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Review of potential management interventions to reduce peat subsidence and CO_2 emissions in the Waikato

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Prepared for: Waikato Regional Council

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Summary

Purpose

The purpose of this review was to identify management options and inform future research directions for improving management practices to reduce peat subsidence and carbon dioxide (CO_2) emissions from drained Waikato peatlands that are largely used for intensive grazing. Waikato Regional Council require this information to help implement Section 14.5 of the Waikato Regional Policy Statement.

Report Outline

We described peat soils and subsidence processes to provide local context (Section 3) and outlined existing knowledge on subsidence and carbon dioxide (CO_2) emissions from peat soils in the Waikato Region, including existing policy and mitigation approaches (Section 4). We reviewed international literature to identify potential management options to reduce peat subsidence and CO_2 emissions, including soil water (Section 5) and land management (Section 6) manipulation. In addition, factors that affect subsidence rates independent of management (Section 7) and management decision support tools and the potential role for policy in achieving change (Section 8) are discussed. We also propose recommendations to inform an ongoing programme of work to reduce peat subsidence and CO_2 emissions from Waikato peatlands (Section 10).

Background

The Waikato Region has about 89,000 ha of peatlands that formed over the past 10–14,000 years from the slow accumulation (mm per year) of peat derived from wetland vegetation under saturated conditions. These peatlands represented unique hydrological and ecological environments, and those that remain support threatened endemic flora and fauna in a unique ecosystem, mostly act as carbon sinks, represent a taonga for iwi, and provide recreational opportunities. Drainage of peatlands for agriculture changes the hydrology, stops accumulation of peat, and results in ongoing land subsidence through shrinkage and consolidation, and CO_2 emissions through biochemical oxidation.

Under drained management these peatlands provide considerable economic value to the Waikato region, for example 67 000 ha of the region’s peatlands are now under high producing exotic grassland (e.g. perennial pastures) which is dominated by dairy farming. However, the consequences of ongoing subsidence and eventual loss of peat include: increased risk and frequency of flooding and inundation; prolonged high soil moisture; reduced wetland sustainability; ponding in catchments due to uneven peat subsidence and reduced drainage gradient; and a requirement to upgrade, repair or install drainage and other infrastructure (e.g. flood protection, pumping, roads and utilities). The impact of subsidence could be exacerbated by sea level rise on the Hauraki plains.

Water management to reduce subsidence and carbon emissions

Several studies have reported reductions in both subsidence and CO_2 emissions when the water table is kept closer to the surface (Table 1). However, high water tables would require pasture species adapted to periodic flooding and a higher water table would require alteration of current intensive grazing practices due to reduced trafficability, productivity and profitability. High water tables could also increase methane and nitrous oxide emissions. Additionally, it is difficult to maintain water tables at the desired level. In summer, when evaporative water loss is high, it is common for paddock boundary and main farm drains to be dry, therefore blocking drains at the paddock and farm scale during the summer period would likely be ineffective. Manipulating drainage depth and catchment outlet level is only one component of a more complex web required to control peat water content. Ultimately, peat soil moisture content is the result of the balance between water inputs (precipitation and irrigation), losses (horizontal and vertical drainage, evaporation), and rate limiting factors (hydraulic conductivity, energy availability, plant stomatal control). Approaches to increase peat moisture content through frequent flooding, subsurface irrigation, or reduced evaporative water loss by selecting plant species with higher water use efficiency could be investigated alongside improved drainage management. Research in the Netherlands has shown that sub-surface irrigation techniques may reduce subsidence and such approaches could also result in increased pasture growth that would likely increase CO_2 uptake and boost productivity and thereby motivate farmers to adopt them. However, while water can to some extent be recycled within the catchment, during dry periods a large and reliable external water supply would be required. Consequently, subsurface irrigation may only be relevant to low-lying organic soils in the lower Waikato and Hauraki Plains where large rivers are nearby.

Land management to reduce subsidence and carbon emissions

Changing some land management practices may reduce subsidence and CO_2 emissions (Table 1). Cropping (e.g. maize) has been shown to increase subsidence and CO_2 emissions and should be avoided where possible. However, frequent cultivation through a cropping cycle is often used to incorporate lime into peat soils to increase soil pH to improve pasture productivity. Recent trialling of lime injection may remove the need for deep cultivation and would support no-till pasture renewal. Subsidence and CO_2 emissions may also be mitigated by reducing nutrient inputs to limit microbial mineralisation. However, reducing nutrient inputs will likely reduce pasture growth affecting both productivity and potentially reducing CO_2 uptake through photosynthesis. Surface amendments of mineral material are inconclusive on their impact on peat subsidence processes.

Table 1. Summary of management practices to mitigate peat subsidence (NR = not reported)

Management practice	Outcome for subsidence	Outcome for CO_2 emissions	Summary
Decrease depth to water table	Reduction	Reduction	Water table depths between 0.25 and 0.5 m recommended but trafficability and productivity may decrease, and N_2O and CH_4 emissions could increase. Additionally, it is difficult to maintain high water tables in summer.
Frequent flooding	Reduction	Reduction	More suited to alternative crops (e.g., rice) rather than permanent grassland
Subsurface irrigation	Reduction	NR	Water supply may be problematic during dry periods and the practice may increase N_2O and CH_4 emissions
Reduce nutrient input	NR	Reduction	Likely to have negative affect on pasture productivity.
Change crop/ pasture type	Reduction	Reduction	Flooded agriculture increases photosynthetic performance through increased productivity for adapted plant species may increase N_2O and CH_4 emissions
Reduce cultivation	Reduction	Reduction	Stop or minimise cultivation by using new technology
Surface amendment (clay layer)	Reduction/ Increase	NR	May decrease subsidence for shallow peats but could increase subsidence for deeper peats.

Non-management factors controlling subsidence and CO_2 emissions

Non-management-related factors that affect subsidence and CO_2 emissions must be understood to develop appropriate mitigation strategies. These factors include organic matter and mineral content, peat depth, time since drainage, and climate change. Subsidence rates are generally higher for deeper peats with higher organic matter content. As time since drainage increases, subsidence rates decline as densification occurs and the fraction of remaining organic matter becomes more recalcitrant. Climate change is likely to increase peat soil temperature and alter precipitation patterns potentially decreasing rainfall and lowering groundwater levels during summer. Both processes are likely to increase subsidence rates. Additionally, sea level rise will only exacerbate anticipated problems for peatlands within tidal zones (e.g. Hauraki Plains).

Recommendations

To reduce peat subsidence and CO_2 emissions from drained peatlands in the Waikato region we recommend a sequence of steps (Fig. 1), and the order of implementation is:

1. Develop a spatial vulnerability index to identify locations where the most severe consequences are likely to occur and determine resource and research prioritisation.
2. Test a range of potential mitigation strategies including priority water management, land management and land use strategies. Management strategies are presented in the order we suggest they be investigated. However, these options should be revisited when results and recommendations from the PEATWISE[1] project are released.
3. Combine knowledge gained from experimental testing of mitigation strategies with modelling of catchment hydrology to develop a spatially appropriate management decision support tool to provide guidance for drainage and land managers to select the most appropriate mix of mitigation approaches.
4. Update good practice guidelines and, if necessary, develop policy incentives or interventions to encourage adoption of management strategies and decision support tools.

In each of these steps, the socio-economic consequences of any decisions and recommendations need to be considered, including the regional- and farm-scale cost benefit of change compared with inaction. Ultimately, where the peat remains drained, improved land and drainage management will only slow subsidence and oxidation and provide a short- to medium-term solution to peat subsidence and CO_2 emissions. While this would meet the goals of Section 14.5 of the Waikato Regional Policy Statement it does mean that all drained peat in the Waikato region would eventually be lost. Therefore, future consideration of alternative land uses will be required to protect the peat resource.

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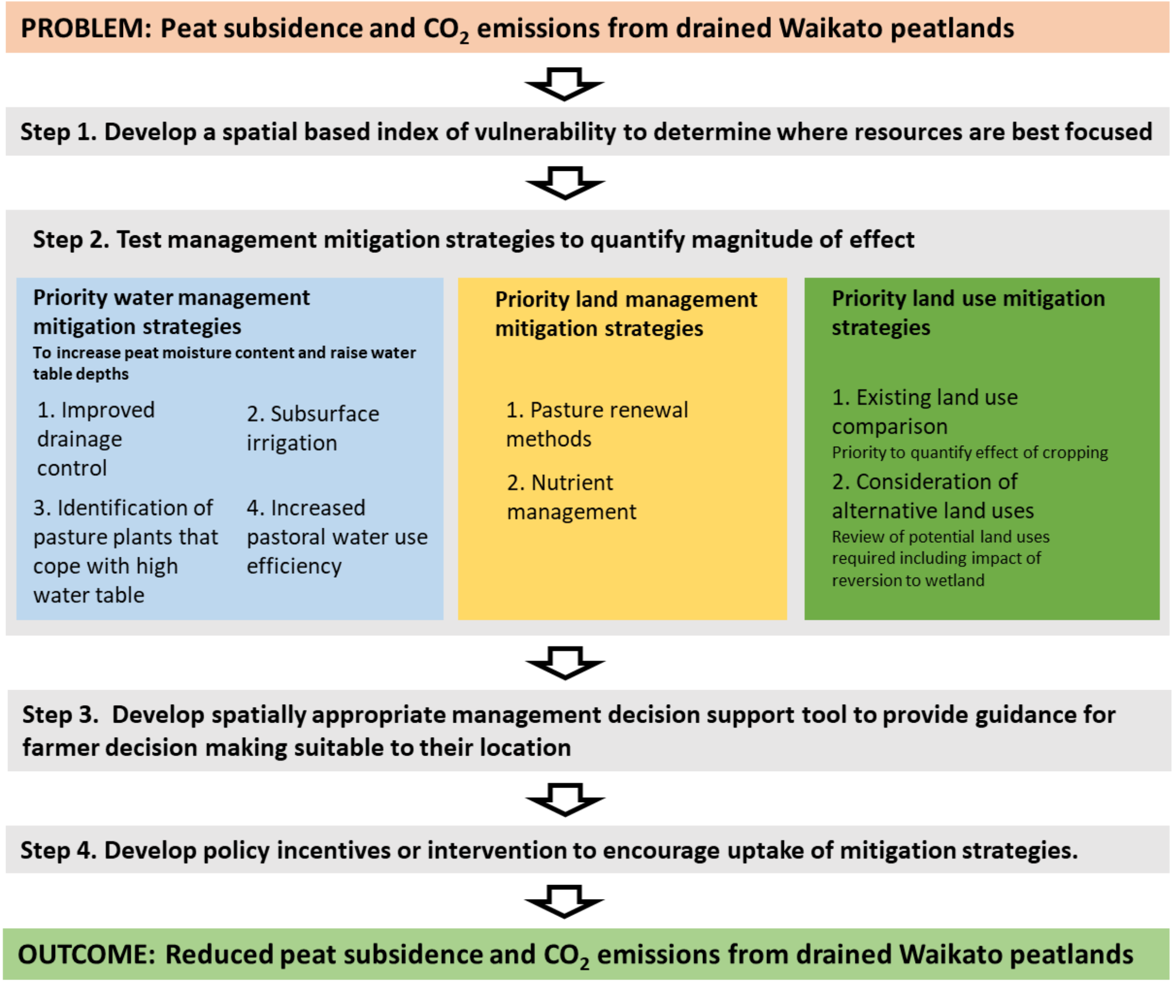
[1] PEATWISE is a large European peatland programme developing and refining sustainable soil and water management practices to reduce GHG emissions from drained peatlands.



PROBLEM: Peat subsidence and CO_2 emissions from drained Waikato peatlands

Step 1. Develop a spatial based index of vulnerability to determine where resources are best focused

Step 2. Test management mitigation strategies to quantify magnitude of effect

Priority water management mitigation strategies

To increase peat moisture content and raise water table depths

1. Improved drainage control
2. Subsurface irrigation
3. Identification of pasture plants that cope with high water table
4. Increased pastoral water use efficiency

Priority land management mitigation strategies

1. Pasture renewal methods
2. Nutrient management

Priority land use mitigation strategies

1. Existing land use comparison
Priority to quantify effect of cropping
2. Consideration of alternative land uses
Review of potential land uses required including impact of reversion to wetland

Step 3. Develop spatially appropriate management decision support tool to provide guidance for farmer decision making suitable to their location

Step 4. Develop policy incentives or intervention to encourage uptake of mitigation strategies.

OUTCOME: Reduced peat subsidence and CO_2 emissions from drained Waikato peatlands

Figure 1. Recommended approach to manage subsidence and CO_2 emissions from Waikato peatlands.

1 Introduction

Drainage of peatlands for agricultural use has been occurring for centuries in the United Kingdom (UK) and Europe (Stephens et al. 1984) and since around the 19th century in many other parts of the world. Drainage results in subsidence processes that include physical shrinkage, consolidation, and biochemical oxidation (Section 3.2) and globally subsidence rates range from a few mm to tens of mm per year (e.g. Stephens et al. 1984; Rojstaczer & Deverel 1995; Gronlund et al. 2008). Ongoing oxidation associated with subsidence from about 65 million ha of drained peatlands globally results in emissions of about 2 Gt of CO_2-C annually (Kaat & Joosten 2009). Globally, agriculturally managed peatlands have been identified as having an important potential role to play in climate change mitigation (Ferre et al. 2019), although at present there is no rational solution to mitigate subsidence and CO_2 emissions despite the long-term and ongoing nature of the problem (Evans et al. 2019). However, many international agencies are striving toward better use of peatlands. For example, the UK have a Peatland Strategy (2018–2040) that includes a range of goals focused on conservation, restoration, and adaptive management, and a large European program (PEATWISE) is developing and refining sustainable soil and water management practices to reduce GHG emissions from drained peatlands.

Drained peatlands in New Zealand, including the Waikato, are also subsiding, and emitting CO_2, and these losses will pose environmental, economic and social challenges for future land management. While there is currently no national level strategy for the management of peat soils, Section 14.5 of the Waikato Regional Policy statement sets a goal to reduce subsidence and CO_2 emissions from drained peat soils. However, there is little robust New Zealand based information on how this can be achieved. Current information on good management practices for developed peatlands in the Waikato is based on information in the guideline 'For Peat's Sake' (Environment Waikato 2006). While still relevant, this guideline is now 14 years old and requires reassessment based on more recent international research. To fill this knowledge gap, we investigated international approaches to mitigating peat subsidence to inform future directions for improved management practices to reduce peat subsidence and CO_2 emissions from drained Waikato peatlands.[2]

2 Review purpose and outline

The purpose of this review was to identify management options and inform research directions to develop improved management practices and reduce peat subsidence and CO_2 emissions from drained Waikato peatlands. Waikato Regional Council require this information to meet the requirements of Section 14.5 of the Waikato Regional Policy Statement. We described peat soils and subsidence processes to provide local context

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[2] In this report, 'peatlands' refers to all areas where peat is found (both under agriculture and as wetlands) and 'peat wetlands' refers to areas of peat that have not be directly drained for agriculture and are comprised of wetland vegetation.

(Section 3) and outlined current knowledge on subsidence and carbon dioxide (CO_2) from peat soils in the Waikato Region (Section 4).

We reviewed management options to reduce peat subsidence and CO_2 emissions, including soil water table and water balance manipulation to maintain or increase peat moisture content (Section 5) and land management practices that lessen negative impacts of activities such as cultivation, nutrient application, and surface amendments (Section 6). In addition, non-management-related factors affecting subsidence rates were reviewed, including organic matter and mineral content, peat depth, time since drainage, and climate change impacts (Section 7). We also briefly discuss management decision support tools and the potential role of policy in achieving change (Section 8); however, these topics could form a review of their own.

Finally, we present recommendations to resolve knowledge gaps and facilitate adoption of management strategies to reduce peat subsidence and CO_2 emissions from Waikato peatlands (Section 10).

3 Peat soils and subsidence processes

3.1 Peat soil definition

The term 'peat soil' is used to maintain consistency with the Waikato Regional Council Policy Statement and other council literature; however, the term peat refers to those soils that are of the Organic Soil Order, including Fibric, Mesic and Humic Subgroups, as defined in the New Zealand Soil Classification (Hewitt 2010). Organic Soils are those derived from wetland or forest litter and consist of organic material (at least 18% organic carbon excluding fresh litter and living plant material) within 60 cm of the soil surface that are either;

1 30 cm or more thick (cumulative) and are entirely formed from peat or other organic soil materials accumulated under wet conditions (saturated with water for at least 30 consecutive days per year, or have been artificially drained), or

2 40 cm or more thick and are formed from partly decomposed or well-decomposed litter.

Internationally, the definition of a peat soils have used a variety of terms and parameters but a common definition, and that used in the UK Peatland Strategy (2018–2040), is 'A wetland soil composed largely of semi-decomposed organic matter deposited in-situ, having a minimum organic content of 30% and a thickness greater than 30 cm' (Finlayson & Milton 2016). This definition aligns well with the New Zealand Soil Classification of Hewitt (2010).

3.2 Subsidence processes

Drainage of a peatland changes the hydrology, stops the accumulation of vegetation material and results in land subsidence and CO_2 emissions. The dominant subsidence processes are physical shrinkage, consolidation, and biochemical oxidation. Shrinkage is the loss of soil volume above the water table from drying and compaction of organic fibres (Hoojier et al. 2012). Shrinkage is partially reversible upon rewetting (Nieuwenhuis & Schokking 1997), and results in oscillations of peatland surface elevation (Strack et al. 2005) to magnitudes of several centimetres (Morton & Heinemeyer 2019) that vary temporally over hourly to seasonal time scales (Egglesmann 1984; Camporese et al. 2006). Shrinkage occurs in both the vertical and horizontal dimensions; however, in the horizontal dimension soil volume is not lost because large voids or cracks are created (Ewing & Vepraskas 2006). Consolidation is mechanical compression below the water table that results in a loss of soil volume. Following drainage, loss of pore water pressure within the peat substrate increases the overburden mass and forces water from the pore space below the water table reducing soil volume (Ewing & Vepraskas 2006). Oxidation results from rapid diffusion of oxygen into the organic material above the water table that stimulates aerobic microbial decomposition of the organic substrate. Carbon is subsequently transferred from the soil profile to the atmosphere resulting in a loss of soil mass and volume (Ewing & Vepraskas 2006), and an increase in the mineral fraction of surface peat.

