drainage class is divided into shallow (< 30 cm) and deep drained (≥ 30 cm) for the nutrient-rich Grassland category, based on the long-term mean water table depth at a location. Considering available information within New Zealand (Kelliher *et al.* 2016, Campbell *et al.* 2021), we assumed all drained Organic Soils are deep drained.

The 2013 WS further stratifies N_2O emission factors for Grassland in temperate zones into nutrient-poor and nutrient-rich, but no longer does this for Forest land. Recognising updated research on methane emissions from drained Organic Soils, the WS also introduces emission factors for both land and drainage ditch areas. This requires knowledge of the proportion of area covered by drainage ditches or implementation of a default assumption of 5 % drainage ditch area within Grassland and Cropland, and 2.5 % ditch area within Forest land (IPCC 2014). The WS further introduced emission factors for estimating off-site carbon losses via dissolved organic carbon (DOC) export. In a New Zealand context, it is most likely that any drained peatlands retaining native vegetation (e.g., degraded *Empodisma robustum* areas) would be assigned to the Wetlands land use category because land use mapping is largely informed by remote sensing of vegetation types, so those areas are not included here.

New Zealand-specific measurements

There are limited GHG emissions data from drained Organic Soils in New Zealand and these are confined to the Waikato region, which contains about 41 % of the national drained area. Schipper & McLeod (2002) estimated total carbon loss over the 40 years since drainage and land conversion to livestock grazing in the Hamilton basin by sampling carbon content in the peat profile down to the Taupō volcanic tephra. They then compared this amount of carbon to that accumulated in an adjacent wetland reserve since the Taupō eruption. Their estimate of carbon (C) loss was 3.7 ± 1.25 t ha^{-1} yr^{-1}. Estimates derived from this number are denoted by 'SM 2002' in Table 2 and Figure 2 (later, in Results).

Subsequent studies have used eddy covariance measurements and compiled farm-scale net ecosystem carbon budgets (NECB) by measuring and estimating all carbon imports and exports. This approach provides detailed information on both the magnitude of losses and the associated controls. Campbell *et al.* (2015) estimated C losses of 2.94 t ha^{-1} yr^{-1} based on eddy covariance data from

Table 1. Area of drained Organic Soils (ha) and peaty-mineral soils aggregated by land use category for New Zealand. Organic soil area is also given separately for nutrient-rich and nutrient-poor areas based on historical wetland classification of the former peatlands they occupy.

Land use category	Nutrient-poor Organic Soil	Nutrient-rich Organic Soil	Total Organic Soil	Peaty-mineral soil
Grassland - high producing	64,930	55,135	120,065	27,075
Grassland - low producing	3,261	6,100	9,361	28,167
Grassland - with woody biomass	1,316	2,576	3,892	31,420
Cropland - annual	783	4,717	5,500	3,367
Cropland - perennial	657	342	1,000	218
Forest land - planted pre-1990	618	1,874	2,492	1,338
Forest land - planted post-1989	950	855	1,806	601
Settlements	824	1,132	1,955	607
Total	75,540	70,388	145,930	92,793

another Hamilton Basin site (denoted 'Rukuhia' in Table 2 and Figure 2). More recently, Campbell *et al.* (2021) established two eddy covariance measurement sites on adjacent dairy farms with differing drainage infrastructure (border drains and spinner drains) within the Moanatuatua peatland south of Hamilton. Their NECB estimates revealed large differences between the two sites, with C losses of 2.23 t ha^{-1} yr^{-1} and 8.47 t ha^{-1} yr^{-1} (Campbell *et al.* 2021). While both sites would be classified as deep drained by IPCC definitions, the surface soil moisture differed considerably due to the physical characteristics of the peat at each site. Surface moisture, rather than water table depth, seemed to drive the difference in carbon losses there. All the available measurements for New Zealand drained peatlands in the Waikato region are best classified as nutrient-poor, according to their original wetland status as raised bogs.

Beyond CO_2, there has been one published study to examine N_2O emissions from drained Organic Soils in New Zealand, conducted at Komakorau in the Hamilton Basin (Waikato Region). Kelliher *et al.* (2016) used flux chamber measurements at a dairy farm within a site that was fenced off from farming activities during measurements over a full year. They estimated mean annual N_2O-N emissions of 1.57 kg ha^{-1} yr^{-1}. There has also been one study aimed to include off-site losses of carbon due to dissolved organic carbon (DOC) export. Campbell *et al.* (2021) used a water balance approach coupled with DOC concentration measurements from water in Waikato peatland drains (Carlson *et al.* 2018) to estimate C losses of 0.25 t ha^{-1} yr^{-1}. No measurements of CH_4 fluxes from drained Organic Soils and drainage ditches in New Zealand have been published.

