Manaaki Whenua
Landcare Research

Estimating carbon emissions from peatland fires at Kaimaumau–Motutangi and Awarua wetlands

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Estimating carbon emissions from peatland fires at Kaimaumau–Motutangi and Awarua wetlands

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Summary

Project and client

- The Department of Conservation (DOC) is responsible for administering extensive areas of peatlands on public conservation land, including at Kaimaumau–Motutangi (hereafter Kaimaumau) wetland in Northland and at Awarua wetland in Southland. Both of these wetlands have very high ecological and cultural values and are part of the Department's Arawai Kākāriki Wetland Restoration Programme.
- Extensive peatland fires occurred at Kaimaumau and Awarua wetlands in 2022. The direct impacts of the fires included loss of soil carbon (C) and the loss of vegetation and habitat for indigenous species. As a result, the fires have contributed to atmospheric carbon dioxide (CO_2) emissions and a decline in wetland values.

Objectives

The aim of this work was to provide estimates of the soil and vegetation C loss from peatland fires that occurred in 2022 at Kaimaumau–Motutangi (Northland) and Awarua (Southland) wetlands. The specific objectives were to:

- estimate the burn depth and area of soil loss from both fires
- quantify the current soil C stocks at both sites
- calculate per hectare and total C loss from both fires.

Methods

- To estimate the spatial extent and severity of soil and vegetation loss we used a spatial sampling approach, whereby sample circles were randomly allocated across the area of interest. Each circle had an area of 2 ha (about 160 m diameter).
- At each of these sampling circles (50 each at Awarua and Kaimaumau) we determined the proportion of burnt soil area, the depth of soil burnt (using a post-fire digital elevation model [DEM], where possible), the pre-fire vegetation type, the proportion of vegetation burnt, and the composite burn index.
- Soil C stocks were measured at Kaimaumau (five sites) and Awarua (five sites). Soils were sampled to 1 m depth.
- At both sites C loss associated with vegetation burning was estimated based on pre-burn vegetation mapping. The proportion of above-ground vegetation C stock lost during the fires was estimated using the composite burn index.
- C stock losses from soil and vegetation were converted to CO_2 so that all results are directly comparable to greenhouse gas accounting metrics and targets that use CO_2 equivalents.
- To estimate the uncertainty associated with mean C losses, we used a bootstrap resampling approach to generate a distribution of possible means, and then calculated the standard deviation and 95% confidence interval from that distribution.

Results

- At Kaimaumau, the estimated total C loss from soil and vegetation was 515,536 t CO_2 (±51,343 t CO_2) over the total estimated burnt area of Organic Soil (2,434 ha) and mineral (527 ha) soil. On average across the area of Organic Soil we estimated a soil C loss of 156.4 ± 19.1 t CO_2/ha and a mean vegetation C loss of 45.6 ± 4.4 t CO_2/ha over the total area.
- At Awarua there was less visual evidence of peat soil loss, and the total estimated C loss from soil and vegetation was 104,693 t CO_2 (±4,707 t CO_2) over the total estimated burnt area of 980 ha (all mapped as Organic Soil). On average across the area we estimated the soil C loss was 47.8 ± 3.5 t CO_2/ha and the vegetation C loss was 59.0 ± 1.3 t CO_2/ha.
- Spatial variation in the depth of Organic Soil loss was high at Kaimaumau, where in some places soil depth loss estimates exceeded 0.4 m, resulting in much larger estimated C losses (>1,000 t CO_2/ha) from more severely burnt areas.

Discussion

- C loss as a result of the fires in 2022 was large. We estimated a total loss at Kaimaumau of 515,536 t CO_2 and at Awarua of 104,693 t CO_2. At the August 2024 Emissions Trading Scheme carbon price of \$53/t CO_2, this amounts to \$27.3 million and \$5.5 million dollars, respectively. This substantial cost represents only one component of the cost of these fires (other costs include firefighting, and the loss of biodiversity value and other ecosystem services).
- Future management effort needs to be focused on fire prevention, including maintaining wetland water levels to reduce susceptibility to fire.
- At both wetlands the fire intensity was spatially variable over short distances, resulting in considerable heterogeneity in the proportion of soil and vegetation burnt. This made areal classification of fire intensity challenging and resulted in uncertainty in estimated C losses.
- Estimating the volume of peat soil loss was difficult. Available pre-fire DEMs were not useful, because low point density, together with the dense vegetation when the LiDAR was captured, resulted in substantial uncertainty in identifying the soil. Higher-point-density LiDAR capture is recommended for vegetated wetlands and would have reduced the uncertainty in soil volume loss estimates considerably.
- Post-fire DEMs produced from point cloud aerial imagery were used to estimate soil volume loss at Kaimaumau. This had to be done manually because it required identifying visual indicators of pre-fire surface height that could not be automated. The depth of soil loss appeared to be much less severe at Awarua, and the post-fire point-cloud-based DEM was not useful there. At Awarua we relied on extrapolation of a Global Navigation Satellite Systems surface survey of burn depth captured during field work, linked to estimates of the composite burn index from examination of aerial imagery.
- We were unable to quantify C loss from burning of peat below ground, especially in cases where it did not result in changes in surface height through surface slumping. Approaches to estimate below-ground C loss associated with fires in peat wetlands require more consideration in future.

Recommendations

Improved management of peat wetlands is required to protect the valuable ecosystem services they provide. While acknowledging that fires have historically occurred from natural events (e.g. lightning strike), increased incidence of fires contributes to C emissions and loss of biodiversity.

Some approaches that may reduce the likelihood of fire associated with human activity include limiting the influence of surrounding land use on water-table levels in the wetland, managing weed and fertiliser incursion into the wetland (these increase vulnerability to external fire sources), and creating and maintaining fire breaks where fire risk is high.

This work was constrained by available resourcing, several recommendations can be made to improve the accuracy of estimated C loss from fires in peat wetlands. Work that would improve our ability to accurately estimate C loss includes:

- improved understanding of current soil and vegetation C stocks in vegetated wetlands through a nationally designed soil and vegetation sampling and survey strategy, with soil sampling to at least 0.6 m depth
- improved LiDAR coverage of vegetated wetlands, captured at a point density that permits accurate prediction of soil surface through dense vegetation
- further development of an image segmentation workflow to quantify burn area in complex heterogeneous peat fires
- further investigation of potential approaches to estimate below-ground peat loss that may have occurred in some circumstances.

1 Background

The Department of Conservation (DOC) is responsible for administering extensive areas of peatlands on public conservation land, including at Kaimaumau–Motutangi wetland (Northland) and at Awarua wetland (Southland). Both of these wetlands have high ecological and cultural values and are part of the Department's Arawai Kākāriki Wetland Restoration Programme.

Extensive peatland fires occurred at Kaimaumau and Awarua wetlands in 2022. Fires have occurred in the past at these sites but have typically been smaller in extent. The direct impacts of the fires included loss of soil and vegetation carbon (C) stocks and habitat for indigenous species. As a result, the fires have contributed to atmospheric C emissions and a decline in wetland values.

In a peatland system fire prevalence is influenced by several factors, including weather/climate, soil surface micro-topography, soil moisture and water-table depth, Organic Soil depth, soil C content and bulk density, and vegetation composition (Benscoter & Wieder 2003). The quantity of organic matter consumed, and hence the emission of greenhouse gases, is further driven by fire characteristics such as intensity, frequency, and duration (Kasischke et al. 1995).

Both fires are considered to have been induced by humans. Natural peatland fires are known to have occurred in New Zealand prior to human arrival, particularly in northern regions, but the increased frequency of peatland fires due to human activities and as a consequence of climate change is a significant concern.

The Te Mana o te Taiao – Aotearoa New Zealand Biodiversity Strategy has identified specific goals for indigenous ecosystems in our response to climate change. For example, Goal 13.1.3 promotes 'Carbon storage from the restoration of indigenous ecosystems, including wetlands, forests, and coastal and marine ecosystems (blue carbon)' and is a key contributor to achieving net zero emissions for New Zealand. Understanding the C emissions from unnatural peatland fires will help DOC to manage the future impact of fires and contribute to this Strategy's goal.