Shrinkage and consolidation increase bulk density and are sometimes collectively referred to as peat densification (Stephens et al. 1984). Densification processes can be very rapid following drain deepening and slow with time but cause no loss of soil mass. In comparison, oxidation is a long-term, on-going process that can result in the complete loss of a peat deposit (Stephens et al. 1984). Other processes such as dissolved or particulate organic C in runoff water, wind and fire also contribute to peat loss but are generally of less importance due to small rates of loss or infrequency.

Often drain deepening or drainage pump installation or upgrades in response to the effects of peat loss repeatedly draw down the water table, resulting in ongoing subsidence and drainage, compounding a drainage-subsidence cycle. If allowed, this process will continue until all the peat is lost (Joosten 2016).

4 Waikato context

4.1 Background

The Waikato Region has about 89,000 ha[3] of peatlands (Fig. 2) that have formed over the past 10–14,000 years from the slow accumulation (typically about 1 mm/year) of peat derived from wetland vegetation under saturated conditions forming thick organic layers, in some cases in excess of 10 m (Davoren 1978). Peat depth typically varies spatially across

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[3] This area estimate is based on the extent of Organic Soils within the Waikato Regional Council boundaries as recorded in S-Map or where this does not exist yet the Fundamental Soils Layer of the New Zealand Land Resource Inventory.

a peatland (Fig. 3) and when peatlands are many metres thick, they contain much more carbon than other terrestrial ecosystems (Joosten 2016). These peat wetlands represented unique hydrological and ecological environments, and those that remain support threatened endemic flora and fauna in a threatened ecosystem, are a carbon sink, represent a taonga for Tangata Whenua, and provide for recreational opportunities. However, drainage of local peat wetlands began in the early 1900s and now most of this area (about 67,000 ha[4]) has been drained for agriculture. Currently, ~75% of the total peatland area in the Waikato is used for pastoral agriculture with the majority being dairy farming, and therefore likely representing a significant contributor to our regional economy. A small percentage of drained peatland is used for horticulture and arable cropping, although cropping of maize for silage, fodder beat, and rape is common on peat dairy farms and runoffs. The most common horticultural use is blueberry production, where the Waikato Region has about 300 ha of blueberries (Stats NZ 2012). In 2016 the national value of the, mostly peat soil-based blueberry industry was estimated to be worth between $20.8 and $41.4 million[5] (Aitken & Hewett 2016), of which the Waikato region would have contributed a sizable portion. A small (53 ha) peat mine for extracting horticultural media operates on the Hauraki Plains, as part of the mining consent, the peat must be restored to its original bog vegetation after mining (Clarkson 2016). Even though drained peatlands are considered degraded from their original state, these unique soils provide a valuable contribution to the regional economy.

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[4] This area estimate is based on the extent of Organic Soils within the Waikato Regional Council boundaries as recorded in the Fundamental Soils Layer of the New Zealand Land Resource Inventory intersected with Landcover database version 5 (compiled in 2018), where the total area of organic soils was 89,085 hectares, and only 13,286 hectares of that was recorded as herbaceous freshwater wetland.

[5] This includes both domestic and export fresh fruit sales of $18.0 and $36.5 million respectively as well as domestic and export processed fruit sales of $2.8 and $4.9 million, respectively.

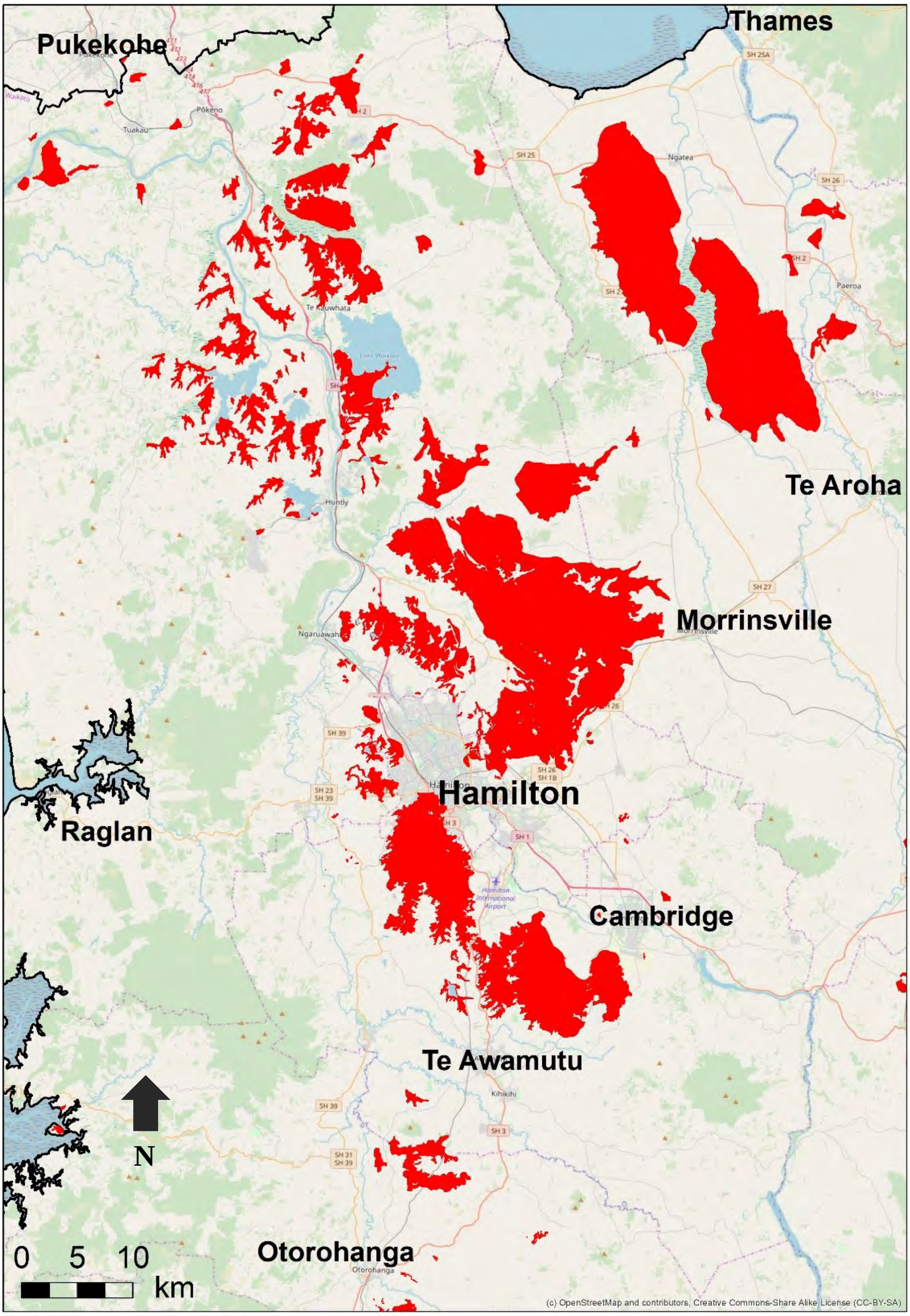

Figure 2. Peatland extent in the Waikato Region is shown in red. These are the main peat areas; there are other, smaller, areas around Reporoa and Taupo. Peatland extent was identified using S-Map where available and the Fundamental Soils Layer where S-Map was not available.

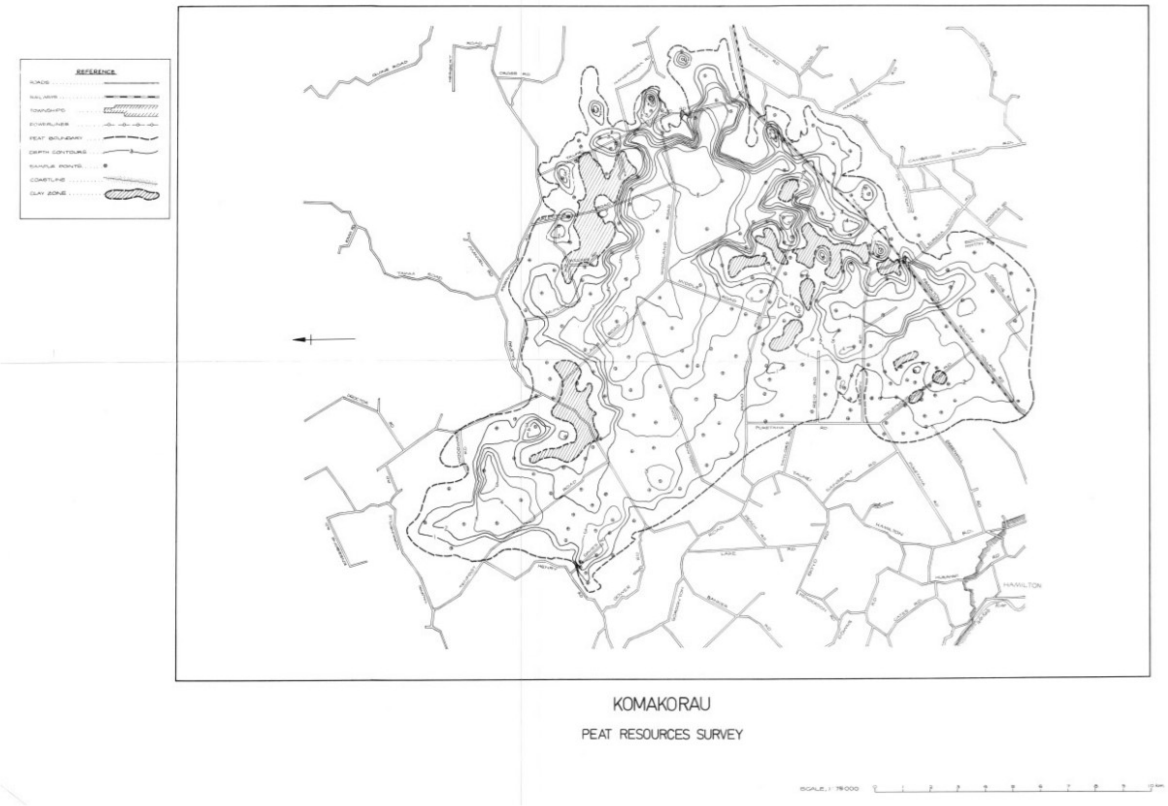

Figure 3. Komakorau bog peat depth contour map, from Davoren (1978).

4.2 Drainage of Waikato peatlands

A typical Waikato farm with managed peat soils consists of paddocks that are about 90 m wide which are crowned in the middle to encourage water to flow toward the paddock boundary drains (Fig. 4). The paddock boundary drains direct drainage water to main farm drains that feed into Board drains. An alternative approach, which is often used during the development phase, is hump and hollow drainage. Here each paddock has three humps ('lands') at about 30 m spacing that run lengthways with 'spinner'[6] drains in the hollows to increase the speed of surface water removal (Fig. 4). These spinner drains then feed into main farm drains.

At the catchment scale, drainage management differs, depending on the ground level of the drained peatland relative to the catchment outlet. In peat areas such as Moanatuatua and Rukuhia ground height and drainage gradient are such that water can drain under gravity. However, detention dams are used in specific locations in the catchment to slow flood peaks. On the Hauraki Plains, the lowland rivers (Waihou and Piako) are tidal for many kilometres inland, therefore during low tide many of the catchments drain under gravity, but as the tide rises flap gates on the outlets close and do not reopen until the tide falls. Under flood conditions when river flows are high and flap gates stay shut for long periods, flood pumps will assist with drainage. In other catchments, such as Swan

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[6] spinner refers to the tractor-mounted device that cuts or clears the drains.

Road in the Lower Waikato, ground levels are so low that pumps operate more frequently. These differing drainage management regimes suggest that strategies for the manipulation of drainage water differs between catchments and therefore so too will the ability to intervene. In general, it seems that there is little known about water table regimes in drained peatlands in the Waikato region: some farmers suggest that optimum water table levels for pastures grazed by dairy cattle are about 0.5 m during winter to avoid water logging and maintain trafficability (H. Snell, Wallace Farms, pers. comm.). This agrees with experience in the Netherlands where optimum water table depths for agricultural production are 0.5 – 0.6 m (Querner et al. 2012).

Data from Moanatuatua peatland in the Waikato region (Pronger 2013) indicated subsidence rates for more intensive hump and hollow drainage management may be higher than for paddock boundary drainage, but the sample size was small and not statistically significantly different between the two drainage strategies. Additionally, because recently drained peats subside more rapidly (Section 5.3), higher subsidence rates for hump and hollow systems, compared with paddock boundary drains, may be due to more recent development.

In another Waikato study, Fitzgerald et al. (2005) showed that deeper drains influence paddock surface height over a greater distance away from the drain compared with shallow drains, suggesting deeper drains influence subsidence rates at a greater distance from the drain. Interestingly, an algorithm developed during this project to predict subsidence away from drains underpredicted subsidence for peat under blueberries, suggesting blueberries may be a land use with lower subsidence than pastoral agriculture.

Figure 4. Typical peatland drainage layout showing the contrast between hump and hollow (left side of image) and paddock boundary drainage (right side of image) (image from Google Earth of Moanatuatua peatland). Arrows show drain location and flow direction.

4.3 Rates of subsidence in the Waikato Region

Pronger et al. (2014) completed the most recent and comprehensive investigation of peat subsidence in the Waikato Region. This work was a re-survey of peat depth measurements used to estimate historic peat subsidence rates between the mid-1920s and early 2000s (McKenzie & McLeod 2004; McLeod et al. 2003; Fitzgerald & McLeod 2004) at Moanatuatua, Rukuhia, and Hauraki Plains peatlands. The Pronger et al. survey estimated the average rate of peat subsidence between 2000 and 2012 to be approximately 19 mm per year (Table 2). This rate represents about 1 m of peat subsidence every 50 years. Other ad hoc studies have been conducted in the Waikato Region (Table 2) using either repeat land surveys of ground level or measuring change in peat thickness by peat depth probing and suggest subsidence rates have reduced through time, except in response to drain deepening. Further, subsidence rates are spatially variable.

At two sites in the Waikato Region, Glover-Clark (2020) measured reversible oscillations in peat surface elevation over 10 months of 46 mm and 66 mm, which were approximately 2.5 and 3.5 times greater than the annual subsidence rate Pronger et al. (2014) estimated, respectively. These oscillations were in the upper range of values in published in international literature (e.g. Egglesmann 1984; Teatini et al. 2004; Zanello et al. 2011) and represent an important process that must be considered when designing management and measurement approaches for subsidence in the Waikato Region.

Table 2. Peat subsidence rates measured for different locations in the Waikato region

Reference	Location	Period	Subsidence (mm per year)	Comments
MacMorran (1944)	Hauraki Plains	Pre 1944	130[A]	A report stating survey records[A] suggested 15 ft (4.6 m) of subsidence along the banks of the Maukoro Canal during ~35 years after the canal was dug by hand.
Hupkins van der Elst (1980)	Moanatuatua & Rukuhia (Lake Cameron)	1958–1963	4–20	Study of mineral content, and peats with a higher mineral content subsided at a lower rate.
Thompson (1980)	-	-	70	Estimate for cropping **but no method for subsidence measurement reported.**
	-	-	20	Estimate for pasture but **no method for subsidence measurement reported.**
Tilsley & Findley (1981)	Lower Waikato (Motukaraka)	1967–1981	48–137	Borehole and averaged ground level measurements along transects. Rates from appendices of borehole information and graphs where peat depth and clay layer depth were measured in 1961 (pre drainage scheme, scheme likely commenced in 1967) and in 1981. Graphs include change in ground level over time. Values quoted were for measurements where a change in peat thickness was determined. Change in ground level was up to 165 mm per year.

Reference	Location	Period	Subsidence (mm per year)	Comments
Bird (1986)	Lower Waikato (Ohinewai)	1959–1983	11	Data based on ground level measurements along several transects. Value is a mean of results which range between 2 and 29 mm/year. This work also reported subsidence of 65 mm/year from an earlier study.
Russell (1993)	Hauraki Plains	1923–1957	32–70	Data based on ground level measurement along several transects in the Pouarua area of the Hauraki Plains. Not all transects were re-measured for each time period.
		1957–1979	20–39	
		1979–1990	16–50	
		1923–1990	40–53	
Schipper & Mcleod (2002)	Moanatuatua	1960s–2001	34	Subsidence was estimated by measuring the depth to a tephra marker bed on drained farmland and in an adjacent remnant peat bog.
McKenzie & McLeod (2004)	Moanatuatua	1920s–2000s	33	Data from peat probing. Re-measured historical surveys of peat depth.
McLeod et al. (2004)	Hauraki Plains	1920s–2000s	18	Data from peat probing. Re-measured historical surveys of peat depth.
Fitzgerald & McLeod (2004)	Rukuhia	1920s–2000s	26	Data from peat probing. Re-measured historical surveys of peat depth.
Tilsley (2011)	Lower Waikato (Motukaraka, Orton, Chruchill East)	1970s–2010	37-72	Repeat of and addition to work of Tilsley & Findlay (1981). Data from a limited number of boreholes. More data likely to be available from other boreholes and extensive ground level survey transects which are not reported here. For example, the appendices present peat depths and locations from 1962 and 1970 with subsidence rates of 15–96 mm per year. The author attributed the majority of subsidence at Motukaraka to silt dewatering rather than peat loss, as the underlying substrate had also subsided.
Pronger et al. (2014)	Moanatuatua	2000s–2012	21	Data from peat probing and represents a re-survey of earlier work by McKenzie & McLeod (2004); McLeod et al. (2004) and Fitzgerald & McLeod (2004). The final value of 19 mm/year is the average of all results and represents a current estimate for the region. Data used in 2016 for Waikato region peat subsidence indicator.
	Hauraki Plains	2000s–2012	17	
	Rukuhia	2000s–2012	17	
	Waikato	2000s–2012	19	
Wyatt (2019)	Muggeridges	2012–2019	26	Preliminary data from 85 ground level measurements spread across the Muggeridges drainage catchment on the Hauraki plains.

Reference	Location	Period	Subsidence (mm per year)	Comments
Glover-Clark (2020)	Moanatuatua	March 2019–January 2020	46–66	Study on reversible peat surface oscillations, over 10 months. Two sites One with border ditch and one with hump and hollow. Difference in peat surface oscillation rates between the two sites due to peat physical properties affecting hydrology rather than drainage design.

Note: A) The subsidence value is an estimate from data presented in the report and the original survey data have not been cited.