Calculation of emissions from drained Organic Soils

We generated estimates of annual drained Organic Soil emissions for New Zealand using different combinations of emission factors for each gas and the areas to which they were applied. These were integrated by both land use and greenhouse gas type using Tier 1 default emission factors from both the IPCC (2006) and the IPCC (2014) guidance, as well as New Zealand-specific annual CO_2 emission factors for each individual site location reported in the available published literature (Schipper & McLeod 2002, Campbell *et al.* 2015, Campbell *et al.* 2021). To estimate drained Organic Soils under Settlements, we applied the nutrient-poor Grassland WS default emission factors according to WS guidance.

We applied annual numbers for carbon losses from individual sites as substitutes for default emission factors to understand the potential range of emissions represented by available measurements. However, the very limited coverage of these data does not meet the standard for development of Tier 2 emission factors (Evans *et al.* 2017). The national-scale emissions derived from each measured annual number, while indicative of the available data, should not be interpreted as unbiased estimates.

Rewetting scenarios

To date no study has measured the effect of peatland restoration on greenhouse gas emissions in New Zealand. Nonetheless, measurements over intact (i.e., never drained) peatlands have demonstrated persistent annual carbon accumulation and strong water table control over greenhouse gas emissions (Campbell *et al.* 2014, Goodrich *et al.* 2015b, Goodrich *et al.* 2017, Ratcliffe *et al.* 2019). These studies provide confidence in the assumption that rewetting will reduce emissions, in agreement with most of the international literature and the WS guidance, albeit with uncertainty in the timeframes. We therefore constructed scenarios to estimate potential emission reduction from rewetting of drained peatlands. To establish the baseline (business as usual) annual emissions for comparison with rewetting scenarios, we used the total drained Organic Soil emissions estimated from the WS Tier 1 default emission factors (IPCC 2014). The estimates derived from the WS are within the range of the New Zealand measurements, which provides some confidence that these are a reasonable proxy. For rewetted areas, we also used Tier 1 default emission factors from the WS. These were stratified by nutrient status for CO_2 and CH_4 according to the same assumptions as for drained Organic Soils. Rewetted areas were also assigned an emission factor for losses due to exported DOC, but N_2O emissions were assumed to be negligible (Table A1).

We projected the avoided emissions attributable to rewetting drained Organic Soils on Cropland and Grassland using three scenarios of annual rewetting area. All three scenarios began with five years (2026–2030) of rewetting 500 ha yr^{-1}, as a relatively conservative assumption, appreciating the likely difficulty in achieving success with rewetting former agricultural land early on. The rewetted area was distributed in proportion to the area within Grassland and Cropland. After five years, we compared three possible trajectories for rewetting from 2031 to 2035 including a continuation of rewetting 500 ha yr^{-1}, an increase to rewetting 1000 ha yr^{-1} and an increase to rewetting 3000 ha yr^{-1}. The avoided emissions in each scenario were the accumulated difference between baseline total drained Organic Soil emissions and the emissions resulting from the rewetting scenario. We intentionally chose not to include the reduction of greenhouse gas emissions due to removal of animals from the land and their associated CH_4 and N_2O emissions. This would require a greater understanding of the spatial distribution of stock numbers than is currently available, although this is discussed briefly below. Note also that none of the drained Organic Soil emissions estimates includes animal emissions.

RESULTS

Estimates of drained Organic Soils emissions

Regardless of the emission factors used, the primary contributor to national drained Organic Soils GHG emissions in New Zealand was CO_2 from Grasslands (Figure 2, Table 2). Using the WS Tier 1 emission factors resulted in total CO_2 equivalent (CO_2e) emissions of 3.86 Mt yr^{-1}, with 3.52 Mt yr^{-1} from Grassland alone. That estimate was very similar to the emissions calculated from the mean of available New Zealand-specific emissions data, which resulted in total CO_2e emissions of 3.61 Mt yr^{-1}. The individual site values taken from published New Zealand-based studies illustrated the range in emissions observed both spatially and through time. Total Organic Soil emissions (as CO_2e) ranged from 3.06 to 4.69 Mt yr^{-1} derived from measurements only a few kilometres apart (Campbell *et al.* 2021). Adding the peaty-mineral soil area to the emissions calculation increased the estimates by nearly 50 % (Figure 2, Table 2). Using the WS Tier 1 default emission factors resulted in total CO_2e emissions of 6.34 Mt yr^{-1} when combining drained Organic Soils and peaty-mineral soil areas.