Peatland restoration is recognised as a nature-based solution for climate mitigation and adaptation and was identified in the Government's first and second Emissions Reduction Plans (ERPs). The ERPs noted that peatlands and coastal wetlands that are drained to provide land for agriculture or housing become long-term sources of CO_2 emissions. Estimates of current emissions from drained peatland in New Zealand are around 4.2 Mt CO_2e per year[1] (Pronger et al. 2022). However, there is at present very limited information available to quantify the CO_2 emissions from peatland fires.

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[1] Million tonnes of carbon dioxide equivalents per year.

2 Objectives

The aim of this work was to provide estimates of the soil and vegetation C loss from peatland fires that occurred in 2022 at Kaimaumau–Motutangi (Northland) and Awarua (Southland) wetlands. The objectives were to:

- estimate the burn depth and area of soil loss from both fires
- quantify the current soil C stocks at both sites to 1 m depth by soil sampling
- calculate per hectare and total C loss from both fires.

This project represents the first detailed assessment of Organic Soil C loss due to large-scale fires in New Zealand peatlands.

3 Methods

3.1 Estimating burn area and burn intensity

At both wetlands the fire intensity was spatially variable over short distances, resulting in high heterogeneity in the proportion of soil and vegetation burned. Figure 1 shows Awarua high-resolution imagery post-fire (top), and image segmentation created using the post-fire aerial images (bottom). Image segmentation is an analytical technique that enables faster and more advanced image processing by partitioning digital images into groups of similar pixels. The image segmentation highlights the complexity of the burn pattern (green pixels show unburnt vegetation, orange and pink pixels moderately burnt areas, and brown pixels higher burn intensity areas). Image segmentation was used at both Awarua and Kaimaumau to explore spatial heterogeneity in the fire pattern.

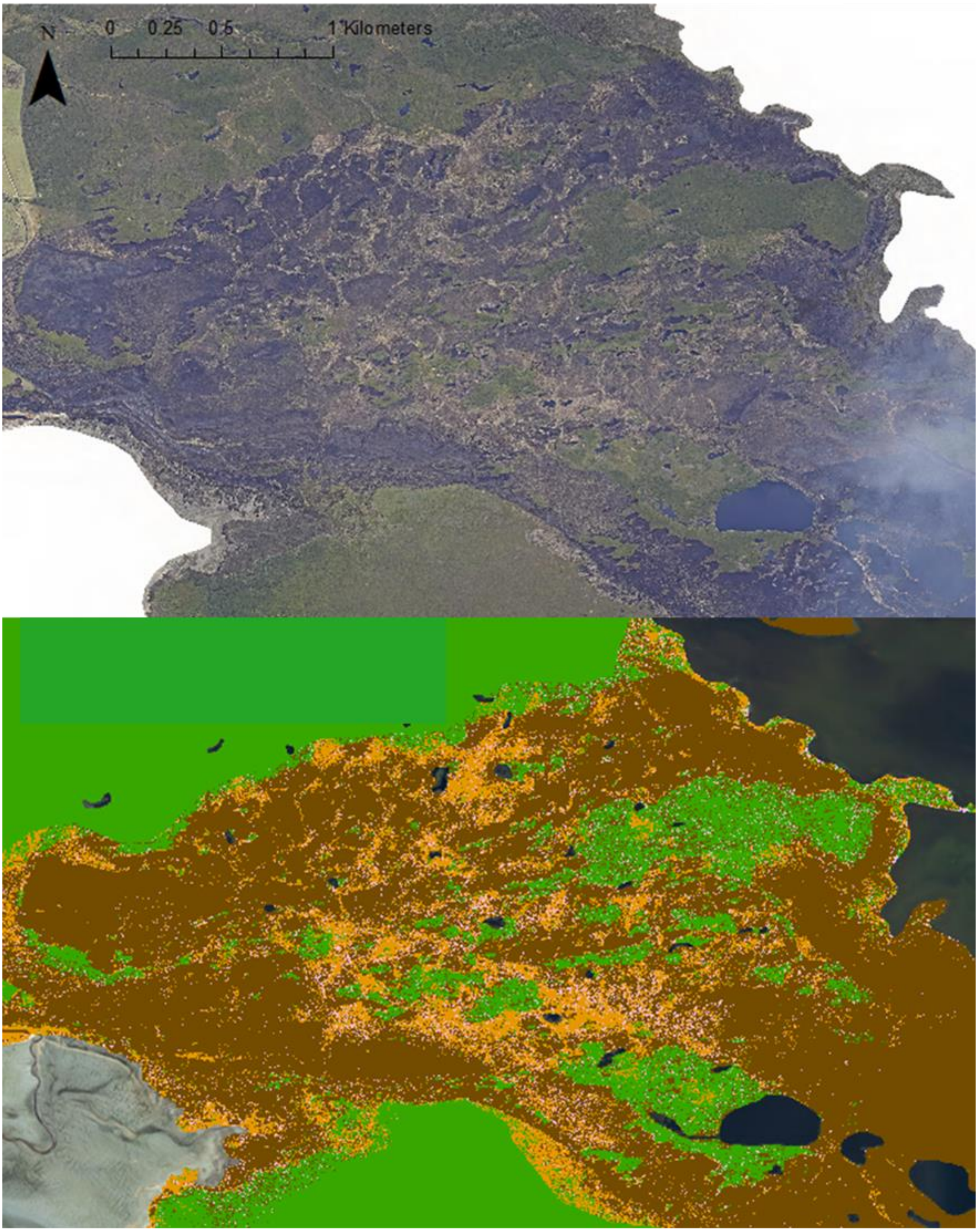

Figure 1. Awarua high-resolution imagery post-fire (top) and image segmentation of the image (bottom), where green shows unburnt vegetation, orange and pink moderately burnt areas, and brown higher-burn-intensity areas.

This degree of spatial complexity (Figure 1) means that disaggregation of the burn area by digitising polygons based on soil or vegetation burn intensity would be difficult, labour intensive, and ultimately inaccurate. Therefore, we used a spatial sampling approach, whereby circular sample plots were randomly allocated across the area of interest (Figure 2). The area of each circle was about 2 ha (160 m diameter). Within each of these sampling circles (50 each at Awarua and Kaimaumau) we determined the proportion of burnt soil area, the depth of soil burnt (where possible), the pre-fire vegetation type, the proportion of vegetation burnt, and the composite burn index (CBI, see section 3.6).