4.4 CO_2 emissions from drained Waikato peatland

Schipper & McLeod (2002) reported long term CO_2-C emissions from drained Organic Soils under pasture in the Waikato region of 3.7 tC/ha/yr. This estimate was based on comparing the difference in C content of peat above a volcanic marker bed in a drained dairy pasture and adjacent natural peatland. Campbell et al., (2015) reported CO_2-C emissions from drained Organic Soils under pasture in the Waikato region of 2.9 tC/ha/yr, they measured ecosystem-scale CO_2-C exchange over dairy pasture using eddy covariance in addition to all C imports and exports to calculate a net ecosystem carbon balance. High spatial and temporal variation in emissions is likely. Using eddy covariance Campbell et al. (2021) measured CO_2-C loss of 2.2 tC/ha/y and 8.5 tC/ha/y from two sites under pasture, situated 2.7 km apart, in the Waikato over a 1-year period. The variation between the two sites studied by Campbell et al. (2021) is like the variation in estimates reported by international studies. CO_2-C emissions from NZ peat soils outside the Waikato Region have not been quantified and the spatial variability of CO_2-C emissions from different peat types, drainage management and diversity of land uses in the Waikato region is not well understood.

Summarising the Waikato studies, an average soil carbon loss can be estimated at 4.3 tC/ha/y, which equates to a total of about 1.06 Mt of CO_2 equivalents annually after converting to CO_2 and extrapolating across the 67 000 ha of drained peatlands under pasture in the Waikato Region. This represents approximately 7.8% of gross total GHG emissions in 2018/19 of 13.71 Mt of CO_2 equivalents for the Waikato region, based on inventory data from Envirostat (2020)[7]. These estimates do not include other soil GHG emissions (e.g. N_2O, CH_4) or those from grazing ruminants (e.g. CH_4).

Organic Soils are included in the NZ National GHG inventory (MfE 2021), using the IPCC 2006 Guidelines (IPCC 2006). CO_2 emissions are reported in the Land Use, Land Use Change and Forestry (LULUCF) sector, N_20 emissions are reported in the Agriculture sector and CH_4 emissions are not reported. Using local land use and soils information and

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[7] Average emissions from drained peatlands in the Waikato region of 1.06 Mt of CO_2 equivalents were added to the total gross GHG emissions of 12.64 Mt of CO_2 equivalents, reported by Envirostrat(2020), prior to calculating the % of emissions represented by drained peatlands. Furthermore, gross GHG emissions excluded sequestration by forestry, which was about 5.5 Mt of CO_2 equivalents.

applying Tier 1 emission factors from the IPCC 2006 Guidelines CO_2 and N_2O emissions from drained Organic Soils in the Waikato region would be 0.98 Mt CO_2 equivalents per year. If Waikato Regional Council (WRC) was to include GHG emissions from Organic soils in the regional GHG inventory, then using local data where possible and adoption of the IPCC 2013 Wetlands Supplement (IPCC 2014) should be considered.

4.5 Consequences of peat subsidence

Consequences of peat subsidence and eventual loss of peat include; increased risk and frequency of flooding and inundation, prolonged high soil moisture, reduced wetland sustainability, ponding in catchments due to uneven peat subsidence and reduced drainage gradient, and a requirement to upgrade, repair or install drainage and other infrastructure (e.g. flood protection, single or secondary pumping, roads and utilities, etc.). The impact of subsidence is likely to be exacerbated by sea level rise in locations such as the Hauraki Plains. Many of these issues are already occurring. For example, McKinnon & Basheer (2016) presented a range of existing and anticipated scenarios where drainage services are being compromised by peat settlement, and in the Lower Waikato out of 35 pumped drainage catchments with peat present 11 pump stations have known drainage issues, 12 pump stations are likely to develop future drainage issues, and 7 already have secondary pumping. Issues exist in the Hauraki area too: to maintain drainage services in the Muggeridges catchment area, WRC intends to upgrade flood protection assets that have been degraded due to peat subsidence (Thaker 2015). Recent media reports suggest this upgrade will cost about $9 million (Waikato Regional Council 2020).

Little is known about the productive performance of the remaining sediments post peat loss, the loss of ecosystem services that will occur once the peat has completely gone or what the costs might be to keep these areas in their current land use. Whether subsidence will result in the eventual loss or reduction in agricultural production depends on local hydrological conditions, drainage options (Biancalani & Avagyan 2014), the physical and chemical properties of the remaining peat, how the remaining peat is managed in the final stages of loss, and economic conditions. Interestingly, there are some areas in the Waikato region where up to 2 m of peat was measured in the 1920s; however, this has long since gone (McLeod et al. 2003). These locations are still farmed, but the change in soil versatility due to the loss of this peat soil is unknown.

The long-term sustainability of some peat wetlands may be threatened due to the drainage and subsidence of adjacent agricultural areas on peat. For example, Moanatuatua (74 ha) Reserve is the last site where a natural population of *Sporodanthus ferrugineus* exists in the Hamilton Basin. If the long-term viability of such ecosystems is under threat from the surrounding land use, then this situation conflicts with the National Policy Statement for Freshwater Management (MfE 2017), which requires the significant values of wetlands are protected.

A less visible consequence of peat subsidence are CO_2 emissions from the oxidation component of subsidence. These emissions contribute to the Waikato regions and national greenhouse gas profile (See Section 4.4). A review of soil carbon change in New Zealand grazed grasslands by Schipper et al. (2017) highlighted that while peat soils cover a small area, they represent a disproportionate contribution to national soil carbon losses and so long as these remain drained this loss will continue until the peat no longer remains. Considering some drained peats in the Waikato were initially as deep as 14 m deep (Daveron 1978), subsidence and losses of carbon could continue for centuries. This ongoing loss differs from mineral soils, which are considered to approach new steady state carbon contents after a few decades (Thornley & Cannell 1997 as cited in Schipper et al 2017). In a 'Motu Note' exploring carbon offset options, Meduna (2017) suggested that, for New Zealand, the protection of intact wetlands and restoration of drained peat soils could provide a mechanism for preventing/reducing future soil carbon losses from soils. However, within existing policy it is not possible to earn carbon credits through wetland protection or restoration (Meduna 2017). Recently, Section 7.6.5 in the Climate Change Commission report indicated that central government may consider placing more focus on carbon loss from drained peatlands.

Section 7.6.5, "The most significant source of land emissions and removals not yet part of Nationally Determined Contribution accounting are emissions from Organic Soils, mostly drained wetlands, and removals from biomass on grasslands, mostly small lots of trees. In line with our principle that accounting should aim to cover all material human cased emission sources and sinks, the Government should investigate the feasibility of including these land areas and uses in target accounting in the future" (Climate Change Commission 2021a).

The position in the Climate Change Commission report (Climate Change Commission 2021a) was further strengthened by a subsequent report which recommended that the New Zealand Government should, develop methods to account for carbon emissions and removals from drained peatlands, include these losses in future target accounting, and avoid any further carbon loss from drained peatlands (Climate Change Commission 2021b).

4.6 Policy

Issues associated with peat subsidence have long been recognised in the Waikato region; for example, van der Elst (1957) published the aptly titled paper *"The dangers of over draining peat".* However, the first clear attempt to develop strategic direction and policy for the management of peatlands was in 1982 (NWSCO 1982). North and South Island working groups were established to identify conflicts and requirements for different land uses on peat soils. Water table control and drainage aspects were deemed to be priorities, especially considering the unknown effects at the time. The report included recommendations for management, conservation, and further research. Whether intentional or not some of the recommendations have been implemented over time but many are still relevant and unresolved, for example, 'We recommend the true cost of agricultural development be determined. We further recommend that peat shrinkage rates be investigated in some detail, by comparing the effects of various agricultural, horticultural and pastoral regimes' (NWSCO 1982).

In the currently operative Waikato Regional Plan (WRC, 2012) there are few rules which relate to the management of peat soils, those that do exist are rules 3.7.4.5, 3.7.4.6 and 3.7.4.7. Likely to be beneficial for a small area of drained peatland, rule 3.7.4.5 requires the setting of minimum water or bed levels for the sustainable management of a number of peat lakes in the region (see the table in section 3.7.7 of WRC, 2012). Setting a minimum level will have a positive impact on soil moisture and water table conditions in peat soils immediately adjacent to peat lakes and therefore could potentially reduce subsidence. Most lakes have had weirs installed on their outlets, at the time of writing only Henderson's Pond and Lake Rotongata were the only lakes not to have weirs already or consents granted with an intention to build over the following summer (P. Reeves, pers. comm.). Rules 3.7.4.6 and 3.7.4.7 are in place to protect water levels in wetlands, and therefore any peat soils in those wetlands. Rule 3.7.4.6 states that drain creation or deepening within 200 m of wetlands identified in the regional plan (e.g. Kopuatai, Moanatuatua) is a discretionary activity.[8] Drainage or deepening of drains in those wetlands with indigenous vegetation is a discretionary activity under rule 3.7.4.7.

From a drainage management perspective, it is considered that existing policy and guidance related to drained peat soils is insufficient (G. Russell & R. Spooner, pers. comms). For example, in some locations land management activities on peat soils (e.g. excessive cropping or drain deepening) have been attributed to local drainage problems. This results in requests for further drainage support and can eventually impact on adjoining landowners. There is no clear guidance as to how such conflicts should be managed or restrictions on those activities that appear to rapidly degrade peat soils.

While the regional plan provides little direction for the management of drained peat under agriculture, the issues have been recognised in the Waikato Regional Policy Statement (WRPS) (WRC 2016a). Policy 14.5 of the WRPS sets out to 'manage the adverse effects of activities resulting from use and development of peat soils, including slowing the rate of subsidence and the loss of carbon by oxidation from peat soils' (WRC 2016a). Implementation methods in the WRPS include controlling activities on peat soils via regional plans to;

- slow the rate of subsidence and carbon loss by oxidation,
- mitigate adverse effects resulting from use and development of peat soils, and
- ensure drainage infrastructure minimises any adverse effects on peat soils.

The WRPS requires WRC to undertake and promote research, and to advocate for good peat soil management practices through environmental education programmes. The purpose of the WRPS is to provide an overview of resource management issues in the Waikato Region and its contents can inform rules in the Waikato Regional Plan.

4.7 Existing mitigation attempts

Strategies have been implemented in some local catchments to attempt to reduce the rate of peat subsidence.

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[8] A discretionary activity requires a resource consent before it can be carried out, the regional council can exercise its full discretion as to whether or not to grant resource consent and as to what conditions to impose on the consent if granted.

Blocking drains at critical times of the year (e.g. late spring/early summer before the drain runs dry) to maintain water levels has been promoted to manage water tables in peat soils. (WRC 2006), especially where drainage falls are small (e.g. 1:1,000) (Bowler 1980). Anecdotal observations suggest this approach has been successful at reducing subsidence at Loch Carron Farm, Island Block (Waikato Regional Council 2006). In the Swan Road catchment, in the Lower Waikato, earth weirs are installed each winter in the upper catchment to maintain water levels into summer; these are later removed. However, their effectiveness is considered doubtful due to sub-surface woody layers that have high permeability (WRC 2016b). Waikato Regional Council (2006) suggests installing sub-surface structures either side of the drain block to help isolate the water table and avoid bypass flow, but whether this would be beneficial or practical where an extensive highly permeable layer exists is unknown.

Importing water into a catchment to maintain summer water levels has been used in the Waikato. The Motukaraka catchment in the Lower Waikato is an example of this practice. Water is transferred from the Maramarua River, via a culvert during summer and dry periods, to maintain minimum levels in the Kopuera Canal. The presumption is that maintaining the water levels in the drains will result in a higher water table in the surrounding peat soils, thereby minimising peat subsidence (Basheer 2002). Some of this water is also used for irrigation.

Seasonal operating regimes for pump stations are also used to manage the water table by retaining water when the ability to recharge is less likely (summer) and to provide a higher level of drainage service when excess water is frequent (winter). The Swan Road catchment is an example of this. During the 'summer season' pump operating regime, the start and stop levels are higher than those during the 'winter season'. The levels are set to allow a certain amount of 'freeboard' prior to pumps starting and not to pump water levels down excessively during summer. At Swan Road the transition between the seasons is linked to flows over an upstream weir, but broadly the change from summer to winter is expected to occur in April or May and from winter to summer in October or November (Waikato Regional Council 2016b).

The strategies described above have been implemented with the goal of reducing peat subsidence in catchments in the Waikato region, however the effectiveness of these strategies have not been monitored.

5 Water management strategies to reduce subsidence and CO_2 emissions

Peat subsidence and CO_2 emissions are initiated by drainage and it is likely reductions in subsidence can be achieved by management strategies that maintain high peat soil moisture content (Ferre et al. 2019); however, increased soil moisture could also increase CO_2 emissions under some conditions (e.g. Saurich et al. 2019). This section will review scientific literature on water movement in peat soils and water management strategies that may increase peat moisture content to reduce subsidence and CO_2 emissions. This information will be useful for guiding future decisions on water management strategies that could be trialled or implemented in the Waikato Region. We begin by discussing water input and movement (infiltration and hydraulic conductivity, Section 5.1) and relationships between soil moisture and the water table (Section 5.2). We then review the effect of drainage and reductions in the water table and soil moisture on subsidence processes (Section 5.3), approaches to increase water inputs (Section 5.4) and decrease water loss through vertical drainage (Section 5.5) and evaporation (Section 5.6). Studies that link subsidence and CO_2 emissions to water management strategies are summarised in Table 3.

5.1 Water infiltration and hydraulic conductivity

The physical and biogeochemical processes of peat subsidence (shrinkage, consolidation, and oxidation) are strongly controlled by soil moisture content (McLay et al. 1992; Thompson et al. 1999). Consequently, knowledge of infiltration rates, water-holding capacity, and hydraulic conductivities are crucial to model and understand hydrological functioning in peatlands (Dettmann et al. 2014) and ultimately to develop approaches to mitigate subsidence. However, quantifying hydraulic properties of managed peat soils is difficult because hydraulic properties vary spatially and temporally with parent vegetation, state of decomposition, and moisture content (Wallor et al. 2018). Pore tortuosity and connectivity are also dependent on decomposition state and parent vegetation and can range from open and connected to dead-ended and isolated (Rezanezhad et al. 2016). The resulting heterogeneity in hydraulic conductivity is suspected to influence rates and patterns of ground water movement in peat soils (Beckwith et al. 2003) and complicates modelling and management of water movement in peatlands.

Soil moisture content is also likely to vary spatially with variation in microform based on past contouring activity. In Canada, Branham and Strack (2014) showed that for a *Sphagnum*-dominated peatland hydraulic conductivity was higher on humps compared with hollows. Hydraulic conductivity also decreased with depth as bulk density increased and macroporosity decreased. It is also likely that hydrophobicity develops on the drier humps as hydrophobicity has often been described and observed (Wallor et al. 2018) in drained peat soils and promotes surface run off directly into surrounding drains in contrast to infiltration. Consequently, soils remain dry following large rainfall events and hydrophobicity likely contributes to peat subsidence. Schumann and Joosten (2008) suggest improving infiltration by avoiding surface sealing and hydrophobicity should lead to increased moisture held in peat soils above the water table and thus decreased subsidence. Surface sealing is likely best avoided by avoiding excessive tillage and stock trampling and hydrophobicity is a consequence of excessive drying of the surface so is likely avoided by keeping water tables high, maintaining vegetation cover, and potentially using irrigation.

5.2 The relationship between the water table and peat soil moisture content

The water table is typically used as a proxy to estimate the boundary of the saturated and unsaturated zone in peatland studies (Tiemeyer et al. 2016). However, the boundary between the saturated and unsaturated zone is not always a direct function of water table depth (Kellner & Halldin 2002) and can exist year-round (Wessolek et al. 2002), seasonally (Price 1997; Glover-Clark 2020) or not at all (Parmentier et al. 2009) and is likely dependent on soil physical properties. Recent research in the Waikato suggests that capillarity may maintain saturated conditions up to 0.6 m above the water table in dry conditions (Glover-Clark 2020). This has also been shown in the US where Reddy et al. (2006) used redox potential measurements to show that anaerobic conditions were maintained above the water table by a capillary fringe. The height of this capillary fringe is likely dependent on antecedent weather and environmental conditions and peat soil properties (particle size, degree of decomposition). Direct measurements of soil moisture can therefore better represent the influence of drought and wetness on processes such as peat oxidation (Ritchie 1998; Tiemeyer et al. 2016). Despite this, most studies use the water table depth as a proxy of the saturation depth and consequently report on relationships between the water table and subsidence. When investigating local drained peat soils, Garrett (2001) found that water table depth was strongly influenced by drain depth and recent weather conditions, and demonstrated a link between water table depth and soil moisture content in the topsoil.

5.3 The water table and subsidence

There is much data from international peatland research that show deeper water tables and episodic lowering of the water table increase subsidence rates for both temperate and tropical peatlands (Hutchinson 1980; Wosten et al. 1997; Dawson et al. 2010a; van den Akker et al. 2012; Deverel et al. 2016; Evans et al. 2019). Some of the best long-term records of peat subsidence and water table levels come from England and the Netherlands. In England, the East Anglian Fenlands are the last extensive remaining lowland peatlands where drainage began in the 17th century, initially by gravity drainage, with pumped drainage starting in the late 1800s, firstly windmill driven, then steam and ultimately diesel driven pumps (Dawson et al 2010). At Holme Fen within the East Anglian Fenlands, Hutchinson (1980) showed cumulative subsidence since drainage began in about 1850 (Fig.5) (this was later than the wider East Anglian Fenlands). Subsidence rates were episodic through time and periods of rapid subsidence aligned with periods of successive water table lowering associated with upgrading of pumped drainage infrastructure.

In the East Anglian Fenlands, attempts to improve drainage management to reduce subsidence were introduced around 1980 based on historic imagery (Dawson et al. 2010b). Dawson et al. (2010) reported on water management strategies used at Methwold Fen. Water table management is complex because of variation in surface levels across the peatland requiring four different water levels to be maintained. During autumn and spring drain water levels are manipulated within paddocks using control structures. Water from internal Drainage Board channels (or from external reservoirs during drought) is pumped into fields via subsurface irrigation pipes spaced at 20-m intervals and buried at 0.7-m depth to maintain water tables at 0.5 m below mean field level. Data presented by Dawson et al. (2010b) suggested the decline in subsidence rates from 20–40 mm/y before 1980 to about 14 mm/y after the 1980s was likely related to improved water table management. However, these observations must be viewed with caution because there were no experimental controls and subsidence rates typically decline through time (see Section 7.2).