New Zealand's total net greenhouse gas CO_2e emissions in 2022 were 59.2 Mt (MfE 2024). Our estimate of drained Organic Soils emissions derived from the WS Tier 1 default emission factors indicates the contribution of these soils amounts to 6.5 % of total net emissions for that year (or 5 % of total gross emissions). If we include the estimates from peaty-mineral soils, the contribution increases to 11 % of total net emissions.

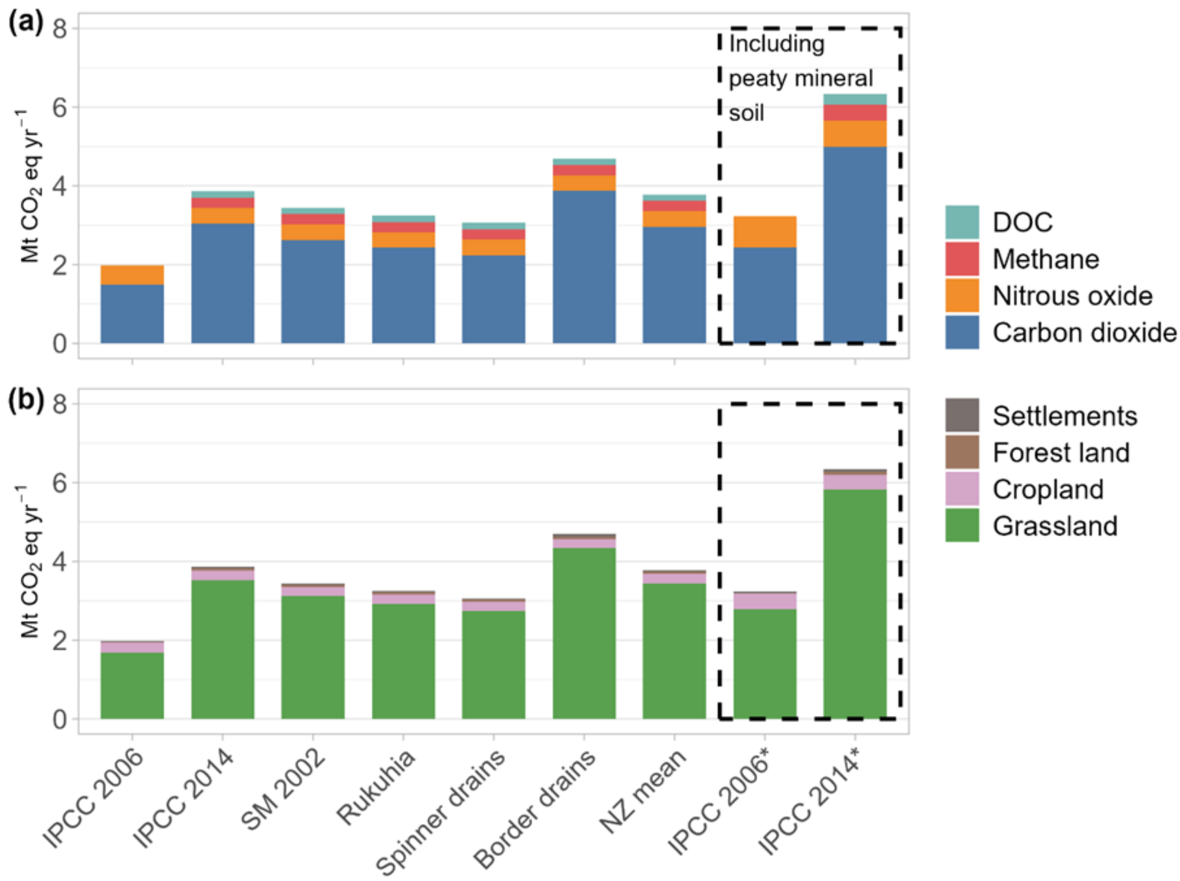

Figure 2. Total drained Organic Soils emissions for New Zealand aggregated by greenhouse gas source (a), and by land use (b). The bars within the dashed box (IPCC 2006* and IPCC 2014*) show estimates for areas that include mineral soils with a peaty surface layer (peaty-mineral soils) in addition to the Organic Soils areas. The numbers used to generate this Figure are also given in Table 2.