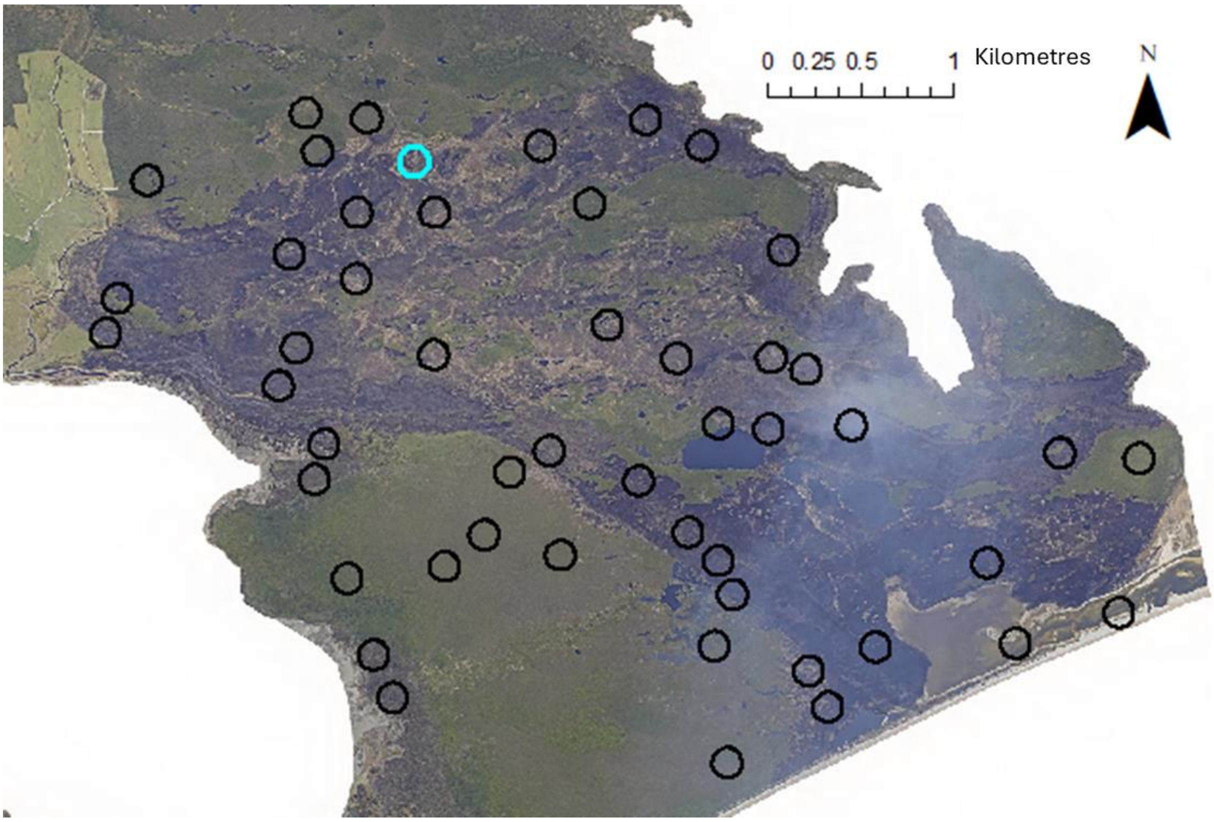

Figure 2. Randomly located circular sampling plots (50) within the area of interest at Awarua. Notes: Each circle had an area of 2 ha (about 160 m diameter). Within each circle we determined the proportion of burnt soil area, the depth of soil burnt, the pre-fire vegetation type, the proportion of vegetation burnt, and the composite burn index.

3.2 Estimating volume of peat loss

At Kaimaumau we estimated the depth of peat burn for sample circles where soil loss was evident from visual analyses of the high-resolution aerial imagery (Figure 3). We selected four locations, one in each quadrant of the circle (NE, NW, SE, SW), to estimate height loss. At each location we used the post-fire DEM (produced from an aerial image point cloud following the approach described by Schindler (2024)) and recorded the height of the upper unburnt surface and the height of the lower burnt surface. The difference between these two heights was then calculated. We also estimated the ratio of lower burnt surface area to the unburnt upper surface from the DEM and recorded this ratio as the proportion of burnt soil for the respective circle. The depth loss was then multiplied by the proportion of the circle area lost to calculate the volume of soil lost.

The depth of soil loss at Awarua was considerably less than at Kaimaumau, and we were unable to determine soil loss from the post-burn point-cloud-derived DEM because the loss to be resolved was typically below the resolution of the DEM (often <10 cm). Therefore, at

Awarua we used the CBI score for each sample circle and related this to detailed ground-based survey estimates of soil loss (five sites), measured while at the sites where soil sampling was done. The most severely burnt sites measured during the field campaign were estimated to have a soil height loss of 18 cm, while moderately burnt sites were estimated to have an average soil height loss of 8 cm. Elsewhere, where visual analysis indicated burning of the soil but the CBI was lower than heavily or moderately burnt, we assumed 5 cm of soil loss.

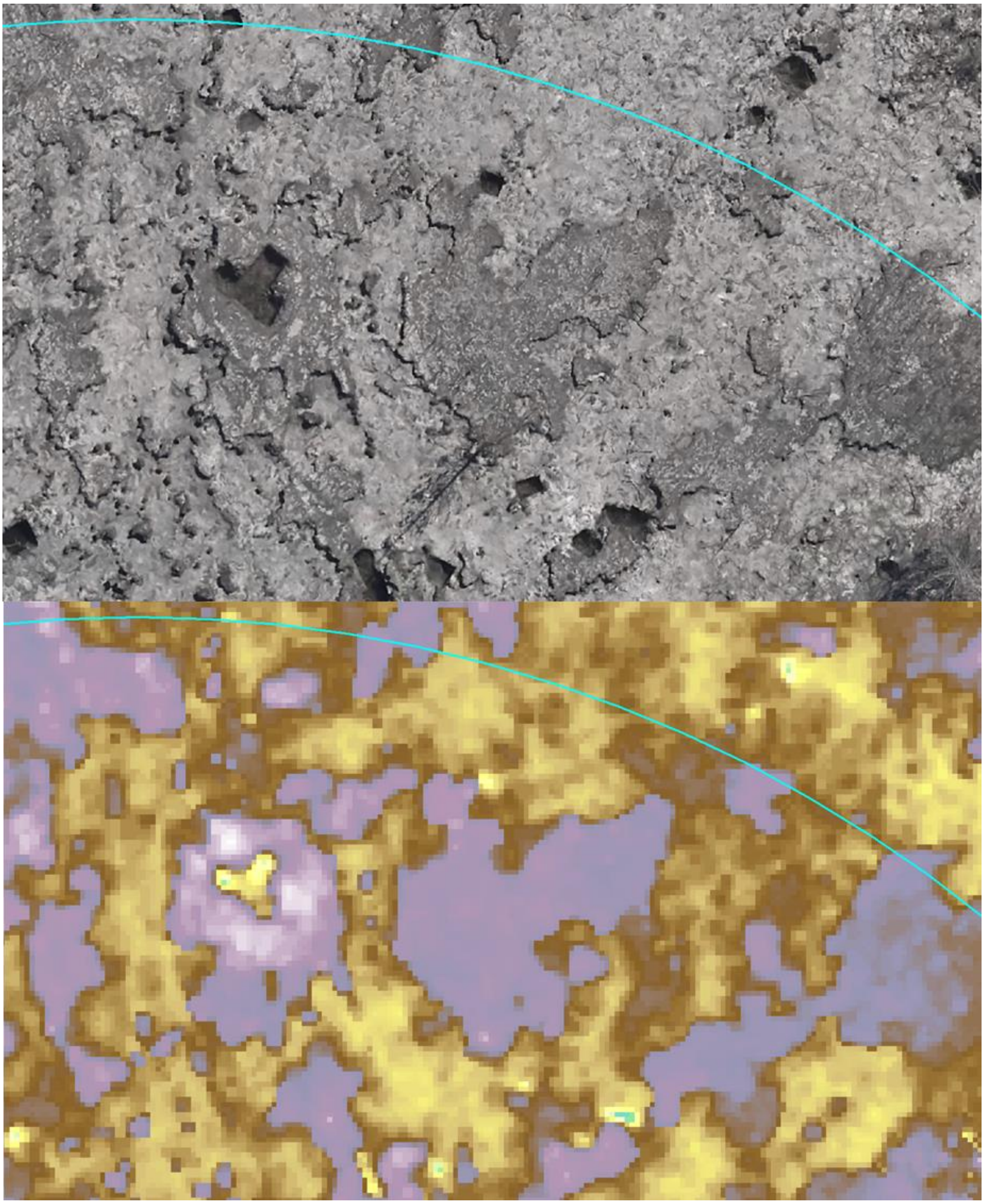

Figure 3. High-resolution aerial imagery of Kaimaumau wetland post-fire (top) and the digital elevation model produced from an aerial imagery point cloud (bottom).
Notes: Purple shows higher unburnt surface, and yellow and brown show the lower surface exposed after peat soil burning.

3.3 Estimating C stock and C loss from soil

Peat soils were sampled in the remaining high/unburnt remnants (e.g. Figure 3 higher surface) adjacent to the most severely burnt areas at both Kaimaumau (five sites) and Awarua (five sites). Soils were sampled with stainless steel sample rings (10 cm diameter, 7.5 cm deep), which were cut into the middle point of each 10 cm depth increment down to 60 cm soil depth. The lower 60–100 cm increment was sampled using a 1 m stainless steel tube sampler (44 mm diameter) and analysed in 20 cm increments. GPS locations for the sites sampled are shown in the Appendix (Table A1). Three additional sites for the 0–10 cm depth soils were also used from previous wetland monitoring plots at Kaimaumau (codes WN23, WN30, WN32) and Awarua (codes DLE01, DLE06, DLE10).

Peat soil C stock was then calculated in 10 cm depth increments in the top 60 cm, and in 20 cm depth increments below 60 cm (increment depth × bulk density × carbon concentration). The calculated C stocks in each 10 cm depth increment was then applied to the estimated depth of soil loss to calculate the likely C loss from the fires at both sites.