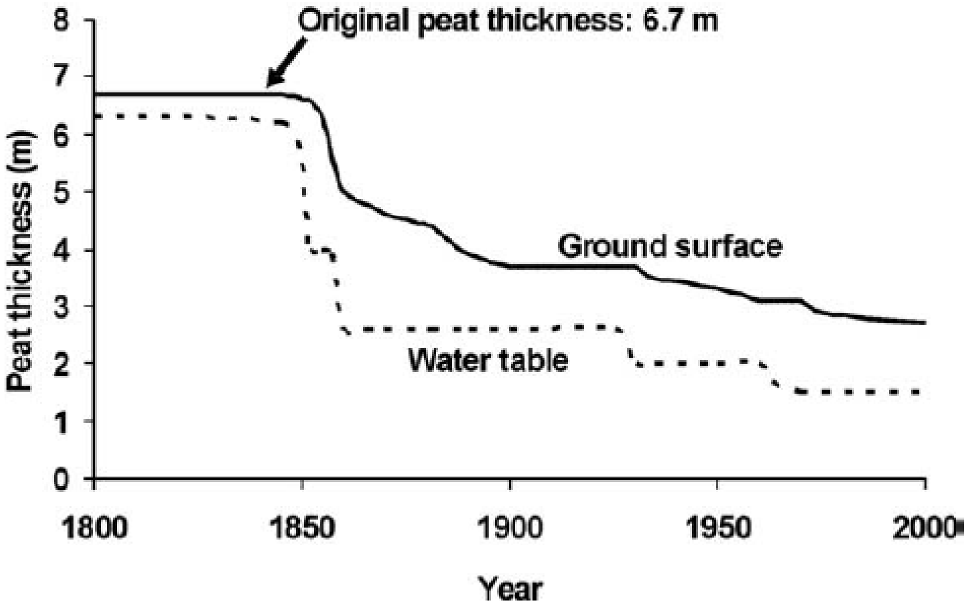


Figure 5. Relationship between water table and peat subsidence at Holme Fen in England where drainage began about 1850 and the water table was successively lowered by pumping upgrades (from Hutchinson 1980).

In the Netherlands, peatland drainage has been occurring for about 1000 years; however, up until about 1870 water tables remained high and drainage was seasonal. Since the introduction of steam driven pumps in the 1870s water tables were able to be maintained at levels that allowed agricultural land use throughout the year (Stephens et al. 1984) and demonstrated a strong relationship between water table lowering and increased subsidence. In one long-term experiment, Schothorst (1977) compared subsidence rates under two different drain water levels at three sites (Zegvelderbroek, Bleskengraaf, and Hoenkoop) between 1969 and 1975. Subsidence rates varied between sites at equivalent drain water levels (likely due to differences in organic matter content of the peat) but at each of the three sites subsidence rates were lower for higher drain water levels (Fig. 6). More recently, van den Akker et al. (2012) reported subsidence rates under different drain water levels and the deepest ground water levels in the same area. Good correlation (correlation coefficient of 0.65) was found between the deepest summer ground water level (GWL) and subsidence rates. Subsidence rates were less than 0.5 mm/y for GWL of 0.6–0.7 m and increased to about 15 mm/y when GWLs approached 1 m depth (Fig. 7).

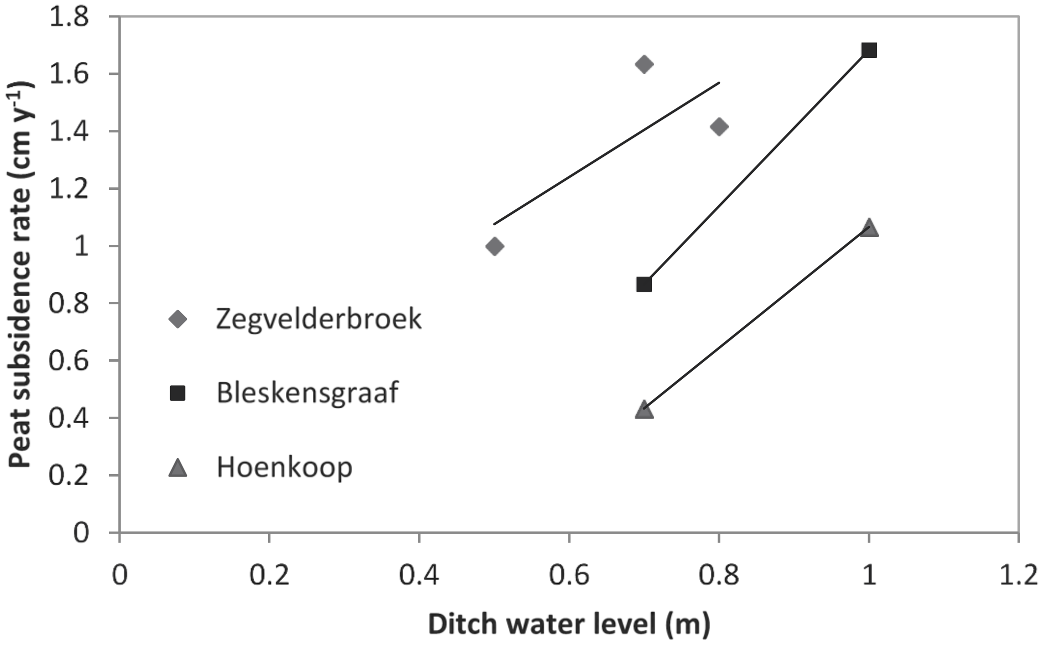


Figure 6. Peat subsidence rates as affected by drain water level at three field sites in the Netherlands (data from Schothurst (1977).

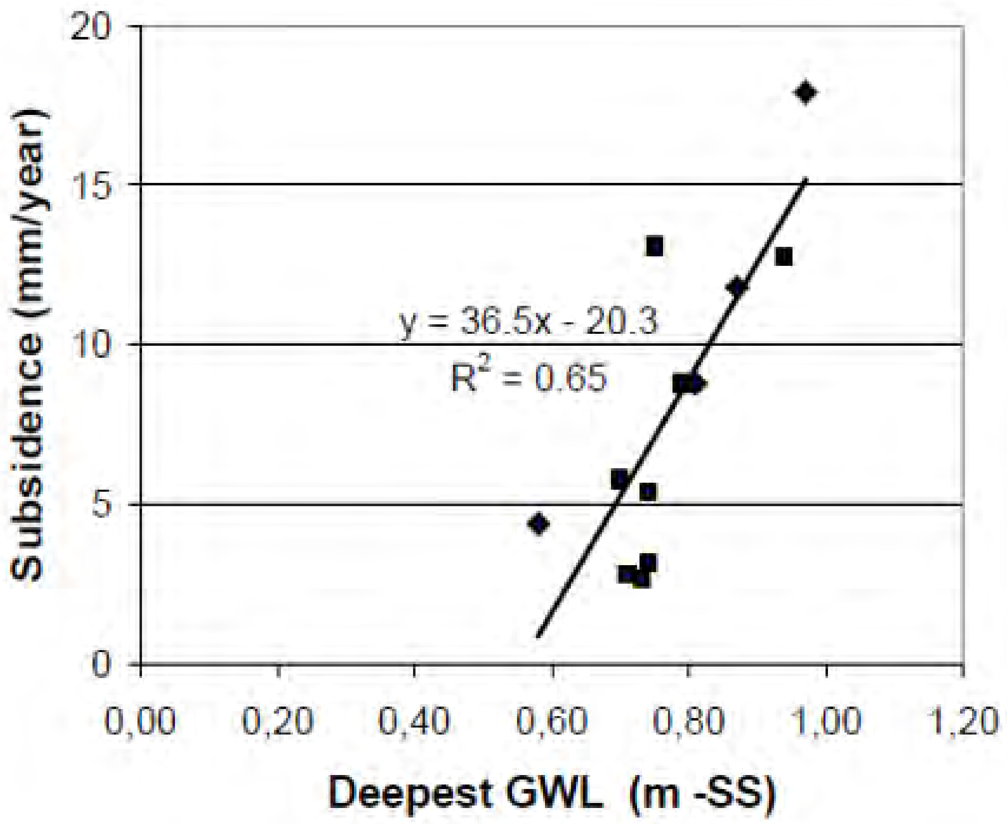


Figure 7. Relationship between subsidence rate and deepest seasonal water table depth for sites in the Netherlands (from van den Akker et al. 2012).

Subsidence rates in tropical peatlands (e.g. Indonesia and Malaysia) have also been highly studied. Nusantara et al. (2018) found strong correlation between water table-depth and subsidence rates ($r^2 = 0.82$) that were higher for secondary peat forest compared with palm oil plantation and corn fields. Increased subsidence for the more natural peat forest vegetation was attributed to deeper water tables. For plantation and forested peatlands in Indonesia, Evans et al. (2019) found the mean water table depth was the best predictor of subsidence rates. Findings suggested that raising the average water table depth to the Indonesian Government's target of 0.4 m below the surface (if practically and economically viable) could reduce subsidence rates by 25–30%. Also in Indonesia, Wosten et al. (1997) showed that for every 0.1 m lowering of the water table, subsidence rates increased by 7 mm/y.

Several relationships have been developed between groundwater level and subsidence rate. Work by Stephens and Stewart (1976) recognised the importance of water table and peat soil temperature where subsidence was predicted based on:

$$\text{Subsidence rate (m/yr)} = ((0.093 + 0.00524 \times (WTD \times 100)) \times 2^{(T-5)/10)})/100$$

Where WTD is the water table depth (m) and T is the peat soil temperature (°C) at 0.1 m depth

In Malaysia Wosten et al. (1997) found the following linear relationship:

$$\text{Subsidence rate (m/yr)} = 0.04 \times \text{groundwater level (m)}$$

This relationship suggests subsidence rates increase by 4 mm for each 0.1 m lowering of the ground water level. However, Wosten et al. (1997) found that this reduces through time and was initially up to 9 mm for every 0.1 m lowering of the water table. Wosten et al. (1997) also tested the equation of Stephens and Stewart (1976), and found their simple linear equation, that did not account for temperature, performed equally well. Wosten et al. (1997) collated data between water table depth and subsidence rates for several global peatland areas including Florida and Indianna (Stephens & Stewart 1976) and the Netherlands (Schothorst 1977). These collated data demonstrated that subsidence rates increased at deeper water table depths across global peatlands and at equivalent water table depths subsidence rates were higher for the warmer peatland areas (Malaysia and Florida) compared with Indiana and the Netherlands (Fig. 8)

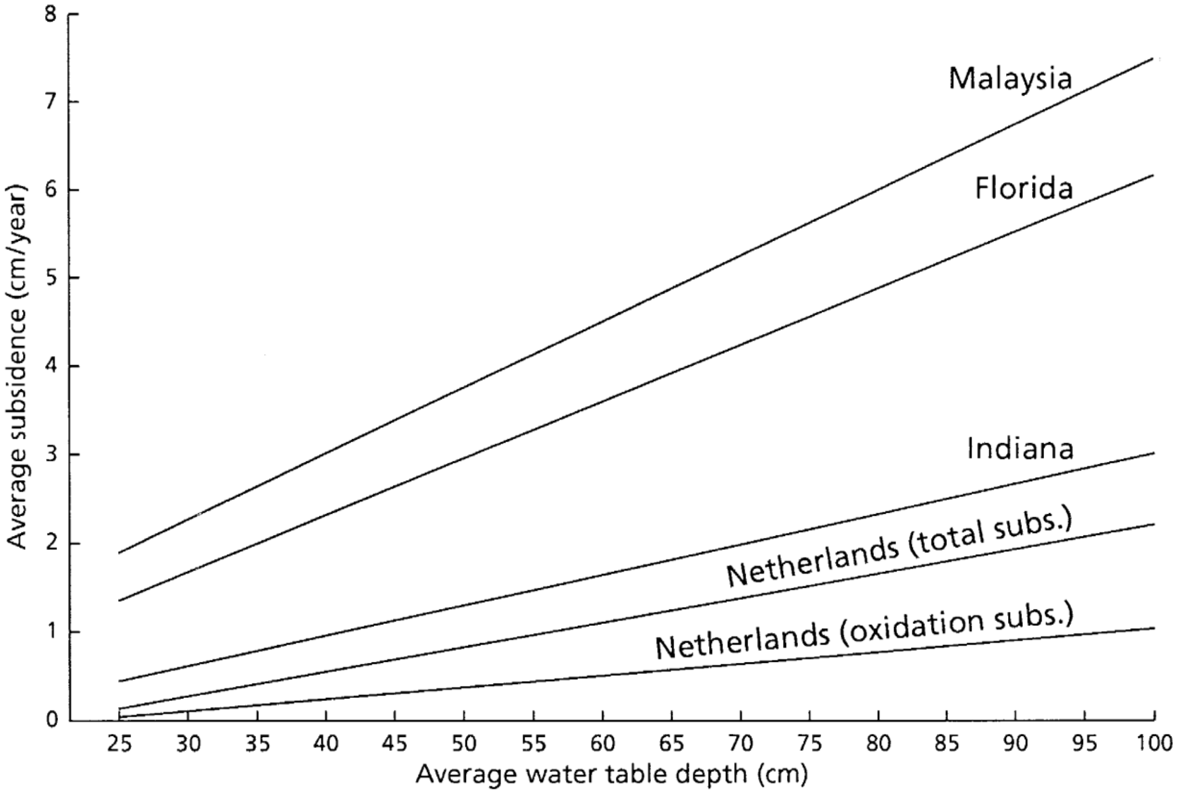


Figure 8. Relationship between peat subsidence and average water table depth for the Netherlands (total subs. is total subsidence and oxidation subs. is subsidence due to oxidation), US (Indiana and Florida) and Malaysia (Figure from Wosten et al. 1997).

5.3.1 Water table and CO_2 emissions

CO_2 production from drained peatlands generally increases as depth to the water table increases. In Norway, Kløve et al. (2010) found CO_2 emissions were highest when water tables were deep and soil temperatures were high. Further, Renou-Wilson et al. (2016) found that keeping the mean annual water table at less than 0.25 m deep minimised GHG emissions from peat soils in Ireland. In the US, Reddy et al. (2006) found CO_2 emissions increased as water table depth increased but the upper layer between 0 and 0.15 m contributed the most CO_2 and for each 0.1 m lowering of the water table below 0.15 m the flux increase was marginal. Modelling by Wessolek et al. (2002) in Germany showed that CO_2 emissions increased as the depth of the rooted soil zone increased but decreased as the decomposition state of the peat increased. Wessolek et al. (2002) suggest that CO_2 emissions are highest when the water table is deep and soil water deficit is high during vegetative growth periods.

However, others have reported that emissions increase as depth to the water table increases. For a ryegrass pasture site in Sweden, Berglund and Berglund (2011) reported higher CO_2 emissions from a treatment with the water table at 0.4 m depth compared to a treatment with a 0.8 m depth to the water table. Lowering the water table increased emissions in situations where soil layers had previously not been aerated, were more easily decomposed, or had low C/N ratios. Berglund and Berglund (2011) state that temperature can be rate limiting at low temperatures while at higher temperatures aeration status becomes more important. However, in extreme conditions of either water logging or desiccation soil moisture can become rate limiting. In a lab experiment, Säurich et al. (2019) showed that CO_2 emissions peaked at between 73 and 95% water-filled pore space, and were lowest under saturated and dry soil conditions.

5.3.2 Drainage and water table manipulation summary

Decreasing depth to the water table will reduce subsidence rates and likely CO_2 emissions. However, manipulation of drainage depth and spacing to control the water table is challenging (Norberg et al. 2018). For example, in the Waikato region, especially during summer and autumn, it is common for paddock boundary and main farm drains to be dry. Clearly, when dry, a drain is no longer affecting peat water content and other processes such as subsurface flow toward larger board drains or upward movement of water through capillarity and surface evaporation are responsible for ongoing water loss. Reddy et al. (2006) demonstrated that capillarity can maintain anaerobic conditions in peat above the water table and Glover-Clark (2020) measured a zone of saturated peat extending 0.6 m above the water table, interpreted at a thick capillary zone, at two sites (one with hump and hollow drainage, one with paddock boundary drainage) during dry conditions. This suggests manipulating drainage depths and water outflow levels is only one component of a more complex web required to control the water table and water content in peat soils. Peat moisture content manipulation for reduced subsidence is likely best viewed as a water balance problem where water inputs (precipitation and irrigation totals and seasonality), losses (horizontal and vertical drainage, evaporation) and rate limiting factors (e.g. hydraulic conductivity, energy availability) all contribute to the volumetric water content of the peat that is ultimately controlling subsidence processes. Furthermore, it is important to consider that any mitigation measure will have benefits as well as drawbacks, and decreasing the depth to the water table has been shown to increase methane (Regina et al. 2014; Tiemeyer et al. 2016) and nitrous oxide emissions (Berglund & Berglund 2011; Kelliher et al. 2016).

5.4 Sub-surface Irrigation

Subsurface irrigation can maintain higher peat moisture content using recycled water from drains within a peatland or imported external water. Typically, infrastructure can be established to enhance drainage during wet periods and irrigate in during dry periods. Subsurface irrigation has been used in the East Anglia Fenlands since the early 1980s. Water from internal Drainage Board channels (or from external reservoirs during drought) is pumped into drained peat fields via subsurface irrigation pipes spaced at 20-m intervals and buried at 0.7 m depth to maintain water tables at 0.5 m below mean field level. Data presented by Dawson et al. (2010) suggested subsidence may have declined from 20–40 mm/y pre 1980 to about 14 mm/y after the 1980s following installation of sub-surface drainage to improve water table management. However, this finding was observational, and it is difficult to separate the effects of the subsurface irrigation from the expected decline in subsidence through time (Pronger et al. 2014).

Subsurface irrigation via submerged drains to raise summer water table levels is also being tested to reduce subsidence rates and GHG emissions in the Netherlands with somewhat mixed results. Experimental work by van den Akker et al. (2012) on organic soils drained for dairy farming showed a 30% increase in water input reduced subsidence and CO_2 emissions by 50% and improved trafficability. In this study, subsurface irrigation was compared to a reference parcel of peatland with no subsurface irrigation that had been monitored since 1970 with a long-term subsidence rate of 10.8 mm y^{-1} and drain depth of 0.55 m (Fig. 9). It was stated that subsurface drains were spaced at 4, 8, and 12 m but results for different drain spacings were not presented.