The potential for emissions mitigation through peatland rewetting

The calculated technical potential for avoided emissions from Grassland and Cropland rewetting in three different annual rewetting scenarios over a period of ten years from 2026 to 2035 is shown in Figure 3. The most conservative scenario (continued rewetting of 500 ha yr^{-1}) results in cumulative avoided CO_2e emissions of 0.53 Mt after ten years, whereas the most ambitious scenario (increasing to 3000 ha yr^{-1} from 2031) results in 1.25 Mt avoided CO_2e emissions over the same decade, despite the increase in annual methane emissions. These scenarios demonstrate the importance of early rewetting because of the non-linear accumulation of avoided emissions that continues through time, provided additional areas are rewetted each year.

DISCUSSION

Drained Organic Soils emissions estimates

Mostly due to inventory reporting conventions governed by the UNFCCC, CO_2 emissions from drained Organic Soils fall within the LULUCF sector rather than Agriculture (MfE 2024). Given that the land uses responsible for most of New Zealand's drained Organic Soil emissions are Grassland and Cropland, it is also useful to consider their magnitude in relation to total agricultural emissions. In 2022, New Zealand reported agricultural CO_2e emissions of 41.713 Mt, meaning Organic Soils are equivalent to 9–15 % of that total despite covering less than 1 % of the land area. Also note that annual net greenhouse gas emissions change from year to year, while the estimate for drained Organic Soil emissions remains

Table 2. Total drained Organic Soil emissions (expressed as CO_2e) for New Zealand (NZ) aggregated by land use and by greenhouse gas (GHG) source using different inventory methods (IPCC 2006 or IPCC 2014) or published measurements from New Zealand (NZ) peatlands (SM, Rukuhia, Spinner drains site, Border drains site; see Methods pages 5–6 for details). Estimates were generated for areas identified as Organic Soils using New Zealand's national greenhouse gas inventory definition, as well as for areas that also included mineral soils with a peaty surface layer (peaty-mineral soils; IPCC 2006* and IPCC 2014*), given their potential for similar emissions. Although there are no emission factors for peaty-mineral soils in either set of IPCC guidance, these were assigned as though the areas were Organic Soil. The numbers given in this Table are also presented in Figure 2. All numbers are in units of Mt yr^{-1}.

		IPCC 2006	IPCC 2014	SM 2002	Rukuhia	Spinner drains	Border drains	NZ mean	IPCC 2006*	IPCC 2014*
LAND USE	Grassland	1.68	3.52	3.12	2.92	2.72	4.33	3.28	2.78	5.83
	Cropland	0.26	0.24						0.40	0.38
	Forest land	0.01	0.05						0.02	0.08
	Settlements	0.02	0.05						0.03	0.06
	Total	1.98	3.86	3.44	3.25	3.06	4.69	3.61	3.23	6.34
GHG	Carbon dioxide	1.49	3.05	2.63	2.43	2.24	3.88	2.79	2.43	5.00
	Nitrous oxide	0.49	0.40						0.80	0.65
	Methane	-	0.26						-	0.42
	DOC	-	0.17						-	0.27
	Total	1.98	3.86	3.44	3.25	3.06	4.69	3.61	3.23	6.34

Note: in the printed table, the values 0.24, 0.05, 0.05, 0.40, 0.26 and 0.17 are centred across the columns IPCC 2014 to NZ mean.

constant in the absence of changes to mapping data (i.e., climate and management effects are not estimated in the inventory). Thus, the percentage contributions of drained Organic Soil given above are indicative of a snapshot in time based on one year's reported national emissions. The overall emissions from peatlands may be even greater, as our calculations do not include the emissions from partially drained peatlands that retain natural vegetation (e.g., drained wetlands on conservation land) or account for emissions from peatland fires, which can be substantial. Estimates of CO_2 emissions from two recent peatland fires ranged from 0.1 Mt (980 ha burned) to 0.5 Mt (2,434 ha burned) (Pronger *et al.* 2024). Taken together (reported emissions plus fires), the large emissions contribution from a relatively small land area of drained Organic Soils technically provides an opportunity for mitigation and considerable avoided emissions over time.