3.4 Estimating vegetation C stock and C loss

At both sites, C loss from vegetation was estimated from pre-burn vegetation mapping for Kaimaumau (Boffa Miskell Limited 2018) and Awarua (Boffa Miskell and Urtica Inc 2010). The proportion of each wetland vegetation structural type (e.g. shrubland, rushland, reedland) was estimated for each sample circle and related to the above-ground C stock estimates for New Zealand wetlands (Easdale et al. 2022). A summary of above-ground C stocks used is presented in Table 1. The proportion of the above-ground vegetation C stock lost during the fires was estimated using the CBI (section 3.6, Table 2).

Table 1. Above-ground carbon stocks (including litter) reported in Easdale et al. (2022) used to estimate vegetation carbon losses at both Kaimaumau and Awarua

	Shrubland (mānuka/ kānuka)	Rushland	Reedland	Fernland	Low-producing grassland
Above-ground carbon stock (t C/ha)	26.3	7.04	10.52	6.14	0.84

3.5 Converting C stock loss to CO_2

C stock losses from soil and vegetation were converted to carbon dioxide (CO_2) so that all results are directly comparable to greenhouse gas accounting metrics and targets that use CO_2 equivalents. For this conversion we assumed all the estimated C loss was converted to CO_2 (this assumption is discussed in Section 5.2).

3.6 Spatial layers used

The spatial layers used were the:

- wetland soil map (peat/not peat), based on the existing Fundamental Soils Layer (FSL) for Northland and Southland
- wetland vegetation map, based on existing vegetation surveys done at Kaimaumau (2018) and Awarua (2010)
- post-fire aerial imagery for both Kaimaumau and Awarua (2022)
- a post-fire DEM produced from aerial imagery captured post-fire (2022).

3.7 Burn severity index

Fire intensity was classified based on simplified application of the widely used composite burn index (CBI). The CBI, developed by Key and Benson (2006), is a well-documented and widely used approach (including for peat soil fires; e.g. Jandt et al. (2021)) for quantifying fire intensity and for ground-truthing remote sensing of burn severity. The CBI is a five-point index that integrates assessment of three fuel layers (substrate, low vegetation, tall shrubs).

The CBI also corelates well with other methods used to quantify fire intensity in peat soils, including the burn severity index (BSI). The BSI is a five-point qualitative assessment system based on the field methods of Dyrness and Norum (1983) used to categorise fire severity in Organic Soil layers (e.g. Bourgeau-Chavez et al. 2020). Table 2 shows that the five categories of the BSI system descriptor correlate closely to the CBI substrate descriptor (except for using an opposite numbering system: BSI uses 1 and CBI uses 5 for unburned). One key advantage of the CBI system is that it is widely used and has well-documented assessment procedures, including descriptors with visual cues that make spatial categorisation from high-resolution aerial imagery more achievable.

Table 2. The widely used composite burn index (CBI, Key and Benson (2006)) and correlation to the burn severity index (BSI, Dyrness and Norum (1983), last column) that has been used in some studies to assess fire severity in organic soil layers

CBI index value	Composite burn index (CBI) base descriptor	CBI substrate descriptor	CBI shrub descriptor	Burn severity index (BSI) base descriptor
5	Unburned	Not burned	Not burned	Unburned peat (index 1)
4	Scorched	Litter partially blackened	Foliage scorched and attached to supporting twigs.	Singed peat (index 2)
3	Lightly burned	Litter charred to partially consumed	Foliage and smaller twigs partially to completely consumed; branches mostly intact; typically, less than 60% of the shrub canopy is consumed.	Lightly burned peat (index 3)
2	Moderately burned	Litter mostly to entirely consumed	Foliage twigs and small stems consumed; some smaller branches (6.4–12.7 mm) still present; typically 40 to 80% of the shrub canopy is consumed.	Moderately burned peat (index 4)
1	Heavily burned	Litter and duff completely consumed	All plant parts consumed leaving only stubs greater than 12.7 mm in diameter.	Severely burned peat (index 5)

3.8 C loss uncertainty analysis

To estimate the uncertainty associated with mean C losses, we used a statistical resampling approach called bootstrapping. This process involved randomly selecting samples (36 at Awarua, 28 at Kaimaumau) from the total available burnt sample circles and calculating the mean of this randomly selected group (this means any given sample circle can be chosen more than once in a group). We repeated this sampling 10,000 times to generate a distribution of possible means, and then calculated the standard deviation and 95% confidence interval from that distribution.

4 Results

4.1 Kaimaumau

4.1.1 Soil C stock

C stocks for Organic Soil sampled at Kaimaumau are summarised in Table 3, including mean bulk density, percentage C, and calculated C stock in each depth increment for each layer for the sites sampled. On average, the total C stock to 1 m depth for the sites sampled was 956 t C/ha and ranged from 853 to 1,154 t C/ha.

Table 3. Soil sampling results for Kaimaumau for each depth increment sampled, showing mean and standard deviation for soil bulk density, organic carbon concentration, and soil carbon stock for each depth increment

Depth increment (m)	Number of samples	Bulk density (t/m3)		Organic C (%)		Organic C stock (t C/ha)	
		Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.
0–0.1	8*	0.31	0.15	27.2	11.7	70.1	24.7
0.1–0.2	5	0.21	0.09	45.7	11.7	91.8	32.0
0.2–0.3	5	0.20	0.08	50.8	14.8	94.9	9.7
0.3–0.4	5	0.22	0.11	49.7	19.0	91.3	14.0
0.4–0.5	5	0.23	0.13	47.9	17.6	90.2	10.8
0.5–0.6	5	0.21	0.13	51.4	15.9	90.2	7.1
0.6–0.8	5	0.20	0.11	52.8	16.4	181.0	18.0
0.8–1	5	0.21	0.14	51.3	17.9	173.5	11.5

* Values presented for the 0–0.1 m depth increment include data from previous wetland monitoring plots that were within the burnt area at Kaimaumau (site codes WN23, WN30, WN32).

4.1.2 Area burned and depth of soil loss

Determining the total area burned was challenging because of the heterogeneity of the fire (Figure 4, and see further detail in section 3.1). Basic delineation of the exterior perimeter of the fire and partitioning of the area between Organic Soil (peat soil) and mineral soil gave a total burn area of 2,433.9 ha for Organic Soil and 526.8 ha for mineral soil. For the Organic Soil area we tested using image segmentation of the area of interest, which suggested a burnt area of 2,128 ha (total area of light and heavy burn in Figure 4), but we were not confident in the result and this approach requires further time investment to develop (see section 5 for further discussion).

The depth of soil loss was estimated from the post-fire DEM for the 23 randomly located, 2 ha circles that were on burnt Organic Soil within the area of interest. Average soil depth loss was 17.2 cm, which covered 23% of the area of the sampling circles on average. However, the depth loss was spatially variable, ranging from no loss to as high as 43 cm, averaged across a 2 ha sampling circle. In some areas, single-point estimates of height loss were as high as 60 cm. The proportion of burned soil area within sample circles was variable, ranging from 5 to 75% of the 2 ha circle.

4.1.3 Estimated soil C loss for Organic Soil

The mean soil C loss was estimated at 156.4 t CO_2/ha, with a bootstrapped 95% confidence interval of 137.3–175.5 t CO_2/ha (Table 4). However, spatial variation was high and individual sample estimates ranged from 6.4 to 1,075.1 t CO_2/ha. This highest value was for a sample circle in a heavily burnt area where mean soil burn depth was 0.45 m over 75% of the area. Averaged over the total burnt area of Organic Soil, the loss from the soil was estimated at 380,572 t CO_2, with a bootstrapped 95% confidence interval of 334,053 t CO_2 to 427,090 t CO_2 (Table 5).