Further research into the effectiveness of subsurface drainage is being assessed within the PEATWISE programme in the Netherlands. In Friesland, four farms have been established with submerged drains at 6-m spacing that are being compared with control sites with no submerged drains. The approach aims to maintain the water table at a more consistent depth through additional drainage in winter and water input during summer (Fig. 10). At each site the water table, soil moisture, subsidence, CO_2 and methane (CH_4) emissions are measured. Water level manipulation was effective up to about 1.5 m horizontal distance from subsurface irrigation pipes and the increase in peat moisture content during summer increased CO_2 emissions. The increased peat moisture content did not appear to reduce subsidence over this short-term study but did reduce interannual peat surface oscillation (C. Fritz, Radboud University, pers. comm.). Summary of mitigation options based on the PEATWISE project results and expert judgement is under preparation and should be examined prior to any experimental research in New Zealand.

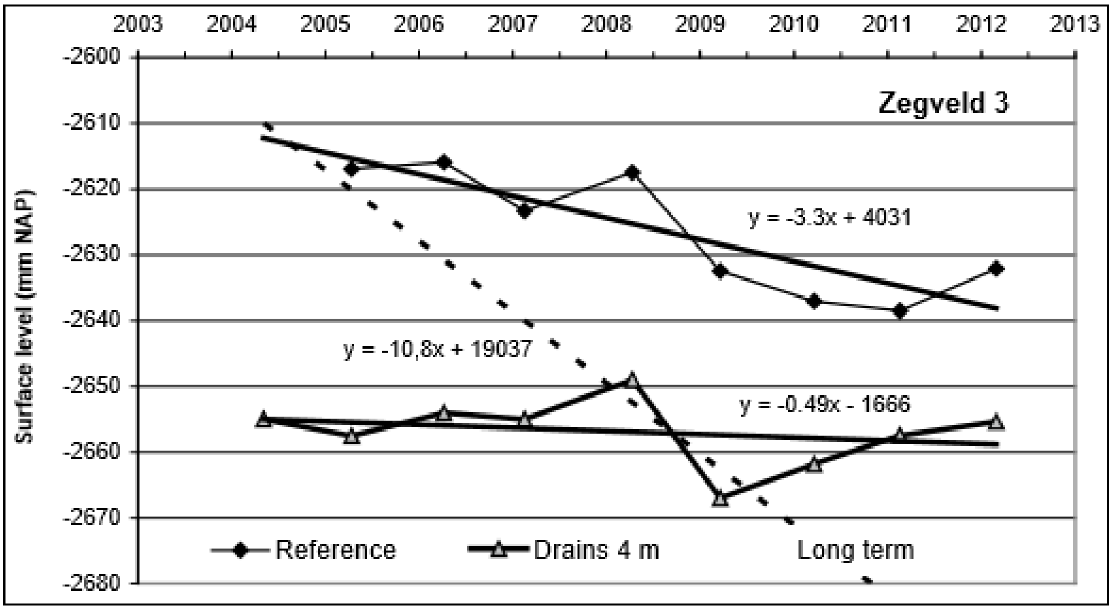


Figure 9.Comparison of subsidence rates between a reference site without subsurface drains and a site with subsurface drains at 4-m spacing at Zegveld in the Netherlands between 2004 and 2012. Dashed line is the long term mean subsidence rate (Figure from van den Akker et al. 2012; NAP is the Dutch national reference level, which is about the average sea level).

Reddy et al. (2006) compared the oxidative component of surface subsidence for peat soil continually drained with 0.15 m to subsidence when flooded and drained at a frequency of 10, 25 and 50 days in the US. They found that frequent flooding and drainage reduced peat oxidation and hence subsidence. Subsidence attributed to oxidation was 5 mm/y under continual drainage and reduced as flooding frequency increased to 1 mm/y for the

10-day flooding frequency. However, there will likely be trade-offs associated with flooding including reduced productivity and trafficability and potential for increased emissions of N_2O and CH_4.

Farmers in the Netherlands are firmly opposed to raising drain water levels because this reduces trafficability and increases risk of surface pugging and therefore require adaptation to maintain intensive land use. However, subsurface drainage and irrigation has multiple advantages including maintaining lower water tables in winter and higher water tables in summer (Fig. 10) that makes farm management during wet periods easier which may facilitate uptake of this mitigation strategy (van den Akker et al. 2012). However, a modelling study by Querner et al. (2012) found that 30% more water was required in summer when using the subsurface drain technique. The availability of extra water, particularly in dry summers, is a problem that is difficult to overcome.

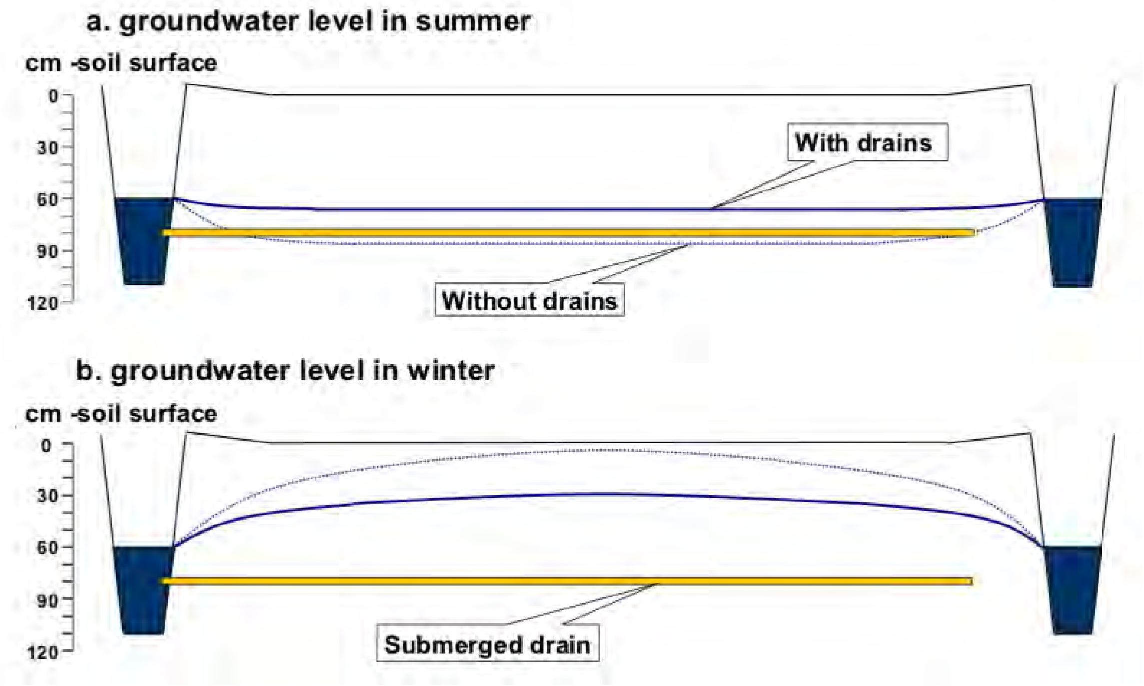


Figure 10. Depiction of how subsurface drains will decrease depth to the water table in summer conditions (a), and act as drainage in the winter (b) to reduce seasonal variation in the water table depth (Figure from van den Akker & Hendriks 2017).

5.5 Effect of underlying substrate

Underlying substrate may also affect subsidence rates through limiting drainage, likely because the clay restricts drainage keeping the peat wetter and enabling better control of the water table. In Germany, Fell et al. (2016) found subsidence rates were lower for peat soils underlain by lime gyttja and clay (2.4–3.9 mm/y) compared with sites underlain by loams or sand (5.4–5.6 mm/y). In the UK (East Anglia), Dawson et al. (2010) also found subsidence rates were lower for peat areas underlain by fen clay.

In the Waikato Region underlying substrate varies spatially between reduced clays that likely inhibit downward water movement, and free sandy substrates that do not inhibit downward water movement. It is also likely some peatland areas are effectively floating on fluid silt and clay layers (e.g. Palmer & Hainsworth 2012). Knowing more about the spatial patterns of underlying substrate may be useful when selecting suitable mitigation strategies to reduce subsidence. Water table control measures will be more successful where peat layers are shallower and underlain by thick layer of relatively impermeable clays. Peatland stratigraphy for many Waikato peatlands is described in Daveron (1978) and may provide spatial information on the distribution of underlying clays in the Waikato region.

5.6 Reducing evaporative water loss

In their natural state, peatlands in the Waikato region are formed from restiad plants that strictly control water loss and thereby maintain high water tables in an environment where evaporative demand would normally not allow high water tables to be maintained for peat accumulation (Campbell & Williamson 1997). When drained for pastoral agriculture, ryegrass and clover pasture replaces the restiads because they are well suited to intensive rotational grazing. However, Pronger et al. (2016) showed that evaporation from ryegrass dominated pastures is strongly controlled by available energy and the pasture plants did not restrict water loss until soil moisture became restricting. Further research by Pronger et al. (2019) indicated that alternative pasture species, and in particular pasture herbs (e.g. plantain and chicory) maybe more water efficient at certain times of the year (e.g. chicory in spring) and maybe able to conserve water. If pasture species that conserve water are identified, surface water loss through evaporation may be reduced thereby increasing soil moisture content and decreasing subsidence and CO_2 emissions.

Table 3. Summary of studies on subsidence and/or CO_2 emissions from drained peatlands in relation to potential mitigation strategies including water table management and drain depth, subsurface irrigation, surface flooding, soil moisture and surface evaporation.

Mitigation strategy	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
Water table (Netherlands)	Dairy farming, permanent grassland	Across 3 sites subsidence rates consistently lower for higher drain water levels	Not reported	Schothorst (1977)	Subsidence rates compared between different drain water levels at 3 sites in the Netherlands between 1969 and 1975.
Water table (Norway)	Natural compared with annual grass and ley	Not studied but long-term subsidence rates in Norway suggested to be about 20 mm/y	Highest emissions when water table deep and temperatures high	Kløve et al. (2010)	Compared natural peatland to ryegrass pasture site, surface graded site, and abandoned cultivated site. Emissions of CO_2 and N_2O depend on temperature, groundwater table and nutrients in groundwater.
Water table (Ireland)	Permanent extensive grassland	Not reported	Recommended maintaining water table	Renou-Wilson et al. (2016)	Compared GHG emissions from adjacent shallow drained (WT –0.26 m) and

Mitigation strategy	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
	(0.6 livestock units/ha)		within 0.25 m of surface and extensive grazing management to minimise CO_2 emissions		rewetted (WT –0.11 m) nutrient poor grassland to analyse relative importance of WT, vegetation, weather, and grazing.
Water table (Sweden)	Grass, silage and hay production	Not reported	Emissions higher when water table at 0.4 m depth compared with 0.8 m depth	Berglund & Berglund (2011)	GHG emissions compared between static WT at 0.4 and 0.8 m using soil monoliths in lysimeters.
Water table Modelling (Germany)	Grass vegetation	Not reported	CO_2 emissions highest with deep water table and high soil moisture deficit during vegetative period	Wessolek et al. (2002)	Modelling study.
Frequent flooding (US)		Flood freq.(days) /subsidence rate (mm/y) 0/5 10/2.5 25/2.7 50/3.5	CO_2 emissions increased as depth to WT increased. 0–0.15-m interval contributed most CO_2 and below 0.15-m depth CO_2 flux did not increase as much with each 0.1 m lowering of the WT	Reddy et al. (2006)	Flooded and drained at 10-, 25-, and 50-day frequency and examined effect on oxidative component of subsidence. Also looked at WT effect on CO_2 emissions.
Water table (Indonesia)	Agricultural, likely palm oil and soybean	Linear relation between groundwater level and subsidence showed annual subsidence rate increased by 4 mm/yr for every 0.1 m lowering of WT	Calculated CO_2 emissions of 26.5 t/ha/y for 0.47 m of peat above WT and was dependent on WT depth	Wosten et al. (1997)	CO_2 estimate sensitive to bulk density.
Water table (maintained at 30 cm	Permanent grassland	Subsidence reduced from 9 mm/y to 2–	Peat mineralisation reduced by	Renger et al. (2002)	Calculated with modelling considering equal importance of peat mineralisation, gas

Mitigation strategy	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
below surface) (Germany)		3 mm/y annually	60-70% of maximum		emissions (CO_2, N_2O, CH_4), and crop production allowing 90% of optimum crop production (unsure which species).
Subsurface irrigation (Zegvald, Netherland)	Dairy farming, permanent grassland	Zegveld 3 Control: 3.3 mm/y 4-m spacing: 0.5 mm/y Zegvald 2 Control: 6.1 mm/y 4-m spacing: 1.3 mm/y	Not reported	van den Akker et al. (2012)	Long-term subsidence rate without irrigation was 10.8 mm/y. Study period was unusually wet reducing subsidence rate of controls.
Subsurface irrigation (East Anglia, UK)	Intensive arable and horticultural farming	Pre-1980: 20–40 mm/y Post-1980: 14 mm/y	Not reported	Dawson et al. (2010)	Subsurface irrigation installed around 1980. Measurements suggest subsidence rates have declined since installation of subsurface irrigation but not a controlled experiment.
Rice cf. corn (US)	Corn cf. rice	Rice field: 0.2–8 mm/y accretion Cornfield: 8.3 mm/y loss	Not reported	Deverel et al. (2016)	Extensimeter measurements in a rice field and nearby cornfield suggested rice may stop, or greatly inhibit subsidence.
Soil moisture content (Waikato, NZ)	Pastoral dairy farming	Not reported	Not reported	Garrett (2001)	Water table depth regulated by drain depth and soil moisture strongly linked to water table depth.
Soil moisture content/ physical soil properties (Waikato, NZ)	Pastoral dairy farming	Hump and hollow drainage: 66 mm (mostly reversable oscillation) Border ditch drainage: 46 mm (mostly reversable oscillation)	Hump and hollow drainage: 1.05 ± 0.66 t C/ha/y Border ditch drainage: 6.66 ± 0.63 t C/ha/y	Glover-Clark (2020)	Differences in soil physical properties influenced hydrology, which appeared to cause differences in peat surface oscillation and CO_2 emissions between sites. Deep water tables and low soil moisture correlated and implicated in period of maximum CO_2 loss.
Drain depth (Waikato, NZ)	Pastoral dairy farming	Subsidence rates higher closer to drains	Not reported	Fitzgerald et al. (2005)	Deeper drains effected subsidence rates for greater distance from the drain.

6 Land management approaches to reduce subsidence and CO_2 emissions

There are a range of land management approaches that may reduce subsidence and CO_2 emissions. Strategies that include reducing land use intensity (Kasimir-Klemedtsson et al. 1997) increase pasture productivity, and thus CO_2 uptake (Campbell et al. 2015; Berglund et al. 2019) maybe most successful. Increased land use intensity is generally associated with increased nutrient input, cropping and stocking rates. Reducing nutrient inputs may reduce microbial oxidation (Brouns et al. 2016; Tiemeyer et al. 2016) and eliminating cropping is likely to reduce subsidence and CO_2 emissions (Berglund & Berglund 2008) but such changes may harm productivity. For example, reducing nutrient input may reduce plant growth and thereby CO_2 uptake through photosynthesis (Berglund et al. 2019). This section reviews land management approaches to reduce subsidence and CO_2 emissions that could be trialled or implemented in the Waikato region. Approaches reviewed include, cultivation (Section 6.1), nutrients and microbial activity (Section 6.2), pasture species selection and management (Section 6.3), and surface amendments (Section 6.4). Studies that link subsidence and CO_2 emissions to land management approaches are summarised in Table 5.

6.1 Cultivation

Cultivation of peat soils likely accelerates subsidence by enhancing the rate of oxidation due to increased aerobic status of the peat. For Waikato peatlands, van der Elst (1980) suggested subsidence rates were twice that for cultivated peats compared with long-term pasture, and Thompson (1980) reported that peat subsidence rates were 70 mm/y under cropping compared with 20 mm/y under pasture; however, details of how these rates were determined were not reported. International evidence also supports higher subsidence rates for cultivated peats. In Sweden, about one quarter of the agricultural peat soils is intensively cultivated, while the balance is largely managed as pastures (Berglund & Berglund 2008). Subsidence rates vary between land uses based largely on land use intensity with high cultivation intensity for annual row crops having the highest subsidence rates of about 25 mm/y (Table 4). In comparison, subsidence rates for annual crops (excluding row crops) are about 15 mm/y, while managed grasslands are about 10 mm/y and extensive land use including trees is about 5 mm/y. Berglund and Berglund (2008) calculated CO_2 emissions based on these subsidence rates and average bulk density of the peat. CO_2 emissions were highest for annual row crops at 8.8 tC/ha/yr and reduced to 5.2 tC/ha/yr for annual crops excluding row crops. In comparison, CO_2 emissions were 1.8 tC/ha/yr for extensive land use and 3.5 tC/ha/yr for managed grasslands. While increased CO_2 emissions were attributed to cultivation intensity, higher intensity crops also require better drainage and hence drainage depth was likely a confounding variable.

Table 4. Subsidence rates and C emissions from agricultural peat soils in Sweden (adapted from Berglund & Berglund, 2008)

Cultivation intensity (crop type)	Subsidence rate (mm/y)	C loss (tC/ha/y)	Area (ha)	Total C loss (Gg/y)
Row crops	25	8.8	3536	31
Annual crops except row crops	15	5.2	60113	310
Managed grasslands	10	3.5	91179	320
Extensive land use incl. trees	5	1.8	96483	170
Sum			251311	831
Total emissions as CO_2 (Gg/y)				3100

In the northeast of Germany, Fell et al. (2016) reported subsidence rates and calculated CO_2 emissions for uncultivated, grassland and arable sites (3729 sites total) for land uses with low to high intensity. Subsidence rates and CO_2 emissions were dependent on peat depth when categorised into peat layers less than 0.3 m depth, between 0.3 and 0.7 m, between 0.7 and 1.0 m and greater than 1 m depth. Subsidence rates were lowest for uncultivated sites but increased as peat depth increased, ranging from 2.6 mm/y to 7.8 mm/y. Grassland sites had significantly higher subsidence rates ranging from 3.2 mm/y to 10.9 mm/y increasing with peat depth. Subsidence rates for arable sites were higher again and ranged from 3.3 mm/y to 11.4 mm/y, depending on peat depth (peat depths greater than 1 m were not included for arable land use because of their rarity). CO_2 emissions were estimated from subsidence rates for shallow peat soils (0.3–0.7-m depth) because the contribution of primary subsidence processes was assumed to be minimal in shallow peats. Cultivated sites had the highest C emissions (6.5 tC/ha/y), followed by grasslands sites (5.6 tC/ha/y), and uncultivated sites had the lowest C emissions (2.34 tC/ha/y). It is likely carbon exports are higher for rotational crops compared to permanent grassland because a larger proportion of the photosynthetic C input is removed from the system (Elsgaard et al. 2012). Therefore, it is likely the combination of enhanced mineralisation and lower carbon inputs explain the higher C emissions from cultivated peat soils.