While the national emissions inventory has not yet adopted the 2013 Wetlands Supplement, Wheatley-Wilson & Wyatt (2024) provide an analysis of drained Organic Soil emissions and their contribution to the regional GHG inventory for the Waikato region that incorporates Tier 1 default emissions factors as well as the New Zealand measurements outlined above. Given this region has the largest proportion of New Zealand's peatlands, the relative emissions contribution was also larger. Using the country-specific data as draft Tier 2 emission factors for Grassland CO_2 along with WS defaults, emissions from drained Organic Soils amounted to 13–18 % of the region's total net emissions for the previous three inventories (2015/16, 2018/19 and 2021/22).

Emissions estimates from other countries with large areas of drained agricultural peatlands demonstrate the variability that results from local conditions and management approaches. This is particularly highlighted in Europe where ample in-situ measurements can lead to country-specific emission factors that differ considerably from the IPCC defaults. Our estimated emissions for New

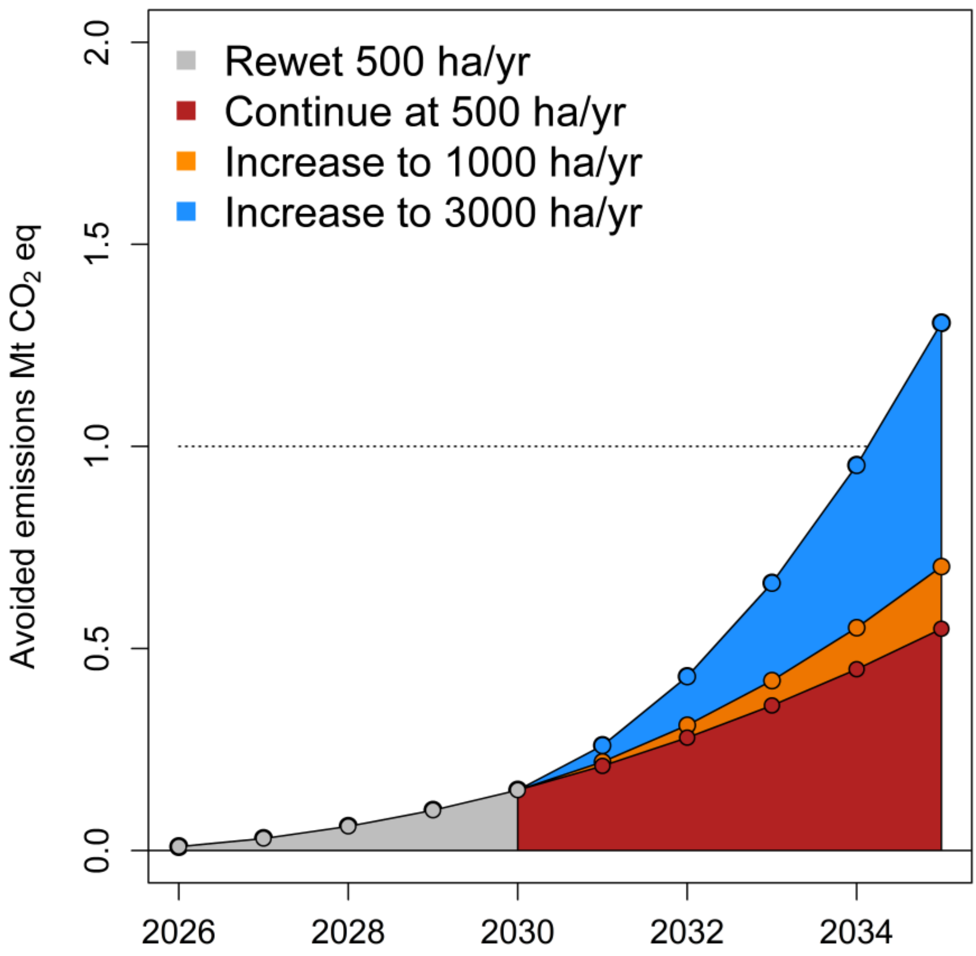

Figure 3. Cumulative potential future avoided emissions from three scenarios of rewetting drained Organic Soils. Baseline emissions for estimating the abatement along with the rewetted emissions were calculated using 2013 IPCC Wetland Supplement Tier 1 default emission factors.