Table 4. Estimated CO_2 loss per hectare for both Organic Soil and vegetation for the burnt area at Kaimaumau

	Soil C loss (t C/ha)	Soil C loss (t CO2/ha)	Vegetation C loss (t C/ha)	Vegetation C loss (t CO2/ha)	Total C loss (t CO2/ha)
Mean loss	**42.6**	**156.4**	**12.4**	**45.6**	**201.9**
Bootstrapped standard deviation	14.2	51.6	1.2	4.4	54.4
95% confidence interval	37.4 – 47.9	137.3 – 175.5	12.0 – 12.9	44.0 – 47.2	181.2 – 222.7

Table 5. Estimated total CO_2 loss for Organic Soil, mineral soil area, and vegetation for the burnt area at Kaimaumau

Total C loss	Area (ha)	Soil C loss (t C/ha)	Soil C loss (t CO2/ha)	Vegetation C loss (t C/ha)	Vegetation C loss (t CO2/ha)	Total C loss (t CO2)
Organic Soil	**2,434**	**103,792**	**380,572**	**30,259**	**110,950**	**491,522**
95% confidence interval	2,434	90,991 - 116,594	334,053 - 427,090	29,177 - 31,341	106,983 - 114,917	441,037 - 542,006
Mineral soil	**527**			**6,549**	**24,014**	**24,014**
95% confidence interval	527			6,315 - 6,784	23,156 - 24,873	23,156 - 24,873
Total	**2,961**	**103,792**	**380,572**	**36,808**	**134,964**	**515,536**
95% confidence interval	2,961	90,991 - 116,594	334,053 - 427,090	35,493 - 38,124	130,139 - 139,790	464,193 - 566,879

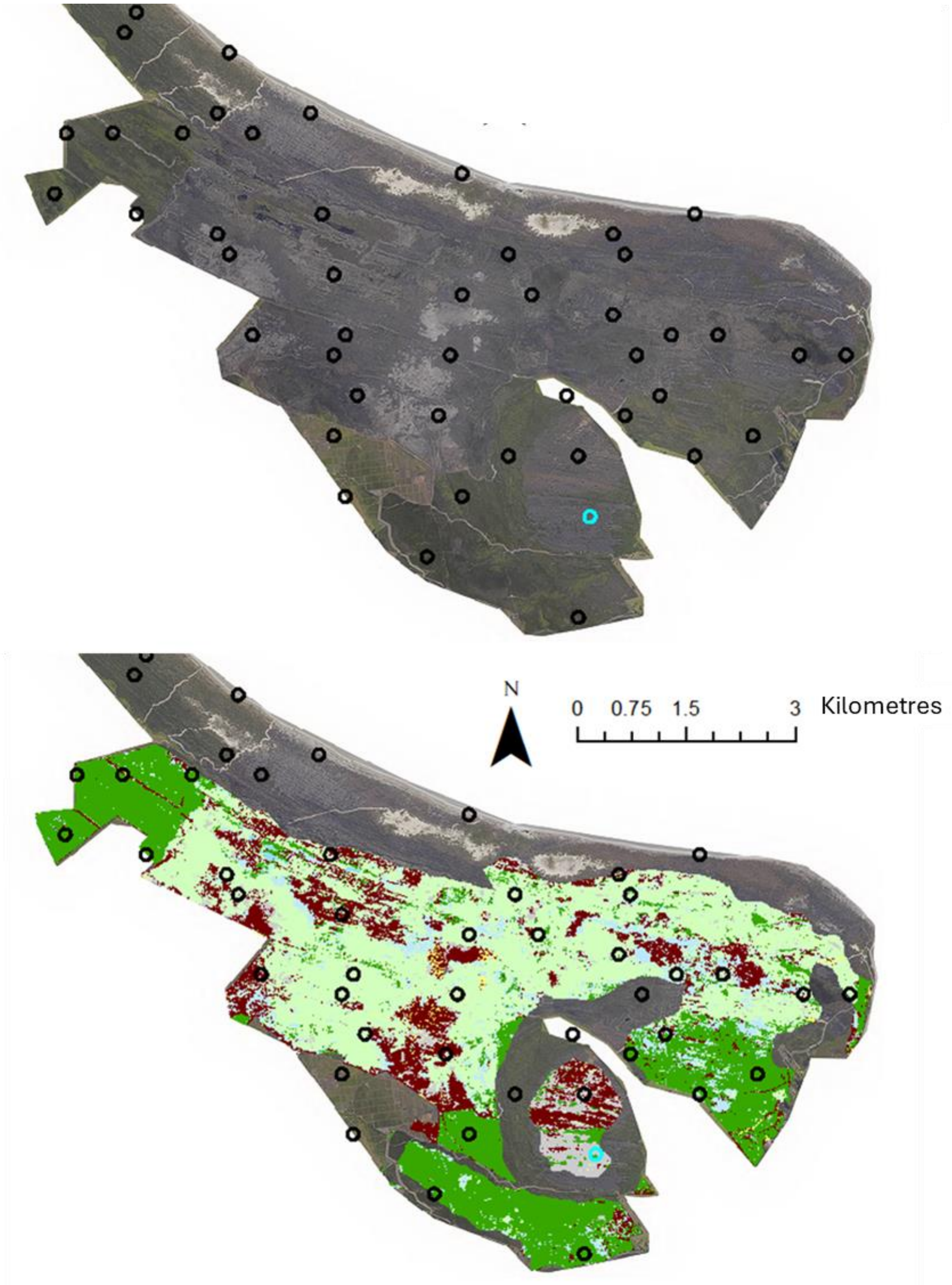

Figure 4. Top panel shows randomly located sample circles (50) within the area of interest at Kaimaumau; each circle had an area of 2 ha (about 160 m diameter). Lower panel shows attempted image segmentation on area mapped as Organic Soil, where dark green suggests unburnt vegetation; light green, light blue, and light grey suggest light burn; and brown suggests deep burn.

4.1.4 Estimated C loss for vegetation

Vegetation proportions were estimated for each sample circle using existing vegetation mapping. Common vegetation structural type was scrub and shrubland, dominated by mānuka. A lesser portion of the area was rushland and reedland. Easdale et al. (2022) calculated a mean above-ground C content (vegetation plus litter layer) of 26.3 t C/ha for mānuka/kānuka scrub, 7.04 t C/ha for rushland, and 10.52 t C/ha for reedland. Using these values and the portion of vegetation burnt (based on the visual analysis of aerial imagery), we calculated a mean vegetation loss of 45.6 t CO_2/ha, with a bootstrapped 95% confidence interval of 44.0–47.2 t CO_2/ha (Table 4). Averaged over the total burnt area (mineral soil and Organic Soil), the total C loss from vegetation was estimated at 134,964 t CO_2, with a bootstrapped 95% confidence interval of 130,139–139,790 t CO_2 (Table 5).

4.1.5 Total estimated C loss

Total C loss on Organic Soil area for the soil and vegetation combined was estimated at 201.9 t CO_2/ha, with a bootstrapped 95% confidence interval of 181.2–222.7 t CO_2/ha (Table 4). Total emissions over the area of burnt Organic Soil was estimated at 491,522 t CO_2, with a bootstrapped 95% confidence interval of 441,037–542,006 t CO_2. Total C emissions for the fire across the mineral soil (vegetation only) and Organic Soil area was 515,536 t CO_2, with a bootstrapped 95% confidence interval of 464,193–566,879 t CO_2 (Table 5).

4.2 Awarua

4.2.1 Soil C stock at Awarua

C stocks for Organic Soil sampled at Awarua are summarised in Table 6, including mean and standard deviation for bulk density, C concentration (%), and calculated C stock in each depth increment. On average, the total C stock to 1 m depth was 511 t C/ha and ranged from 363 to 688 t C/ha, calculated from the four sites where we had all depth increments. Table 6 does not include a sixth site sampled that only had peaty material in the top 20 cm and did not classify as an Organic Soil, so was not used to calculate C stocks for the Organic Soil area.

Table 6. Soil sampling results averaged across each depth increment sampled at Awarua, showing soil bulk density, organic carbon, concentration, and soil carbon stock

Depth increment (m)	Number of sites sampled	Bulk density (t/m^3)		Organic C (%)		Organic C stock (t C/ha)	
		Mean	Std Dev.	Mean	Std Dev.	Mean	Std Dev.
0–0.1	8*	0.08	0.02	54.60	4.81	46.93	16.22
0.1–0.2	5	0.08	0.04	51.46	4.16	38.93	16.12
0.2-0.3	5	0.09	0.05	52.30	6.26	45.06	17.27
0.3–0.4	5	0.10	0.06	49.79	9.07	46.28	20.54
0.4–0.5	5	0.09	0.05	53.07	8.45	48.03	19.05
0.5–0.6	5	0.10	0.04	54.12	8.65	53.19	14.53
0.6–0.8	4**	0.10	0.04	58.19	3.23	119.28	43.27
0.8–1	4**	0.09	0.03	59.37	2.93	103.47	33.66

* Values presented for the 0–0.1 m depth increment include data from previous wetland monitoring plots that were within the burnt area (codes DLE01, DLE06, DLE10).