6.2 Nutrients and microbial activity

Nitrogen (N) and phosphorus (P) are commonly applied to pasture systems to enhance plant productivity, but they also promote soil microbial activity and decomposition of peat. Raised peat bogs are typically nutrient-poor environments where soil microbial activity can be limited by nutrient availability (Reddy et al. 2006). Therefore, application of fertilisers and large quantities of animal excreta (which also contain high C, N, and P) are likely to enhance peat decomposition (Hooijer et al. 2012) and therefore subsidence and CO_2 emissions.

In the Netherlands, Brouns et al. (2015) found that pulses of organic and inorganic fertiliser increased microbial biomass growth rates to be four times higher in agricultural peat fields compared with peat nature reserves. Later work (Brouns et al. 2016) showed the soil microbial community in agricultural fields contained more r-strategists, which react quicker to changing conditions, compared with *K*-strategists, which dominated peat nature reserves. Higher P availability may have driven these changes resulting in higher decomposition rates and consequently CO_2 emissions.

In the UK, Kechavarzi et al. (2010) collected peat soils from a wildlife conservation area subject to summer grazing (West Sedgemoor) and an intensive arable site (Methwold Fen). Samples were collected from three depths at each site, equilibrated to four moisture contents corresponding to water pressure potentials (–0.1 to –10 m) and incubated at three temperatures (10, 22, and 30°C) in a lab experiment. N was added to achieve C/N ratios of 10:1, 5:1 and 2.5:1 and CO_2 emissions measured. They found CO_2 emissions were higher from treatments with higher C/N ratios (Fig. 11) indicating N fertiliser addition increases mineralisation.

These findings suggest that excessive nutrient additions to peat soils, especially nutrient-poor raised bogs, may increase decomposition rates and consequently CO_2 emissions and subsidence. Farmers should be encouraged to adhere to nutrient budgets and potentially to select for pasture species that cope with more nutrient-poor and acidic conditions. This would likely mean a move away from ryegrass-dominated pastures to lower producing species (e.g. brown top), which will no doubt have negative implication for pasture production and potentially profit (although the two are not always intrinsically linked).

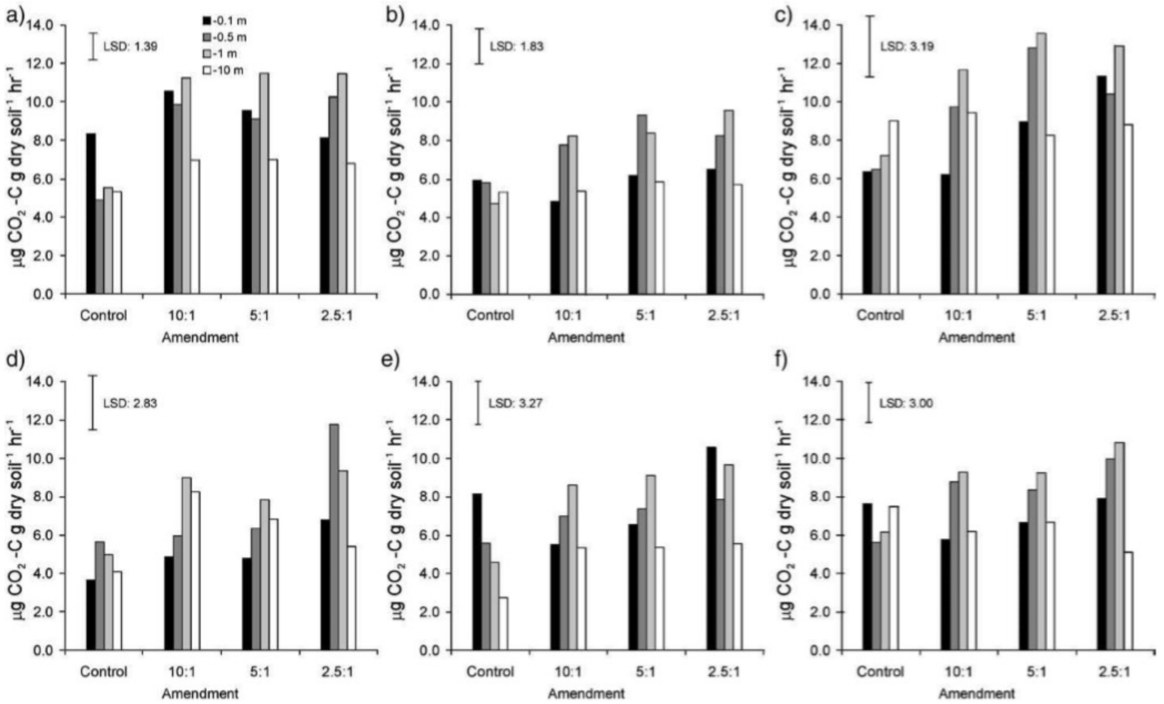


Figure 11. Effect of changing the C/N ratio on CO_2 emissions from peat soils at West Sedgemoor: a) peaty loam, b) humified peat, c) semi-fibrous peat and Methwold Fen: d) amorphous peat, e) semi-fibrous peat, f) fibrous peat at four water pressure potentials (black = –0.1 m, dark grey = –0.5 m, light grey = –1.0 m, and white = –10 m) (from Kechavarzi et al. 2010).

6.3 Pasture species selection and management

The C balance of grazed peatlands is strongly influenced by pasture growth and consequently grazing management practices can influence CO_2 emissions. Using a mobile eddy covariance system, Campbell et al. (2015) demonstrated that total respiration losses (soil and plant) were almost identical between three pasture sites with large differences in water table depths. However, large differences in net ecosystem exchange of C occurred between sites that was related to variation in photosynthetic uptake. Photosynthetic uptake was reduced for sites with deep water tables because of pasture water stress. These findings suggest that optimising water table depths may have dual benefits of increased pasture productivity and decreased CO_2 emissions.

It may be possible to select pasture species that are more productive on peat soils under wet conditions (Wichtmann et al. 2016) and hence fix more CO_2 relative to emissions. In Sweden, for example, Berglund et al. (2019) showed that both reed canary grass and tall fescue were more productive on peat soils than timothy. Dry matter yields for both reed canary grass and tall fescue increased relative to timothy each year, and the final of three years yields were 13.5 t/ha/y for tall fescue and 14.4 t/ha/y for reed canary grass compared with 11.7 t/ha/y for timothy. The calculated C capture efficiency (ratio of C in above ground biomass and roots to emitted CO_2) was 0.61 for timothy compared with 0.70 for reed canary grass and 0.71 for tall fescue. Therefore, the ratio of carbon fixed to emissions can be manipulated by optimising selection of pasture species. However, some alternative grasses may behave like weeds in the New Zealand context, threatening indigenous wetland vegetation, and these risks should be considered prior to experimenting with these types of approaches.

6.4 Surface amendments

A cover layer of mineral soil material over peat can reduce subsidence rates by limiting mineralization (van der Akker et al. 2008). Results from the Netherlands (van den Akker et al., 2008) indicate that a clay cover layer <40 cm thick reduced subsidence rates by about 6 mm/y across a range of drain water levels (Fig. 12). For grassland sites in Germany, Fell et al. (2016) found that for shallow peats between 0.3 m and 0.7 m a mineral layer of between 0.1 and 0.3 m thick reduced subsidence rates from 5 mm/y to 2.7 mm/y. However, for peat up to 1 m depth a mineral layer did not have any significant effect on subsidence, and for peats deeper than 1 m a mineral layer may have increased subsidence rates (but the sample size was small).

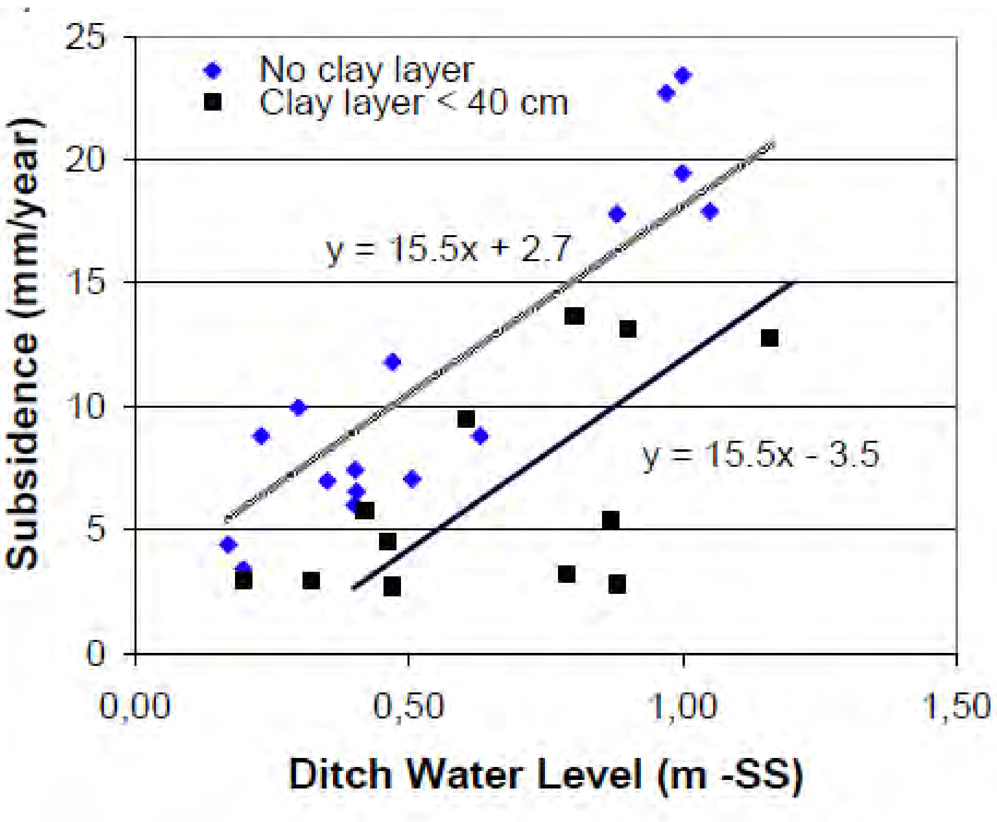


Figure 12. Relationship between drain water level and subsidence rates for sites with a clay cover layer (black squares) compared to no clay cover layer (blue diamonds) in the Netherlands (van den Akker et al. 2008).

In a laboratory study, Säurich et al. (2019) examined the effect of adding sand to peat on total GHG emissions. In topsoils no effect of adding sand was observed on emissions of any GHGs but for lower horizons sand addition increased CO_2 emissions. Their findings indicated nutrient status influenced GHG emissions more than peat type and sand additions and did not support adding sand to peats as a mitigation option to reduce GHG emissions. However, interest in this mitigation strategy is ongoing: in Sweden, as part of the PEATWISE project, a field experiment has been set up to examine the effect of mixing sand into the top 15 cm of the peat on trafficability and CO_2 emissions. No results were available at the time of writing this review but even if there is no effect on CO_2 emissions, an increase in trafficability may allow water tables to be kept closer to the surface.

For cultivated peatlands, Dessureault-Rompré et al. (2020) examined the potential of adding crop biomass amendments to mitigate CO_2 emissions from vegetable cropping systems in Montreal, Canada. Decomposition dynamics of sorghum, miscanthus, and willow were studied in the field and results were used to run a long-term simulation. Amendments of 7.5 t C/y miscanthus or 10 t C/y willow were sufficient to mitigate C loss from these cropped peat soils. In contrast, sorghum was less suited as a soil amendment because it decayed rapidly. Further work is required to examine the long-term effect on the physical and biochemical soil properties including C stabilisation and alteration of microbial communities. Crop biomass amendments are likely only suited to cropped peat soils (not common in the Waikato Region) and crop biomass needs to be harvested from within the farm boundary in a manner to avoid negative impacts elsewhere.

Table 5. Summary of studies on subsidence or CO_2 emissions from drained peatlands in relation to potential mitigation strategies related to land management

Mitigation strategy (location)	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
Cultivation (Sweden)	Intensive cropping compared to grassland and extensive land use	Subsidence rates (mm/y) Row crops: 25 Annual crops: 15 Managed grasslands: 10 Extensive: 5	CO_2 emissions (tC/ha/y) Row crops: 8.8 Annual crops: 5.2 Managed grasslands: 3.5 Extensive: 0.5	Berglund & Berglund (2008)	CO_2 emissions calculated from subsidence rates and average bulk density. Normal Swedish drainage level suggested to be 0.8 m ± 0.5 m (authors did not specify if range (± 0.5 m) was spatial or seasonal variation).
Cultivation (Germany)	Arable compared to grassland and uncultivated site	For shallow peats (0.3-0.7 m) Arable: 5.7 mm/y Grassland: 5 mm/y Uncultivated: 2.1 mm/y	CO_2 emissions (t/ha/y) Arable: 6.5 Grassland: 5.6 Uncultivated: 2.3	Fell et al. (2016)	Subsidence and C emissions reported for shallow peats between 0.3 and 0.7 m depth. The study used shallow peats because they wanted to calculate C emissions from subsidence rates where primary subsidence processes were largely absent. Subsidence rates for peats deeper than 1 m were greater than 10 mm/y.
Nutrients (Netherlands)	Hay meadow compared to native reserve	Not reported	See comments	Brouns et al. (2015)	Compared CO_2 emissions from nutrient rich meadow to nutrient poor reserve for both bog and fen peat, microbial growth 4 times higher for nutrient rich meadows.
Nutrients (UK)	West Sedgemoor: Wild-life conservation Methwold: intensive arable	Not reported	N application increased CO_2 emissions.	Kechavarzi et al. (2010)	Examined role of soil moisture, temperature and nutrient application on CO_2 emissions.
Increased productivity (linked to WT) (NZ)	Dairy grazing	Not Reported	CO_2 emissions were lower for more productive pasture.	Campbell et al. (2015)	Large differences in net ecosystem exchange of C occurred between sites that was related to variation in photosynthetic uptake. Photosynthetic uptake was reduced for sites with deep water tables as a result of pasture water stress.

Mitigation strategy (location)	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
Pasture species selection for increased productivity (Sweden)		Not Reported	Ratio of C in above ground biomass and roots to emitted CO_2 was 0.61 for timothy compared with 0.70 for reed canary grass and 0.71 for tall fescue.	Berglund et al. (2019)	Dry matter yields for both reed canary grass and tall fescue increased relative to timothy each year and in the final of 3 years yields were 13.5 t/ha/y for tall fescue and 14.4 t/ha/y for reed canary grass compared with 11.7 t/ha/y for timothy.
Surface amendments (clay layer) (Netherlands)	Pasture	Reduced subsidence by about 6 mm/y across range of drain water levels for shallow peat only	Not reported	van den Akker et al. (2008)	Clay cover layer < 40 cm thick reduced subsidence rates by about 6 mm/y across a range of ditch water levels for shallow peat only.
Surface amendments (mineral layer) (Germany)	Grassland	Mineral layer of between 0.1 and 0.3 m thick reduced subsidence rates from 5 mm/y to 2.7 mm/y for shallow peat	Not reported	Fell et al. (2016)	For peats deeper than 1 m a mineral layer may have increased subsidence rates (but the sample size was small).
Surface amendments (sand) (Germany)	Grassland soils in lab experiment	Not reported	In topsoils no effect of adding sand was observed on emissions of any GHGs but for lower horizon sand addition increased CO2 emissions.	Säurich et al. (2019)	Findings indicated nutrient status influenced GHG emissions more than peat type and sand additions and did not support adding sand to peats as a mitigation option to reduce GHG emissions.
Organic amendments (Canada)	Vegetable cropping	Not reported	7.5 t C/y miscanthus inputs required to offset C loss. 10 t C/y willow inputs required to offset C loss.	Dessureault-Rompré et al. (2020)	Decomposition dynamics of sorghum, miscanthus, and willow were studied in the field and results were used to run a long-term simulation. Results showed that amendments of miscanthus or willow were sufficient to mitigate C loss from these soils. In contrast, sorghum was less suited as a soil amendment because it decayed rapidly.

7 Factors independent of land and drainage management that control subsidence and CO_2 emissions

The following section reviews studies that investigated rates of peat subsidence and CO_2 emissions due to factors independent of land and water management. These include, peat type and organic matter content (Section 7.1), time since drainage, peat depth and subsidence partitioning (Section 7.2), and climate change and temperature (Section 7.3).These factors must be understood to implement land and water management strategies to reduce peat subsidence and CO_2 emissions. The example studies discussed below are summarised in Table 6.

7.1 Peat type and organic matter content

Peat organic matter (OM) content and the recalcitrance of the organic material will influence subsidence rates and CO_2 emissions in drained peat soils independent of management. In general, peats with lower OM content and more recalcitrant material subside slower (van der Elst 1980) and emit less CO_2 as a result of reduced decomposition rates. In the UK (East Anglia), Taft et al. (2017) measured GHG emissions from both bare and cultivated peat at sites ranging from low OM content to high. For both bare and cultivated peat, CO_2 emissions were lowest for the low organic matter content site and increased as organic matter content increased. In the US, Reddy et al. (2006) fractionated peat into labile, moderately labile, and recalcitrant fractions and showed that peat with a higher labile fraction emitted more CO_2. Reddy et al. (2006) also found the recalcitrant fraction varied between different parent vegetation types.

More humified peat typically subsides slower than more fibrous material. The higher plant fibre content is typically an indication that the material has not been drained for as long and therefore has not been exposed to aerobic decomposition for as long. Kechavarzi et al. (2010) reported that deeper more fibrous peat had higher oxidation potential than surface peats despite its more recalcitrant nature. In the UK (East Anglia), Dawson et al. (2010a) found subsidence and peat decomposition rates were higher for more fibrous and semi-fibrous peats compared to more humified layers. Areas once classified as fibrous peats had degraded more toward humified peat.

These findings have implications for management strategies to reduce subsidence. First, sites that have more recently been drained can be expected to subside faster and emit more CO_2 independent of management or land use. Second, periodic drain deepening to improve drainage, which exposes previously saturated peat layers, can be expected to enhance subsidence and CO_2 emissions. Consequently, drain deepening activity should be minimised and when necessary, carefully monitored using accurate level surveying and integrated with catchment outflow water levels and catchment drainage plans.