Zealand's drained Organic Soils are higher than those reported for Ireland despite the much greater area of Grassland (332,000 ha) on drained Organic Soils there (Aitova *et al.* 2023). This is due to the recently developed country-specific CO_2-C emission factor proposed in that study for Grassland CO_2 (1.30 t ha^{-1} yr^{-1}), which is much lower than the Tier 1 default (5.3 t ha^{-1} yr^{-1}; IPCC 2014) and lower than the limited measurements available from within New Zealand (Table A1). The recent adoption of this country-specific value in Ireland had a considerable effect on the estimated emissions from drained Organic Soils under Grassland in their national inventory report (EPA 2024). In contrast, an updated compilation of flux data from drained Organic Soils in Germany shows that CO_2-C emissions from Grasslands there (8.3 t ha^{-1} yr^{-1}) are higher than the defaults (Tiemeyer *et al.* 2020, IPCC 2014). The higher updated emission factors for Germany are potentially related to deeper drainage and greater fertiliser application rates (Bechtold *et al.* 2014, Tiemeyer *et al.* 2016, Untenecker *et al.* 2017) than is typical for drained Organic Soils in Ireland (Renou-Wilson *et al.* 2014, Tuohy *et al.* 2023).

While emissions from poorly drained carbon-rich soils that do not meet the Organic Soils definition are not included in WS guidance, the area they cover is likely to be substantial. There is growing recognition of the potential for drained peaty-mineral soils in agricultural settings to be significant emissions sources at national scales. Paul *et al.* (2018) identified a considerable area of drained and agriculturally managed histic and humic soils in Ireland that may be emitting up to 9 Mt yr^{-1} of CO_2 (Paul *et al.* 2018). Denmark has also reflected the likely contribution of the Danish equivalent of peaty-mineral soil by reducing the WS default emission factors by 50 % and applying these to the appropriate land use categories on carbon-rich soils that do not meet the Organic Soil definition (Nielson *et al.* 2022). Without evidence to inform selection of the most appropriate emission factors for peaty-mineral soils in New Zealand, we used the conservative approach of taking WS defaults as they stand. Given the area covered by these soil types, a country-specific understanding of the full drainage-related soil emissions spectrum is essential to underpin accurate capturing of their contribution to national emissions.

Potential emissions mitigation through rewetting

The scenarios explored by the calculations of technical potential for avoided emissions from Grassland and Cropland with Organic Soil reinforce evidence for the potential effectiveness of rewetting as a GHG emission mitigation strategy (e.g. Günther *et al.* 2020), given that even the most ambitious scenario presented here involves rewetting only < 12 % of the total area of Organic Soils over ten years, after which more than 1 Mt of CO_2e emissions are avoided. Other countries have already proposed ambitious rewetting or restoration goals. For example, the UK climate change committee recommended restoring 55–70 % of peatlands in the United Kingdom by 2050 (Wentworth 2022), and policy analysis in Germany has recognised and begun investigating barriers and obstacles to rewetting as a national-scale emission reduction strategy (Wichmann & Nordt 2024).

It is also useful to consider the effect of rewetting on a per-hectare basis to provide context that may be more relevant to individual land managers, farmers or policy makers considering market-based incentive mechanisms for drained Organic Soil rewetting. Using emission factors from the 2013 WS and considering Grassland as an example, one hectare (ha) of drained Organic Soil on Grassland in an area of former nutrient-poor bog in a temperate region like New Zealand emits 24.05 t ha^{-1} yr^{-1} CO_2e due mostly to CO_2. If that same hectare were to be rewetted, the CO_2 flux would become roughly neutral and CH_4 emissions would increase, resulting in total CO_2e emissions dropping to 3.4 t ha^{-1} yr^{-1}. Therefore, the avoided CO_2e emissions per hectare for this hypothetical Grassland would be 20.67 t ha^{-1} yr^{-1}.

Given that rewetting does not necessarily dictate a change of land use, the example in the previous paragraph excludes any consideration of avoided emissions that might result from reducing cow numbers if an area of drained Organic Soil used for dairy grazing were to be retired after rewetting. Farm system modelling covering the range of low to high intensity dairy farms across New Zealand indicated the associated CO_2e emissions (excluding soil carbon and nitrogen mineralisation) ranged from 11 to 18 t ha^{-1} yr^{-1} (Ledgard & Falconer 2015). Adding these avoided agricultural emissions (largely made up of enteric methane) to our estimate of avoided Organic Soil emissions would increase the technical potential CO_2e emissions abatement to 31.67–38.67 t ha^{-1} yr^{-1}. Note also that these avoided emissions estimates do not include the potential for an area to regain carbon sink status. Over longer terms, if drained Organic Soil areas under dairy farming were actively restored with native peatland vegetation, the ecosystems may regain capacity to become annual carbon sinks (i.e., shift beyond simply avoiding emissions). Understanding the real effect of rewetting on emissions, rather than simply comparing managed Organic Soils with unmanaged peatlands, is an ongoing challenge with recent results suggesting the effects are not particularly consistent with 2013 Wetland Supplement emission factors (Tong *et al.* 2025) and there may be important temporal dynamics to account for (Kalhori *et al.* 2024).