** Lower depth samples were not collected at one site where overlying sphagnum meant we were unable to sample the lower depth (the sampling approach was limited to 1 m total depth).

4.2.2 Area burned and depth of soil loss

Determining the total area burned was challenging because of the heterogeneity of the fire (see section 3.1). Based on the total area of interest and the ratio of burnt to unburnt area in the 50 randomly positioned sampling circles, we estimated a burn area of 980 ha. In contrast to Kaimaumau, the total area of interest at Awarua was mapped as Organic Soil, so partitioning between Organic and mineral soil area was not needed.

We also tested using image segmentation of the area of interest, but we were not confident in the result, and this approach requires further time investment to develop. Despite this, using the image segmentation approach resulted in an estimated heavily burnt area of 815 ha and a lighter or partial burn area of 177 ha, summing to 993 ha, which is very similar to the estimate based on the sampling circles. We used an area of 980 ha.

The depth of soil loss at Awarua was considerably less than at Kaimaumau, and in fact we were unable to determine soil loss from the post-burn DEM because it was typically below the resolution of the DEM (often <10 cm). Therefore, at Awarua we used the CBI score and related this to ground-based survey estimates of soil loss measured while at the site for soil sampling.

The most severely burnt site measured during the field campaign was calculated to have a soil height loss of 18 cm (CBI of 1). Moderately burnt sites were estimated to have an average soil height loss of 8 cm (CBI of 2), and elsewhere, where there appeared to be burning of the soil, we assumed 5 cm (CBI of 3) of soil loss. The proportion of burned soil area within sampling circles averaged 25% of the area, but ranged from 0 to 90% of the area in the 2 ha sample circles.

4.2.3 Estimated soil C loss for Organic Soil

The mean soil C loss was estimated at 47.8 t CO_2/ha, with a bootstrapped 95% confidence interval of 44.3–51.3 t CO_2/ha (Table 7). Losses ranged from 0 to 257.6 t CO_2/ha. The highest value was from a sample circle in a heavily burnt area, where mean soil burn depth was estimated at 18 cm (CBI of 1) over 90% of the area. Averaged over the total burnt area of Organic Soil, the C loss from the soil was estimated at 46,874 t CO_2, with a bootstrapped 95% confidence interval of 43,416–50,332 t CO_2 (Table 8).

4.2.4 Estimated C loss from vegetation

The burnt area was largely scrub and shrubland, dominated by dense mānuka (82% of the burnt area). A lesser portion of the area was rushland (12%), with the remaining area (6%) made up of mossland, fernland, and tussockland. Using these values and the proportion of vegetation burnt based on the visual analysis of aerial imagery, we calculated a mean vegetation loss of 59.0 t CO_2/ha, with a bootstrapped 95% confidence interval of 57.7–60.3 t CO_2/ha (Table 7). Averaged over the total burnt area, the total C loss from vegetation was estimated at 57,819 t CO_2, with a bootstrapped 95% confidence interval of 56,570 to 59,067 t CO_2 (Table 8).

4.2.5 Total estimated C loss

Total C loss for the soil and vegetation combined at Awarua was estimated at 106.8 t CO_2/ha, with a bootstrapped 95% confidence interval of 102.0–111.6 t CO_2/ha (Table 7). Total emissions over the burnt area were estimated at 104,693 t CO_2, with a bootstrapped 95% confidence interval of 99,986–109,400 t CO_2 (Table 8).

Table 7. Estimated carbon loss per hectare for Organic Soil and vegetation for the burnt area at Awarua

	Soil C loss (t C/ha)	**Soil C loss (t CO2/ha)**	**Vegetation C loss (t C/ha)**	**Vegetation C loss (t CO2/ha)**	**Total C loss (t CO2/ha)**
Mean loss	**13.0**	**47.8**	**16.1**	**59.0**	**106.8**
Bootstrapped standard deviation	2.9	10.8	1.1	3.9	3.6
95% confidence interval	12.1 – 14.0	44.3 – 51.3	15.7 – 16.4	57.7 – 60.3	102.0 – 111.6

Table 8. Estimated total CO_2 loss for Organic Soil and vegetation for the burnt area at Awarua

Total C loss	**Area (ha)**	**Soil C loss (t C/ha)**	**Soil C loss (t CO2/ha)**	**Vegetation C loss (t C/ha)**	**Vegetation C loss (t CO2/ha)**	**Total C loss (t CO2)**
Total loss estimate	**980**	**12,784**	**46,874**	**15,769**	**57,819**	**104,693**
95% confidence interval	980	11,855 - 13,712	43,416 - 50,332	15,417 - 16,121	56,570 - 59,067	99,986 - 109,400

5 Discussion

5.1 C loss from peatland fires

C loss from the peatland fires in 2022 was large. We estimated a total loss at Kaimaumau of 515,536 t CO_2 (±51,343 t CO_2) and at Awarua of 104,693 t CO_2 (±8,485 t CO_2). At Kaimaumau we estimated an average soil C loss of 156.4 ± 19.1 t CO_2/ha and a vegetation C loss of 45.6 ± 1.6 t CO_2/ha. In some areas the depth of Organic Soil loss exceeded 0.4 m, resulting in much larger estimated C losses (>1,000 t CO_2/ha).

At Awarua, there was less visual evidence of peat soil loss. On average across the area of Organic Soil at Awarua we estimated a soil C loss of 47.8 ± 3.5 t CO_2/ha and a vegetation C loss of 59.0 ± 1.3 t CO_2/ha.

During the period 2026–2030 (ERP2) New Zealand's ERP target is to reduce gross GHG emissions from an average of 72.5 Mt CO_2-e/yr (2022–2025) to 61 Mt CO_2-e/yr, requiring a reduction in emissions of 11.5 Mt CO_2-e/yr. The total combined emissions from both fires (0.62 Mt CO_2) represents about 5.4% of this required reduction in annual emissions. Therefore, assuming peatland fire emissions were included in New Zealand's emissions accounting, avoiding large peatland fires is important to reach ERP targets.

Default IPCC Tier 1 Organic Soil fuel consumption values for undrained peat wetland fires is 66 ± 20 t dry matter (DM) per hectare (Table 2.8 in IPCC 2014), which equates to 33 ± 10 t C/ha (assuming DM is 50% C) or 121 ± 37 t CO_2/ha. The mean estimate at Awarua is lower than this range, probably because soil loss was not large at this site. The mean per hectare loss at Kaimaumau, where soil loss was large, was above this range, but still lower than the default IPCC Tier 1 Organic Soil fuel consumption mean loss rate for drained peatlands of 336 t DM per hectare, (Table 2.8 in IPCC 2014) which equates to 168 t C/ha (assuming DM is 50% C) or 616 t CO_2/ha assuming all C loss is converted to CO_2.

At the present Emissions Trading Scheme carbon price (August 2024) of $53/t CO_2, total emissions amount to $27.3 and $5.5 million dollars for Kaimaumau and Awarua, respectively. This substantial cost represents only one component of the cost of these fires. Other costs include firefighting, loss of air quality, and loss of biodiversity value and other ecosystem services. Future effort needs to be focused on fire prevention through improved management.

At both wetlands the fire intensity was spatially variable. Some areas were severely burnt with large losses of peat soil and most of the vegetation, while in other areas the fire appeared to have passed through quickly and only scorched vegetation. Capturing this spatial variation in C loss in these heterogenous fire environments was difficult, and there were many uncertainties that would take considerably more time and resources to quantify. Our approach to estimating uncertainties using bootstrap resampling was chosen to maximise the available information. However, in using this approach we assume that our samples or estimates capture all the relevant uncertainty we might be interested in. Given we know this is not true, as noted above, the uncertainties may be underestimated. Below we provide further detail on these limitations and how estimates can be improved in future.

5.2 Limitations and further work

Estimating the volume of peat soil loss was difficult. The low resolution of geospatial data (LiDAR point density of the pre-fire LiDAR), together with the dense vegetation where the LiDAR was captured, resulted in substantial uncertainty in identifying the soil surface in the available pre-fire DEMs. Therefore, LiDAR-derived DEMs pre-fire were not useful for differentiating heights between pre- and post-fire DEMs.