7.2 Time since drainage, peat depth and subsidence partitioning

As time since drainage increases, the rate of subsidence typically decreases (Fig. 13) as rapid initial shrinkage and consolidation rates decline and bulk density increases (Pronger et al. 2014). Because of this decline in shrinkage and consolidation, the relative contribution of oxidation to total subsidence increases over time despite the overall decline in subsidence rates (in the absence of further drain deepening). Data collated by Pronger (2013) (and published by Pronger et al. 2014) from temperate global peatlands demonstrated that the contribution of oxidation to total subsidence was a function of time (Fig. 14). For example, about 20 years after drainage oxidation contributed about 30% to total subsidence (Ewing & Vepraskas 2006), but in the Netherlands, 540 years after drainage, oxidation accounted for about 85% of total subsidence (Schothorst 1977). The reduction in subsidence rates over time has also been observed in the UK (Dawson et al. 2010) and in tropical peatlands in Indonesia where Wosten et al. (1997) found subsidence rates were about 130 mm/y over the first 14 years after drainage, declined to 46 mm/y between 14 and 28 years after drainage, and then declined further to 20 mm/y 28 years after drainage (Fig. 15).

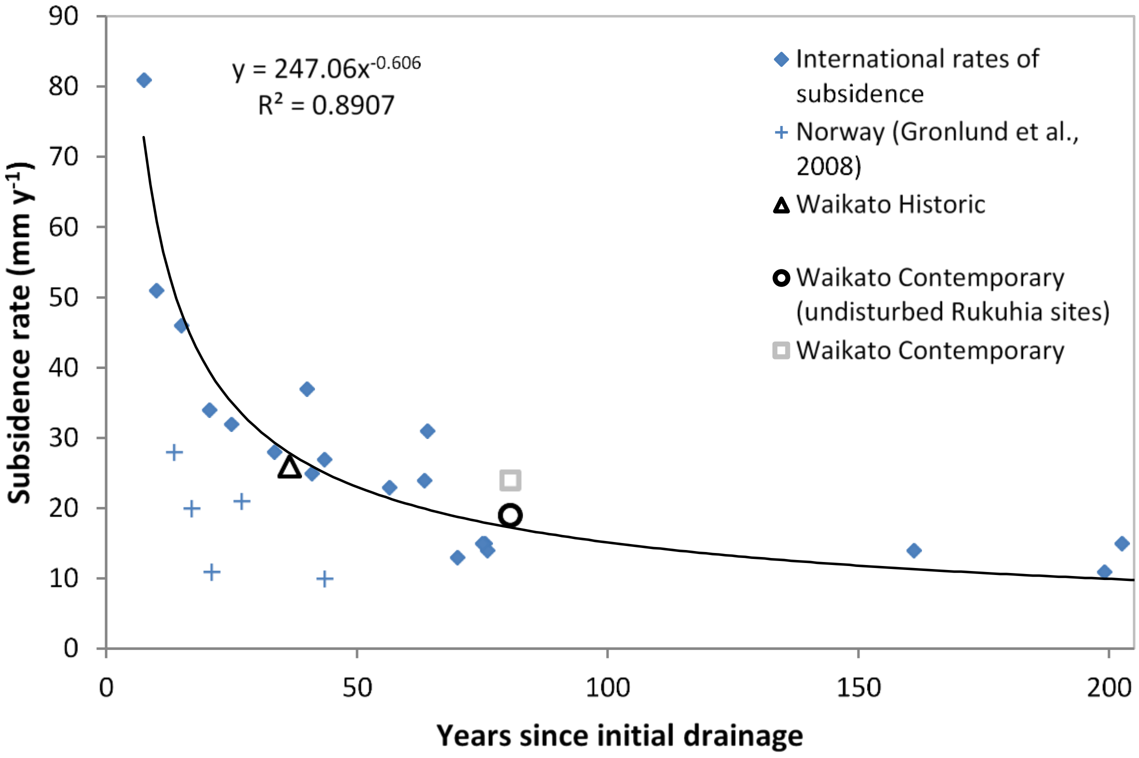


Figure 13.Relationship between subsidence rate and time since drainage with line of best fit fitted to international data and Waikato subsidence rates added to show fit with international data (best fit equation excludes data for Norway from Gronlund et al. (2008) because of the colder climate) (figure from Pronger 2013).

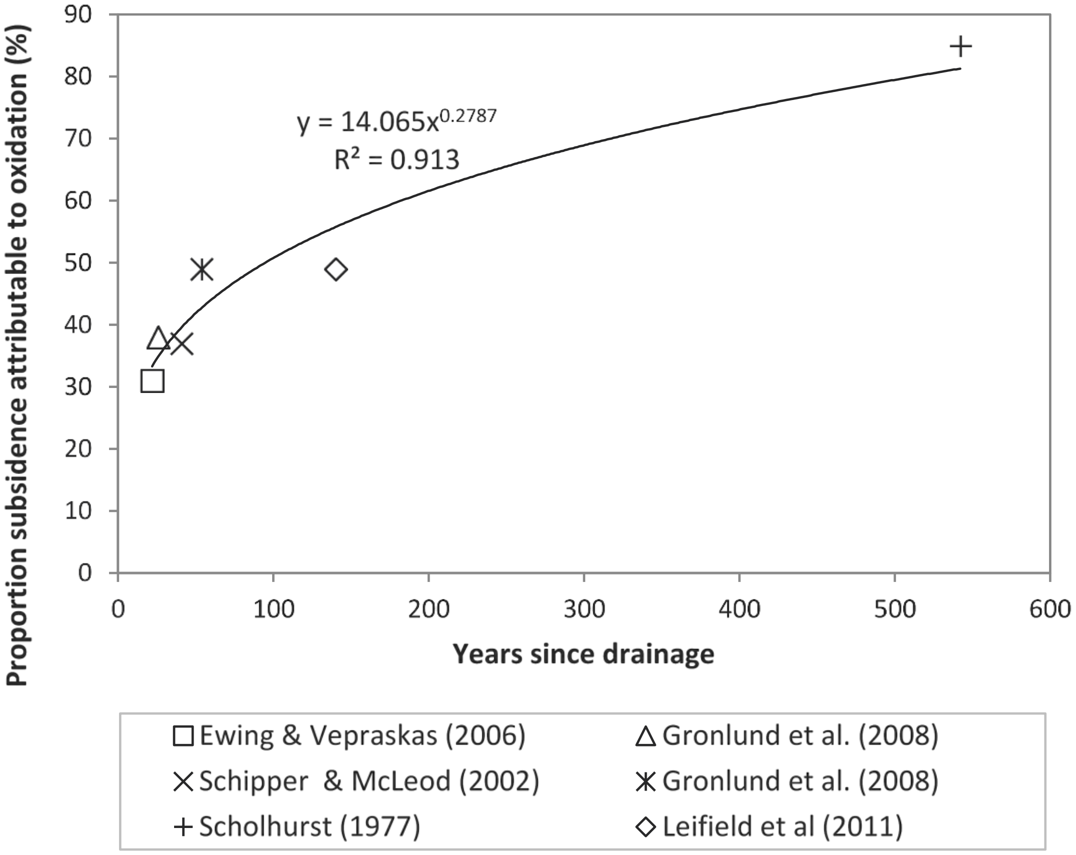


Figure 14. Relationship between proportion of subsidence attributable to oxidation and time since drainage (figure from Pronger 2013).

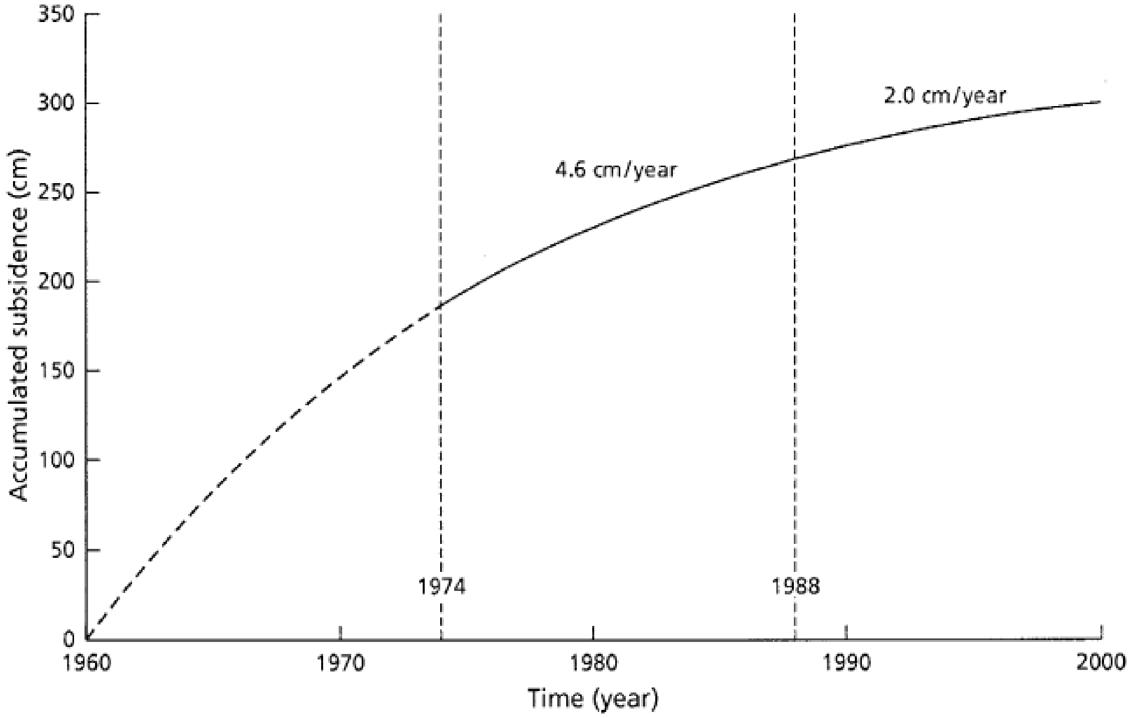


Figure 15. Relationship between time since drainage (1960) and subsidence rate for tropical peatlands in Indonesia (figure from Wosten et al. 1997).

Subsidence rates are also often lower for shallow compared with deep peat. For example, for relatively shallow peat soils in Germany, Fell et al. (2016) showed that subsidence rates were effectively nil for peats less than 0.3 m thick and increased as peat thickness increased to greater than 10 mm/y for peats thicker than 1.0 m (Fig. 16).

In the Waikato, subsidence rates were initially likely up to 200 mm/y immediately following drainage (van der Elst 1980) but declined with time and are currently about 20 mm/y (Pronger et al. 2014). Here in the Waikato, Schipper and McLeod (2002) calculated that over the first 40 years after drainage, oxidation contributed to about 37% of total subsidence (by comparing the amount of C in a peat layer above a known tephra marker bed with that in an adjacent nature reserve). It was also evident in the work of Pronger et al. (2014) that subsidence rates in the Hauraki area, which had been drained longer and included more shallow peat areas, were lower than for other more recently drained deeper peat areas in the Waikato region. Clearly, as time since drainage increases, cumulative subsidence results in less peat depth and we expect total subsidence rates to decline. This effect is independent of land use and management and must be considered as a potential confounding variable when comparing subsidence rates under different land uses or effectiveness of potential mitigation strategies.

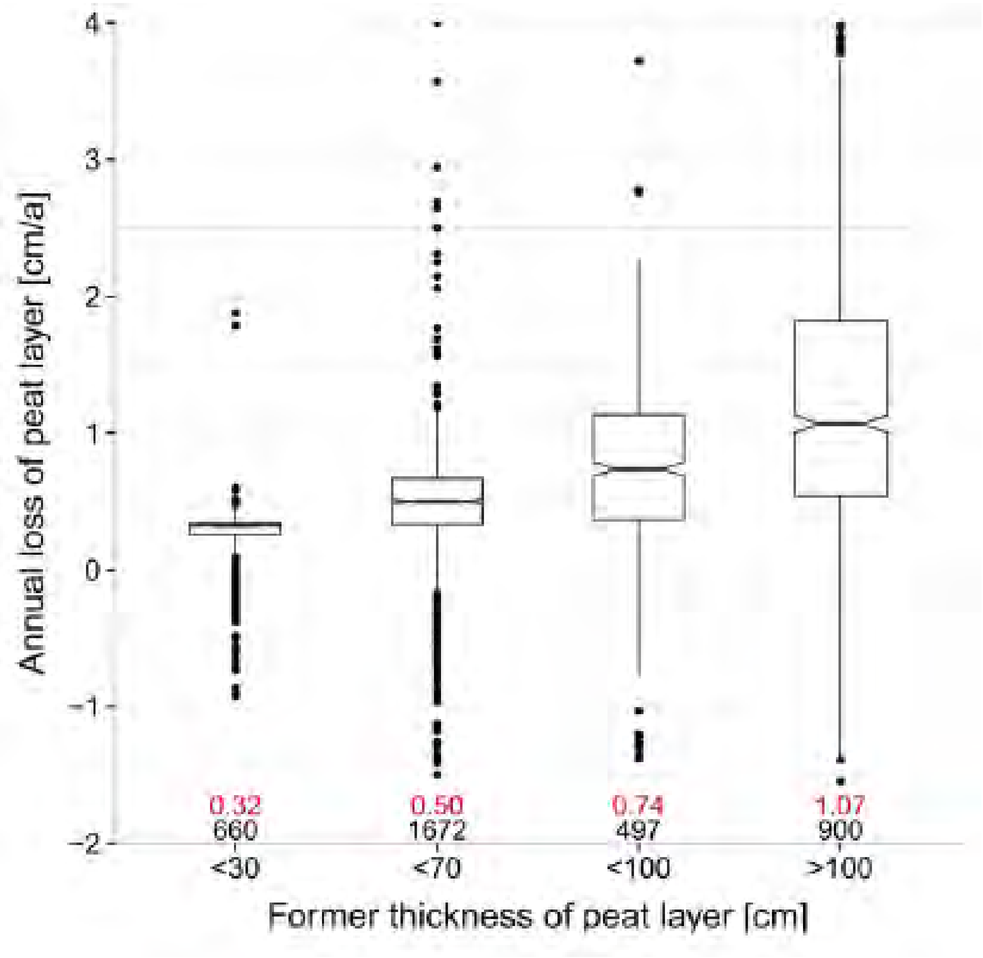


Figure 16. Subsidence rates (cm/y) for peat soils for a range of initial peat thicknesses in Germany from Fell et al. (2016). Black numbers on top of x axis are sample numbers (land use not distinguished) and red numbers are median annual subsidence rates (cm).

7.3 Climate change and temperature

Climate change is likely to result both in increases in peat soil temperature (Kløve et al. 2010), and where summer rainfall declines and drought becomes more frequent, lower groundwater levels during summer (Querner et al. 2012). Both processes are likely to increase subsidence rates and CO_2 emissions. Additionally, sea level rise will only exacerbate anticipated problems for peatlands within tidal zones (e.g. Hauraki Plains).

Several studies have shown that CO_2 emissions from peat soils increase as temperature increases (Kløve et al. 2010; Elsgaard et al. 2012) because the oxidation component of subsidence is temperature dependent. In Norway, Kløve et al. (2010) found emissions were highest when the groundwater table was low and soil temperatures were high, while in the Netherlands, Elsgaard et al. (2012) found soil temperature, rather than water table depth, was the main driver of ecosystem CO_2 emissions from peat soils. In Finland, Makiranta et al. (2009) similarly found temperature to be the dominant control on CO_2 emissions, but measured decreased temperature sensitivity with lower average water table depth.

Scenario modelling by Querner et al. (2012) for the Netherlands suggested that climate change can have large effects on subsidence rates and CO_2 emissions. Four potential climate change scenarios were tested based on existing climate change scenarios for the Netherlands. Scenarios were based on a 2°C-temperature increase and ranged from a moderate increase in summer rainfall and evaporation (both increase 3%) to a large reduction in summer rainfall (–19%) and increase in evaporation (+15%). Under the moderate scenario, subsidence increased by about 15% but under the more extreme scenario groundwater levels were predicted to reduce by about 0.15 m during summer and subsidence rates to increase by 68%. On average, relationships developed for the Netherlands between lowest summer groundwater levels and subsidence rates suggested an increase in subsidence rates of 25% for a 2°C increase in mean temperature.

In the Waikato Region, climate change may bring increased risk of drought, especially in the Hauraki district (Wang et al. 2015) with regional forecasts of the time spent in drought ranging from minimal change to more than double (MfE 2018). Regionally, it has been predicted that, relative to 1995, temperatures are likely to be between 0.7°C and 3.1°C warmer by 2090, with 10 to 60 extra days where maximum temperature exceeds 25°C, thereby contributing to increased potential evaporation. By 2090 winter rainfall is expected to increase at Rukuhia by between 4 and 8%, but spring rainfall is expected to decrease by 6% (MfE 2018). An overall consequence may be that peatland water tables become deeper more frequently during summer, leading to increased dryness and subsidence. These regional climatic changes are likely to affect both subsidence rates and CO_2 emissions from peatlands. However, predicting the impacts is difficult because of the variability in regional climate and management interactions, together with likely increases in atmospheric CO_2 concentrations. Models can be useful for disentangling the complexity and predicting the likely effects under different climate scenarios, but they include inherent uncertainty that is difficult to quantify.

Table 6. Summary of studies on subsidence or CO_2 emissions from drained peatlands in relation to non-management related factors.

Non-management effect	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
Organic matter content (UK, East Anglia)	Cropped peat compared to Bare peat	Not reported	CO_2 emissions (t/ha/y) Bare soil Low OM: 13.0 Med OM: 21.5 High OM: 26.0 Cropped soil Low OM: 19.2 Med OM: 30.9 High OM: 28.3	Taft et al. (2017)	Total GHG emissions measured for cropped and bare peat at sites with low to high organic matter content.
Peat depth (Germany)	Mix of arable, grassland and uncultivated sites	3 mm/y for peat < 300 mm deep 5 mm/y for peat < 700 mm deep 7 mm/y for peat < 1000 mm deep 11 mm/y for peat > 1000 mm deep	Not reported by depth of peat	Fell et al. (2016)	Subsidence rates for 3,729 sites across Germany for range of initial peat depths.
Time since drainage	Synthesis of temperate peat sites across globe	Decrease with time since drainage	Not reported	Pronger et al. (2014)	Strong relationship between time since drainage and subsidence rate across temperate peatlands globally, also contribution of oxidation to subsidence shown to increase with time since drainage.
Time since drainage	Tropical peatland	46 mm/y 1974–1988 20 mm/y 1988–2000	Not reported	Wosten et al. (1997)	Subsidence in Indonesian tropical peatlands decreased as time since drainage increased. Wosten et al. (1997) also showed subsidence rates were higher for tropical peatlands compared with temperate at equivalent time since drainage, suggesting temperature is also important.