Practical considerations for rewetting and future work needed

One barrier to emissions mitigation via rewetting drained Organic Soils is incentive. In New Zealand, most of these areas are privately owned and used for intensive dairy grazing. There are limited incentive mechanisms to drive either behaviour change away from productive use or emissions mitigation action on these areas. New Zealand elected to include only the mandatory categories within the LULUCF sector when setting its nationally determined contribution (NDC) as a party to the Paris Agreement (NZ 2021). This means that emissions from drained peatlands are not included in New Zealand's international emission reduction accounting and any subsequent abatement cannot be counted toward meeting the country's NDC target. Because of this, these emissions are also not included in New Zealand's emissions trading scheme (ETS), which is the government's primary tool for driving emission reductions. Exclusion from policy does not mean that emissions are not occurring or that they are not open to management.

In the absence of government regulated emissions accounting and market trading mechanisms, voluntary schemes offer potential for incentivising emission reductions. There are methodologies developed for recognising avoided emissions from rewetting or restoring drained peatlands in voluntary carbon markets (e.g., VERRA; Emmer & Couwenberg 2017), but these have yet to be explored in, or tailored for, New Zealand. Work is needed to test and validate these methodologies but also to determine the potential financial incentive a voluntary carbon market might provide to a farmer or landowner given the associated cost of monitoring, reporting and verification requirements.

Although a considerable proportion of drained Organic Soils are highly productive land, some areas are becoming unmanageable because of nutrient leaching risks and seasonal flooding, exacerbated by continued subsidence (e.g., Thakur 2015). If additional on-farm drainage or pumping becomes uneconomical, farmers may choose to simply abandon some paddocks or areas. This does not necessarily constitute rewetting but may provide opportunities for research into effective ways of maintaining high water tables throughout summer, and into the associated effects on emissions through time, without the need to compensate for lost agricultural productivity. There are also areas of Organic Soils on public land that have been affected by adjacent drainage (Mason *et al.* 2024), providing similar opportunities to test rewetting approaches for the purposes of emission reduction. Estimating the occurrence of such areas would also allow us to refine scenarios for the potential size of emissions mitigation in the near-term. Targeting such areas may also contribute to the Ministry for the Environment's carbon neutral government programme and goals of the Aotearoa New Zealand Biodiversity Strategy 2050 (e.g., 13.1.3 "Carbon storage from the restoration of indigenous ecosystems, including wetlands, forests, and coastal and marine ecosystems (blue carbon), is a key contributor to achieving net zero emissions for Aotearoa New Zealand").

The trade-off between productivity and emissions reduction may also be relieved if some portion of the rewetted area can be converted to an alternative productive use such as paludiculture (i.e., wet agriculture). Paludiculture candidate species with potential viability in New Zealand include *Typha* or flax/harekeke (*Phorium tenax*) (Wehi & Clarkson 2007, Vroom *et al*. 2018). While international evidence suggests paludiculture can lead to substantial emission reduction (Fritz & Couwenberg 2018), more work is needed to understand the potential markets available for New Zealand paludiculture crops or livestock, and the associated emission reductions.

Regardless of incentive, the ability to sufficiently raise and maintain water levels in New Zealand's drained peatlands has not been established. There are drained peatland areas where the surface elevation is near or below nearby surface water levels, and proximity to a water source is not a limitation. In other areas however, peatlands are gravity-drained and relatively far from a sufficient water source for proactive rewetting. Given that summer evaporation typically renders peatland drains inactive, and the balance of precipitation and evaporation largely controls summer water levels (Campbell *et al.* 2021, Speranskaya *et al.* 2024), there would be considerable difficulty in restricting evaporation even if drains were filled or blocked. For drained peatlands in such situations, a robust rewetting approach needs to be developed and tested to allow the emission reduction potential to be realised. Alternatively, evaporation needs to be slowed potentially through establishment of native vegetation, particularly a healthy *E. robustum* coverage to restrict water loss. Whether restoration using this approach and with minimal weed invasion is possible remains an open question, but successful restoration of mined peats has been demonstrated locally (Schipper *et al.* 2002).