At Kaimaumau we were able to estimate soil loss from the post-fire DEM produced from point cloud aerial imagery captured shortly after the fire. Height loss was determined manually by identifying remnant higher surfaces in the most severely burnt areas (Figure 5) and calculating the difference between this and the lower burnt surface in randomly positioned 2 ha sample circles. However, in some instances there was uncertainty whether sharp changes in soil surface topography represented peat burn depth from the most recent fire. Some of these features could have been related to a previous and complex fire history. Future estimates of soil volume loss for peatland fires would benefit from capturing high-point-density LiDAR over vegetated wetlands. Pronger et al. (2020) tested helicopter-based LiDAR with a point density of 45–50 points/m^2 over managed drained peatlands and determined a change detection threshold of 0.05–0.06 m for pasture.

Figure 5. Image taken in May 2023 (about 18 months post-fire) showing a small section of remnant surface about 40 cm above the burnt surface and where the fire has burnt in underneath, potentially resulting in slumping of the surface.

We were unable to quantify C loss from peat burning below ground, especially in cases where it did not result in changes in surface height through surface slumping. In natural, intact peatlands (including these sites) a higher water table would typically reduce the likelihood of below-ground fire (relative to drained peatlands). However, because these fires occurred in summer when water tables were low, there was a higher probability of this occurring.

At Awarua the absence of any observed surface slumping (at the areas we visited during field work) indicate this may not have been a large contribution. In contrast, at Kaimaumau surface slumping was evident (and where this occurred, our method should have accounted for associated losses), but fire could also enter through the many gum digger holes and probably did not always result in surface slumping. At least where the water table was low, it is likely that additional loss of C would have occurred locally to these gum digger holes. We have not attempted to estimate the C loss associated with this component, and our C loss estimates therefore may be conservative. Approaches to estimate below-ground C loss associated with fires in peat wetlands require more consideration in future.

An additional source of vegetative C loss that may not have been adequately accounted for at Awarua was living sphagnum mosses. In the pre-fire vegetation mapping there was little sphagnum mapped (moss fields), and 82% of the area burnt was mapped as scrub or shrubland dominated by mānuka. However, post-fire it was evident that sphagnum had been present, potentially beneath the mānuka, in a patchy distribution. During soil sampling as part of this work we sampled through living sphagnum, and at one site it was estimated to contain about 34 t C/ha. We are uncertain how much sphagnum was lost during the fire, and future work is required to better account for this component. More generally, there is a need for better estimates of C stocks in soil (McNeill & Mudge 2023) and vegetation (Easdale et al. 2022) of wetlands. This requires a focused, nationally coherent sampling strategy.

Active year-round vegetation growth in New Zealand's peat wetlands continuously fixes CO_2 from the atmosphere (e.g. Goodrich et al. 2017). Following fire, loss of actively photosynthesising vegetation stops this C uptake, while microbial decomposition of the peat continues. In pastoral systems the absence of active vegetation growth during periods where vegetation is sprayed out can result in considerable loss of soil C through continued respiration (Rutledge et al. 2017).

For intact peatlands the rate of recovery will depend on many factors, including the quantity and species of viable seed stored in the upper peat layers, which influences future plant community dynamics (Wilson et al. 2022). The impact of fire on the balance between C uptake through photosynthesis and decomposition requires further consideration to determine the contribution of this potential lost uptake, which may persist for some time.

At both wetlands the fire intensity was spatially variable over short distances, resulting in high heterogeneity in the proportion of soil and vegetation burned and high uncertainty in the burnt area estimates. To reduce labour and human error/judgement from this process, we attempted to use an image segmentation approach. Image segmentation enables faster and more advanced image processing by partitioning digital images into groups of similar pixels. Initial attempts at image segmentation (see Figure 1 and Figure 4) highlight the complexity of the burn pattern.

Image segmentation also provides a potential approach to quantifying burn intensity over large areas with large short-range spatial variation, where manual disaggregation and digitising of polygons based on soil or vegetation burn intensity would be difficult, labour intensive, and ultimately inaccurate. We used differences in surface texture and colour to group areas into unburnt, lightly burnt, and heavily burnt areas. That way, complex and patchy areas could be split into different CBI areas. Due to budget constraints on this project we were unable to take this approach to its full potential, but it warrants more exploration.

Finally, to calculate CO_2 emission from the loss of C from the Organic Soils and vegetation we assumed all the estimated C loss was converted to CO_2. During the combustion of organic material at high temperatures most of the burnt organic matter is converted to CO_2. However, at lower combustion temperatures typical of smouldering combustion, CO emissions can increase (IPCC 2014). Further investigation is required to determine what proportion of the C loss from these fires may have been emitted as CO. This uncertainty does not affect the estimates of total C loss from the fires but could affect the greenhouse warming potential of the emitted C.

6 Recommendations

Improved management of peat wetlands is required to protect the valuable ecosystem services they provide. While acknowledging that fires have historically occurred from natural events (e.g. lightning strike), increased incidence of fires contributes to C emissions and loss of biodiversity.

Some approaches that may reduce the likelihood of human-induced fire include limiting the influence of surrounding land use on water-table levels in the wetland, managing weed and fertiliser incursion into the wetland (these increase vulnerability to external fire sources), and creating and maintaining fire breaks where fire risk is high.

Several specific recommendations can be made to improve the accuracy of estimated CO_2 loss from future fires in peat wetlands. Work that would improve our ability to accurately estimate CO_2 loss includes:

- improved understanding of current soil and vegetation C stocks in vegetated wetlands through a nationally designed soil and vegetation sampling and survey strategy, with soil sampling to at least 60 cm depth
- improved LiDAR coverage of vegetated wetlands, captured at a point density that permits accurate prediction of soil surface through dense vegetation
- further development of an image segmentation workflow to quantify burn area in complex heterogeneous peat fires
- further investigation of potential approaches to estimate below-ground peat loss that may have occurred in some circumstances.

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Appendix – Organic Soil sampling locations and lab results

Table A1. Soil sample locations at Kaimaumau and Awarua

Site number	Kaimaumau		Awarua	
	Latitude	Longitude	Latitude	Longitude
1	-34.907582	173.210057	-46.566895	168.512847
2	-34.906005	173.205102	-46.562463	168.539605
3	-34.897353	173.216163	-46.571805	168.518193
4	-34.902934	173.215208	-46.587355	168.554757
5	-34.905771	173.243971	-46.591853	168.561778
6	NA	NA	-46.592981	168.556397

Table A2. Kaimaumau Organic Soil analysis results

Sample number	Site	Date sampled	Sample upper depth (cm)	Sample lower depth (cm)	Initial water content (%, w/w)	Dry BD (t/m3)	Air dry soil water content (%)	Organic C (%)	Total N (%)	C:N ratio
1	1	18/10/2023	1	9.5	44.5	0.32	**7.04**	**32.15**	**0.89**	36.15
2	1	18/10/2023	11	18.5	156	0.19	**10.80**	**59.02**	**1.18**	49.92
3	1	18/10/2023	21	18.5	258	0.17	**9.62**	**60.18**	**1.07**	56.07
4	1	18/10/2023	31	38.5	345	0.17	**9.13**	**60.98**	**1.06**	57.69
5	1	18/10/2023	40	50	431	0.18	**9.53**	**59.20**	**0.96**	61.44
6	1	18/10/2023	50	60	549	0.15	**9.08**	**60.95**	**1.06**	57.58
7	1	18/10/2023	60	80	605	0.14	**8.61**	**62.63**	**0.98**	63.59
8	1	18/10/2023	80	90	606	0.14	**8.50**	**64.27**	**0.94**	68.08
9	2	18/10/2023	1	9.5	24.3	0.55	**3.96**	**10.76**	**0.70**	15.28
10	2	18/10/2023	11	18.5	91.8	0.28	**6.19**	**29.99**	**0.77**	39.10
11	2	18/10/2023	21	18.5	256	0.16	**9.05**	**53.63**	**1.02**	52.72
12	2	18/10/2023	31	38.5	394	0.15	**9.04**	**61.38**	**1.09**	56.38
13	2	18/10/2023	40	50	448	0.16	**8.72**	**58.55**	**0.99**	59.37
14	2	18/10/2023	50	60	456	0.15	**9.07**	**58.73**	**0.96**	60.95
15	2	18/10/2023	60	80	516	0.15	**8.70**	**63.46**	**1.03**	61.75
16	2	18/10/2023	80	100	552	0.14	**9.12**	**57.07**	**0.90**	63.34
17	3	19/10/2023	1	9.5	73.0	0.39	**5.27**	**24.20**	**0.79**	30.75
18	3	19/10/2023	11	18.5	156	0.30	**7.36**	**37.70**	**0.98**	38.47
19	3	19/10/2023	21	18.5	311	0.18	**11.19**	**58.74**	**1.00**	58.96
20	3	19/10/2023	31	38.5	364	0.18	**9.84**	**56.66**	**1.15**	49.13
21	3	19/10/2023	40	50	417	0.16	**9.75**	**52.20**	**0.86**	60.85