An additional barrier restricting the role of rewetting in national-scale emission reductions is the lack of dynamic wetland mapping capabilities. To account for avoided emissions, we must be able to identify areas where rewetting has occurred and monitor through time to ensure higher water tables are maintained. Where peatland restoration is initiated, New Zealand's current approach to land use mapping will, in theory, capture the transition from e.g. Grassland to Wetland by detecting changes in surface vegetation (MfE 2024). However, if rewetting occurs without a subsequent land use transition or for paludiculture, then a robust method for monitoring or tracking water table depth is required. The challenge of dynamically mapping water table at national scale is not unique to New Zealand. Even in countries with extensive Organic Soil emissions databases and ongoing monitoring programmes, national-scale maps of water table depth relevant for Organic Soil emissions scaling have only been developed for discrete time periods (Tiemeyer *et al.* 2020, Bechtold *et al.* 2014). Research in this area should progress in tandem with improving understanding of emissions and development of Tier 2 and Tier 3 methods for New Zealand.

In the short-term, New Zealand should improve Organic Soil emissions estimates by first adopting the 2013 WS, which it has signalled its intention to do (MfE 2024). Emissions from peaty-mineral soils may be of similar magnitude to Organic Soils and, therefore, a better understanding of these emissions is required as well as consideration to including them in future inventories. While there are barriers to large-scale rewetting including data limitations, practical water table management and economic incentive, the opportunity for emissions reduction is substantial and warrants more work to refine estimates of current emissions and develop approaches for reducing them.

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AUTHOR CONTRIBUTIONS

JPG, JP, LS and PM conceived the project. JPG conducted the analysis and drafted the text with support from JP. RP performed spatial analysis. All authors provided critical feedback and helped shape the methodology, analysis and overall manuscript.

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Appendix

Table A1. Emission factors used to generate estimates of drained Organic Soil emissions for New Zealand and the potential for avoided emissions upon rewetting. The application of emission factors for each land use or sub-category is described in the manuscript. DOC = Dissolved organic carbon.

	Land use category	Land use sub-category	Emission factor	Reference
Carbon dioxide as CO_2-C (t ha^{-1} yr^{-1})	Grassland		2.5	IPCC 2006
	Cropland		10	IPCC 2006
	Forest land		0.68	IPCC 2006
	Grassland	drained, nutrient-poor	5.3	IPCC 2014
	Grassland	shallow drained, nutrient-rich	3.6	IPCC 2014
	Grassland	deep drained, nutrient-rich	6.1	IPCC 2014
	Cropland	drained	7.9	IPCC 2014
	Forest land	drained	2.6	IPCC 2014
	Grassland	drained, nutrient-poor	3.7	Schipper & McLeod 2002
			2.94	Campbell *et al*. 2015
			1.96	Campbell *et al*. 2021
			8.25	Campbell *et al*. 2021
	Rewetted	nutrient-poor	-0.23	IPCC 2014
	Rewetted	nutrient-rich	0.5	IPCC 2014
Nitrous oxide as N_2O-N (kg ha^{-1} yr^{-1})	Grassland		8	IPCC 2006
	Cropland		8	IPCC 2006
	Forest land	nutrient-rich	0.6	IPCC 2006
	Forest land	nutrient-poor	0.1	IPCC 2006
	Grassland	drained, nutrient-poor	4.3	IPCC 2014
	Grassland	shallow drained, nutrient-rich	1.6	IPCC 2014
	Grassland	deep drained, nutrient-rich	8.2	IPCC 2014
	Cropland	drained	13	IPCC 2014
	Forest land	drained	2.8	IPCC 2014
Methane as CH_4 (kg ha^{-1} yr^{-1})	Grassland	drained, nutrient-poor	1.8	IPCC 2014
	Grassland	shallow drained, nutrient-rich	39	IPCC 2014
	Grassland	deep drained, nutrient-rich	16	IPCC 2014
	Cropland	drained	0	IPCC 2014
	Forest land	drained	2.5	IPCC 2014
	Drainage ditch	shallow drained grassland	527	IPCC 2014
	Drainage ditch	deep drained grassland	1165	IPCC 2014
	Drainage ditch	deep drained cropland	1165	IPCC 2014
	Drainage ditch	drained forest land	217	IPCC 2014
Methane as CH_4-C (kg ha^{-1} yr^{-1})	Rewetted	nutrient-poor	92	IPCC 2014
	Rewetted	nutrient-rich	216	IPCC 2014
DOC as CO_2-C (t ha^{-1} yr^{-1})	Organic Soil	drained	0.31	IPCC 2014
	Organic Soil	rewetted	0.24	IPCC 2014