Sample number	Site	Date sampled	Sample upper depth (cm)	Sample lower depth (cm)	Initial water content (%, w/w)	Dry BD (t/m3)	Air dry soil water content (%)	Organic C (%)	Total N (%)	C:N ratio
22	3	19/10/2023	50	60	500	0.14	**9.56**	**60.93**	**0.99**	61.65
23	3	19/10/2023	60	80	582	0.15	**9.32**	**62.10**	**0.90**	69.28
24	3	19/10/2023	80	100	583	0.14	**8.69**	**63.27**	**0.86**	73.42
25	4	19/10/2023	1	9.5	45.3	0.41	**6.53**	**17.01**	**0.71**	24.08
26	4	19/10/2023	11	18.5	197	0.21	**11.29**	**52.88**	**1.03**	51.44
27	4	19/10/2023	21	18.5	325	0.17	**11.04**	**56.88**	**0.89**	**64.16**
28	4	19/10/2023	31	38.5	389	0.17	**10.81**	**53.06**	**0.81**	**65.19**
29	4	19/10/2023	40	50	446	0.17	**11.01**	**52.30**	**0.76**	**68.74**
30	4	19/10/2023	50	60	523	0.16	**10.62**	**52.69**	**0.90**	**58.70**
31	4	19/10/2023	60	80	540	0.15	**10.43**	**50.94**	**0.64**	**79.31**
32	4	19/10/2023	80	100	516	0.16	**9.65**	**51.11**	**0.78**	**65.58**
33	5	19/10/2023	1	9.5	1583	0.05	**8.31**	**48.86**	**0.73**	**67.06**
34	5	19/10/2023	11	18.5	1026	0.08	**7.84**	**48.67**	**0.71**	**68.12**
35	5	19/10/2023	21	28.5	248	0.34	**6.13**	**24.66**	**1.09**	**22.56**
36	5	19/10/2023	31	38.5	190	0.42	**5.24**	**16.32**	**0.72**	**22.73**
37	5	19/10/2023	40	50	179	0.46	**6.52**	**17.01**	**0.63**	**27.21**
38	5	19/10/2023	50	60	187	0.43	**6.53**	**23.68**	**0.45**	**53.09**
39	5	19/10/2023	60	80	198	0.40	**9.38**	**24.99**	**0.48**	**52.34**
40	5	19/10/2023	80	90	139	0.45	**5.97**	**20.80**	**0.34**	**61.48**

Table A3. Awarua Organic Soil analysis results

Sample number	Site	Date sampled	Sample upper depth (cm)	Sample lower depth (cm)	Initial water content (%, w/w)	Dry BD (t/m3)	Notes	Air dry soil water content (%)	Organic C (%)	Total N (%)	C/N ratio
1	1	13/12/2023	1	9.5	824	0.02	sphagnum	10.4	48.7	0.75	65
2	1	13/12/2023	11	18.5	850	0.02	sphagnum	9.9	48.9	0.67	73
3	1	13/12/2023	21	28.5	764	0.03	sphagnum	10.0	49.6	0.66	75
4	1	13/12/2023	31	38.5	770	0.06	peat soil	9.0	52.4	1.1	46
5	1	13/12/2023	41	48.5	1562	0.05	peat soil	9.0	52.5	1.4	37
6	1	13/12/2023	51	58.5	1846	0.05	peat soil	8.3	53.8	1.3	40
7	1	13/12/2023	61	68.5	1826	0.05	peat soil	8.7	52.9	1.3	40
8	1	13/12/2023	71	78.5	1635	0.06	peat soil	8.4	52.7	1.7	31
9	1	13/12/2023	80	100	1087	0.07	peat soil	8.5	54.3	1.7	31
10	2	13/12/2023	1	9.5	929	0.08		8.7	53.5	1.5	36
11	2	13/12/2023	11	18.5	1212	0.07		9.1	55.0	1.5	37
12	2	13/12/2023	21	18.5	987	0.09		8.1	58.0	1.6	37
13	2	13/12/2023	31	38.5	720	0.12		6.6	57.3	1.4	41
14	2	13/12/2023	40	60	805	0.11		7.5	63.3	1.1	55
15	2	13/12/2023	60	80	787	0.11		7.6	63.0	1.1	59
16	2	13/12/2023	80	100	804	0.11		7.2	62.6	1.3	49
17	3	14/12/2023	1	9.5	690	0.04	sphagnum	8.8	51.7	0.71	73
18	3	14/12/2023	11	18.5	1228	0.06	peat soil	8.3	54.2	1.3	43
19	3	14/12/2023	21	18.5	1628	0.06	peat soil	9.0	54.0	1.4	38
20	3	14/12/2023	31	38.5	1555	0.06	peat soil	9.2	55.1	1.5	37
21	3	14/12/2023	41	48.5	1569	0.06	peat soil	9.2	51.8	1.5	35
22	3	14/12/2023	51	58.5	1526	0.06	peat soil	9.1	55.6	1.6	35
23	3	14/12/2023	60	80	1233	0.08	peat soil	9.1	56.3	1.8	31

Sample number	Site	Date sampled	Sample upper depth (cm)	Sample lower depth (cm)	Initial water content (%, w/w)	Dry BD (t/m3)	Notes	Air dry soil water content (%)	Organic C (%)	Total N (%)	C/N ratio
24	3	14/12/2023	80	100	1205	0.09	peat soil	8.6	56.8	1.9	30
25	4	14/12/2023	1	9.5	77.8	0.38	peat soil	3.3	19.5	0.54	36
26	4	14/12/2023	11	18.5	59.1	0.80	peat soil	2.3	9.8	0.32	31
27	4	14/12/2023	21	18.5	23.2	1.21	stony soil	1.8	8.6	0.28	31
28	4	14/12/2023	31	38.5	14.1	1.53	stony soil	2.0	9.1	0.32	29
29	5	14/12/2023			57.3	0.00	Litter	7.8	48.8	1.0	48
30	5	14/12/2023	1	9.5	566	0.10		9.9	50.5	2.1	24
31	5	14/12/2023	11	18.5	465	0.15		7.3	44.4	1.7	26
32	5	14/12/2023	21	18.5	466	0.17		6.5	41.6	1.4	29
33	5	14/12/2023	31	38.5	432	0.20		6.5	34.0	1.2	29
34	5	14/12/2023	40	60	554	0.17		8.6	39.9	1.2	32
35	5	14/12/2023	60	80	598	0.15		9.3	56.0	1.2	48
36	5	14/12/2023	80	100	672	0.13		10.0	49.3	1.0	47
37	6	14/12/2023	1	9.5	803	0.06		7.8	50.8	0.78	65
38	6	14/12/2023	11	18.5	1217	0.06		8.2	51.4	1.1	45
39	6	14/12/2023	21	18.5	1105	0.08		8.5	53.0	1.0	52
40	6	14/12/2023	31	38.5	1429	0.07		9.2	52.9	1.1	50
41	6	14/12/2023	41	48.5	1312	0.07		9.4	53.8	1.4	39
42	6	14/12/2023	51	58.5	1120	0.08		9.6	56.8	1.6	36
43	6	14/12/2023	60	80	1091	0.06		9.1	57.0	1.5	37
44	6	14/12/2023	80	100	1084	0.06		9.3	58.7	1.4	41

Notes: Site 5 did not meet the requirements for an Organic Soil so was not used for the mean C stock presented in Table 6. Sample numbers 1–3 at Site 1 and 17 at Site 3 were sphagnum and were not included in the Organic Soil C stock presented in Table 6. Litter collected at Site 5 (sample 29) was also not used in calculations for soil C stocks.