Non-management effect	Current land use	Effect on subsidence	Effect on CO_2 emissions	Author	Comments
Climate Change (Zegvald, Netherlands)	Dairy farming	2°C increase in temp for range of rainfall and evaporation scenarios increased subsidence rates by 15–68% with mean increase about 25%	Not reported	Querner et al. (2012)	Modelling effect of range of climate change scenarios on subsidence rates.
Climate Change (Finland)	Forested (four out of six sites were previously agricultural before afforestation)	Not reported	Temperature main control of CO2 emissions, but optimum WTD (60 cm)	Mäkiranta et al. (2009)	CO_2 emissions increased until WTD 60 cm, and further drop in WTD decreased CO_2 (surface dryness). Average WTD affected temperature sensitivity of CO_2 emissions. Concluded that warmer climate will only increase CO_2 emissions if the decrease in moisture content of surface peat is minor.
Soil Temperature (Netherlands)	Eight sites including permanent grassland and range of arable sites	Not reported	Soil temperature, as opposed to water table depth, was the main driver of CO_2 emissions.	Elsgaard et al. (2012)	Annual estimates of net ecosystem exchange of CO_2 and carbon balance made using flux chamber technique and modelling of ecosystem respiration and gross primary production.
Soil Temperature (Norway)	Natural compared with annual grass and ley	Not studied but long-term subsidence rates in Norway suggested to be about 2 cm/y	Highest emissions when water table deep and temperatures high	Kløve et al. (2010)	Compared natural peatland to ryegrass pasture site, surface graded site, and abandoned cultivated site. Emissions of CO_2 and N_2O depend on temperature, groundwater table and nutrients in groundwater.

8 Decision support tools

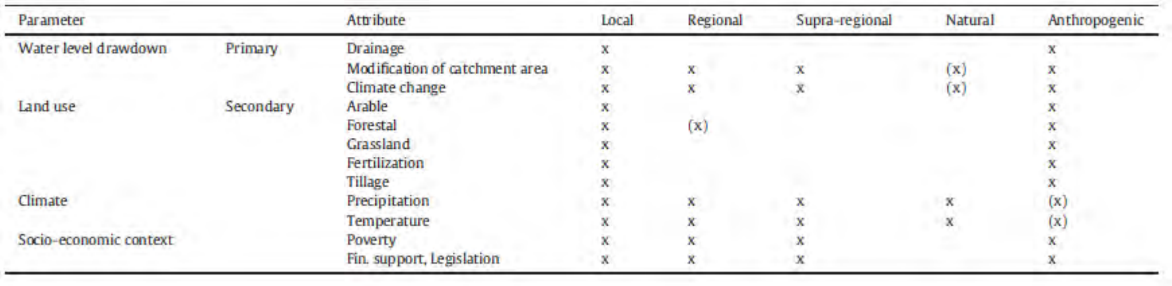
8.1 Vulnerability index

Making decisions on where to focus limited resources for mitigation efforts should consider physical vulnerability to CO_2 loss and subsidence and socio-economic vulnerability of landowners and communities. For example, Fell et al. (2016) developed an index of vulnerability for peatland C loss in Germany that considers primary and secondary stressors (Table 7). For their index, the primary factor driving vulnerability to C loss was the water table regime, which must remain high for peatland development and persistence. Primary stressors were therefore those affecting the regime, including drainage, modification of the catchment area, and climate change. Secondary stressors were those that apply to an already disturbed system and impact the magnitude of C loss. These include land use and land use intensity, climate and socio-economic factors that affect the water level and microbial activity (Fell et al. 2016). The index first considered the possible annual rate of C loss together with the total C stock (Ci). This initial factor is then multiplied by a land use and land use intensity factor (Lf), an underlying substratum factor (Uf) and a mineral cover factor (Mf):

$$Vi = Ci * Lf * Uf * Mf$$

The vulnerability of peatlands must also be viewed in a socio-economic context because poverty and financial stressors may result in practices that are not sustainable. In countries with public subsidies for agriculture and forestry sustainability protection these pressures are reduced (Fell et al. 2016). However, where public subsidies are absent, uptake of management practices that are expensive or do not have other aligned production benefits may be limited. Given the underlying preference for a free market in NZ, sustainable management of peatlands is challenging, and policy incentives or intervention may need to be considered (see Section 8.3)

Table 7.Primary and secondary stress factors used by Fell et al. (2016) to develop and carbon loss vulnerability index for peatlands in Germany.



Parameter		Attribute	Local	Regional	Supra-regional	Natural	Anthropogenic
Water level drawdown	Primary	Drainage	x				x
		Modification of catchment area	x	x	x	(x)	x
		Climate change	x	x	x	(x)	x
Land use	Secondary	Arable	x				x
		Forestal	x	(x)			x
		Grassland	x				x
		Fertilization	x				x
		Tillage	x				x
Climate		Precipitation	x	x	x	x	(x)
		Temperature	x	x	x	x	(x)
Socio-economic context		Poverty	x	x	x		x
		Fin. support, Legislation	x	x	x		x

8.2 Decision support models

Making decisions where complex trade-offs are involved requires robust information and transparent approaches that can be communicated to stakeholders. The development of decision support models (e.g. Knieß et al. 2010) will likely be an important component of development of management practices to reduce subsidence. A range of models are currently developed for examining the effect of changes in peat management on broader scale hydrology and farm economics. de Vos et al. (2006) developed the Waterpas model, which links several sub-models to simulate dairy farm management, hydrological conditions and pasture growth so that relationships between hydrology and farmer income can be determined. Based on a farm-scale case study in The Netherlands, de Vos et al. (2006) showed that raising the water table from 0.6 to 0.4 m may result in a decrease in pasture production and consequently a reduction in farmer profit. More recently, de Vos et al. (2010) upscaled from farm to catchment scale using the Zegvald Polder as a case study where scenarios for a 0.1, 0.2 and 0.3 m raising of the water table from the reference situation (0.6 m depth) was modelled (see Fig. 17). Costs to farmers increased as the water table depth reduced because of decreased pasture production and the need to buy in additional feed. However, Dutch farmers who take steps toward supporting nature conservation can get financial compensation. de Vos et al. (2010) also point out that for full environmental evaluation, the effect of hydrological changes on nutrient losses to surface and groundwater and GHG and ammonia emissions should be included.

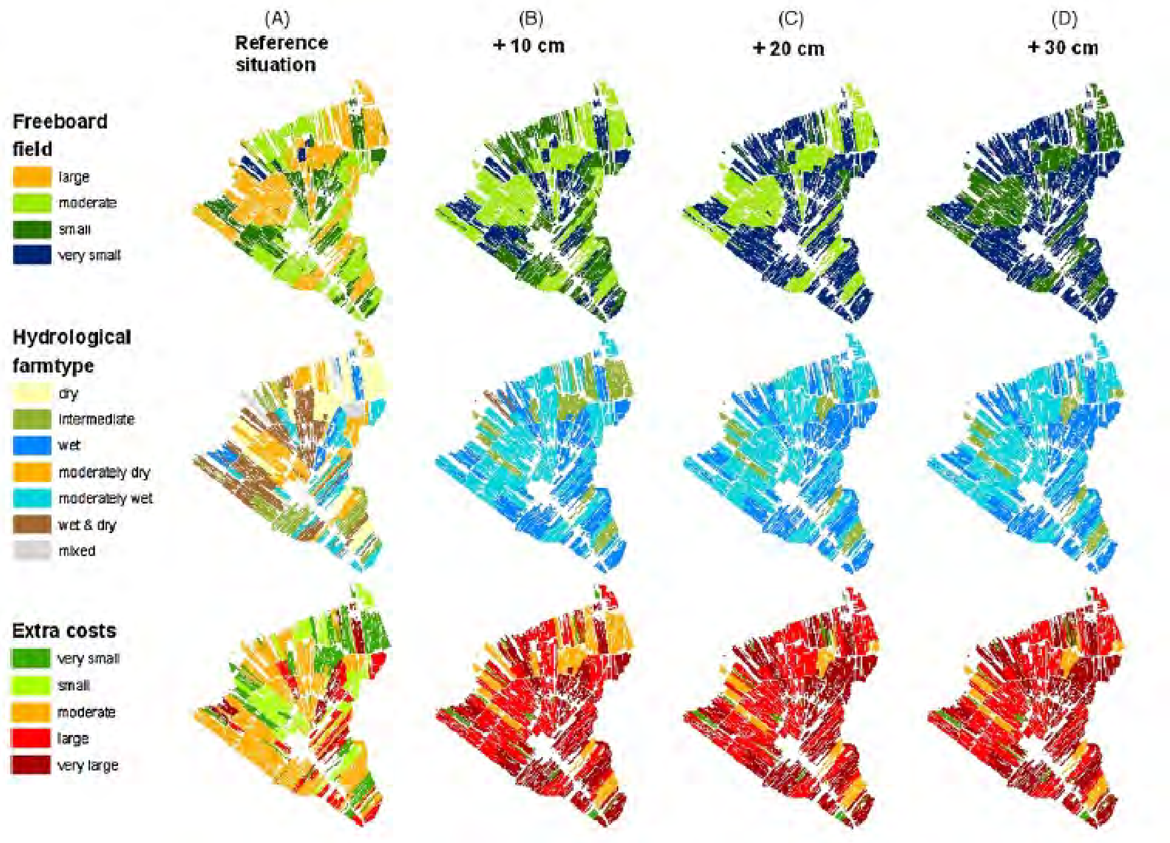


Figure 17. Average freeboard for a modelled catchment where the reference situation (A) was compared to a range of increases in water table level (+10 cm, +20 cm, +30 cm) and the effect on hydrological farm type and additional costs compared to the reference situation (from de Vos et al. 2010).

8.3 Policy interventions to promote sustainable use of organic soils

Recognising that short-term economic gains are often prioritised over environmental impacts, there is likely a need for policy intervention to promote sustainable use of organic soils and incentivise farmers to make management changes. A review on sustainable drained peatland management in Switzerland by Ferré et al. (2019) concluded that the main challenges for adopting change were current land use profitability and the difficulty of integrating new management practices that reduce subsidence and CO_2 emissions, particularly in smaller farming operations. Similarly, in Ireland, Renou-Wilson et al. (2014) noted that a government-led approach would be required to implement reductions in grazing regimes for promotion of C uptake, as well as maintaining higher water tables. To develop improved management practices for Nordic organic soils, Kløve et al. (2017) recommended a collaboration between landowners, farmers, and regional decision-makers, and any decisions or plans to consider socio-economic benefits and drawbacks, as well as short- and long-term environmental impacts. Similar challenges to widespread adoption of management approaches may emerge in the Waikato Region, especially where agricultural productivity is compromised to achieve environmental benefits, and so a top-down approach may have to be considered.

9 Conclusions

Management approaches to reduce peat subsidence and CO_2 emissions have been reviewed and are summarised in Table 8. Several studies have reported reductions in both subsidence rates and CO_2 emissions when the water table is kept closer to the surface. Maintaining a water table as high as 0.25 m depth has been promoted by some (e.g. Renou-Wilson et al. 2016). However, such shallow water tables challenge intensive land use by reducing trafficability, productivity, and profitability (de Vos et al. 2010) and could increase CH_4 and N_2O emissions. A water table depth of about 0.5 m is anecdotally favoured by NZ peat farmers. It is also challenging to maintain water tables at the desired depth to avoid excessive wetness in winter and dryness in summer. In summer when evaporative water loss is high it is common for paddock boundary and main farm drains to be dry and therefore having little impact on peat water content and blocking drains would be ineffective. Reddy et al. (2006) demonstrated that capillarity can maintain anaerobic conditions in peat above the water table, and emerging research in the Waikato indicates the saturated zone may extend well above the water table (Glover-Clark, 2020). This suggests that manipulating drainage depths and water outflow levels is only one component of a much more complex strategy required to maintain peat water content.

Peat soil water management is likely best approached as a water balance issue where water inputs (precipitation and irrigation totals and seasonality), losses (horizontal and vertical drainage, evaporation), and rate limiting factors (e.g. hydraulic conductivity, energy availability, plant stomatal control) all contribute to the volumetric water content of the peat that influences subsidence processes. Approaches to increase peat moisture content through frequent flooding or subsurface irrigation or reduce evaporative water loss (e.g. increased plant transpiration efficiency) could be investigated alongside improved drainage management. Research in The Netherlands appears to show significant reductions in subsidence with subsurface irrigation techniques (van den Akker et al. 2012) and such approaches could also result in increased pasture growth that would likely reduce CO_2 emissions and boost productivity and thereby motivate farmers to adopt. However, while water can be recycled within the catchment to some extent, during dry periods a large and reliable external water supply would be required. Consequently, subsurface irrigation may only be relevant to low-lying organic soils in the lower Waikato and Hauraki zones where large rivers are nearby.

In addition to water balance management there are some land management options that may reduce subsidence and CO_2 emissions. Cropping (e.g. maize) should be avoided where possible on peat soils because frequent cultivation of peat soils accelerates mineralisation (Berglund & Berglund 2008). However, in addition to cropping, frequent cultivation has been necessary to incorporate lime into peat soils to manage soil acidity. This may be mitigated by the adoption of injection of lime down to 0.4 m without the need for deep cultivation. The potential for this approach to reduce subsidence and CO_2 emissions deserves further investigation and may allow no till pasture renewal. There is also some evidence that subsidence and CO_2 emissions can be mitigated by reducing nutrient inputs to reduce microbial oxidation (Brouns et al. 2016). However, reducing nutrient inputs will likely reduce pasture growth affecting productivity and potentially increasing CO_2 emissions through reduced productivity (e.g. Campbell et al. 2015).

There is still considerable uncertainty about the magnitude of reductions in subsidence and CO_2 emissions that could be gained by implementing any, or a combination of, the management approaches reviewed, and further experimental research is required to investigate the potential of these management practices to achieve desired outcomes (see Section 10). It is likely that a combination of several management practices will be needed to achieve the desired reductions in subsidence and CO_2 emissions. The mix of suitable approaches could be expected to vary spatially, depending on localised environmental conditions and existing land use and management practices. All mitigation options have potential environmental and economic trade-offs, and these should be considered when prioritizing options to pursue. Making decisions where complex trade-offs are involved requires robust information with a strong scientific underpinning. The development of vulnerability index and decision support models (e.g. Knieß et al. 2010) will likely be an important component for selection and implementation of management practices to reduce peat subsidence and CO_2 emissions. Ultimately, policy incentives or intervention may also be required to encourage uptake of desirable mitigation options.

Finally, it is important to acknowledge that the decisions to drain Waikato’s peatlands were made by previous generations, and the present-day farmers and landowners have inherited that legacy. Improved education and awareness of the adverse effects of continued agricultural use are critical if the necessary improvements are to be adopted by these present-day stakeholders. While this review focused on potential management practices that could be used under existing land use, future work is also required to consider potential reductions in subsidence and CO_2 emissions that may be achieved by changing land use and the social, cultural, and economic consequences of land use change.

Table 8. Summary of management practices reviewed with implications for subsidence rates and CO_2 emissions (NR = not reported)

Management practice	Study	Outcome for subsidence rates	Outcome for CO_2 emissions	Summary
Maintaining the water table closer to the surface	Schothorst (1977)	Reduction	NR	Water table depths of 0.5 m are common but potentially these could be as high as 0.25 m depth (e.g. Renou-Wilson et al. 2016) but trafficability and productivity may decrease (de Vos et al. 2010) and N_2O and CH_4 emissions could increase. Additionally, it is difficult to maintain high water tables in summer
	van den Akker et al. (2012)	Reduction	NR	
	Renou-Wilson et al. (2016)	NR	Reduction	
	Klove et al. (2010)	NR	Reduction	
	Berglund & Berglund (2011)	NR	Increase	
	Wessolek et al. (2002)	NR	Reduction	
	Wosten et al. (1997)	Reduction	Reduction	
	Renger et al. (2002)	Reduction	Reduction	
Frequent flooding	Reddy et al. (2006)	Reduction	Reduction	This mitigation is more suited to alternative crops (e.g. rice) as opposed to permanent grassland
	Deverel et al. (2016)	Reduction	NR	
Subsurface irrigation	van den Akker et al. (2012)	Reduction	NR	No studies include effect on CO_2. A suitable water source is likely to be problematic during dry periods and the practice may increase N_2O and CH_4 emissions
	Dawson et al. (2010)	Reduction	NR	
Reduce nutrient input	Kechavarzi et al. (2010)	NR	Reduction	Reducing nutrient input may reduce CO_2 emissions and potentially subsidence but likely to affect pasture productivity
Change crop/pasture type	Deverel et al. (2016)	Reduction	NR	Increasing photosynthetic performance may reduce CO_2 emissions
	Berglund et al. (2019)	NR	Reduction	
Reduce cultivation	Berglund & Berglund (2008)	Reduction	Reduction	Stop or minimise cultivation by avoiding cropping and explore potential benefits of new technologies (e.g. lime injection and no-till pasture renewal)
	Fell et al. (2016)	Reduction	Reduction	
Surface amendment (clay, sand, organic matter)	van den Akker et al. (2008)	Reduction	NR	Mixed results; may decrease subsidence for shallow peats but could increase subsidence for deeper peats
	Fell et al. (2016)	Reduction/Increase	NR	
	Dessureault-Rompré et al. (2020)	NR	Maintain organic C	

10 Recommendations

To reduce peat subsidence and CO_2 emissions from drained peatlands in the Waikato Region we recommend a sequence of steps (Fig. 18) implemented in the following order:

1. Develop a spatial vulnerability index to identify locations and timescales where the most severe consequences are likely to occur and use this to prioritise resources and research.
2. Test a range of potential mitigation strategies that include priority water management, land management and land use strategies. Management strategies shown in Figure 18 (Step 2) have been numbered to indicate the order in which we suggest these should be investigated. Additionally, these options should be revisited following development of a vulnerability index and when results and recommendations for the PEATWISE Project are released.
3. Combine knowledge gained from experimental testing of mitigation strategies with modelling of catchment hydrology to develop a spatially appropriate management decision support tool to provide guidance for drainage and land managers to select the mix of appropriate mitigation approaches.
4. Update good practice guidelines and, if necessary, develop policy incentives or interventions to encourage uptake of management strategies and decision support tools.

In each of these steps, the socio-economic consequences of any decisions and recommendations need to be considered, including the regional- and farm-scale cost benefit of change compared with inaction. In the following sections we expand on the steps shown in Figure 18 and identify knowledge gaps that may limit implementation and resources required to achieve each step.

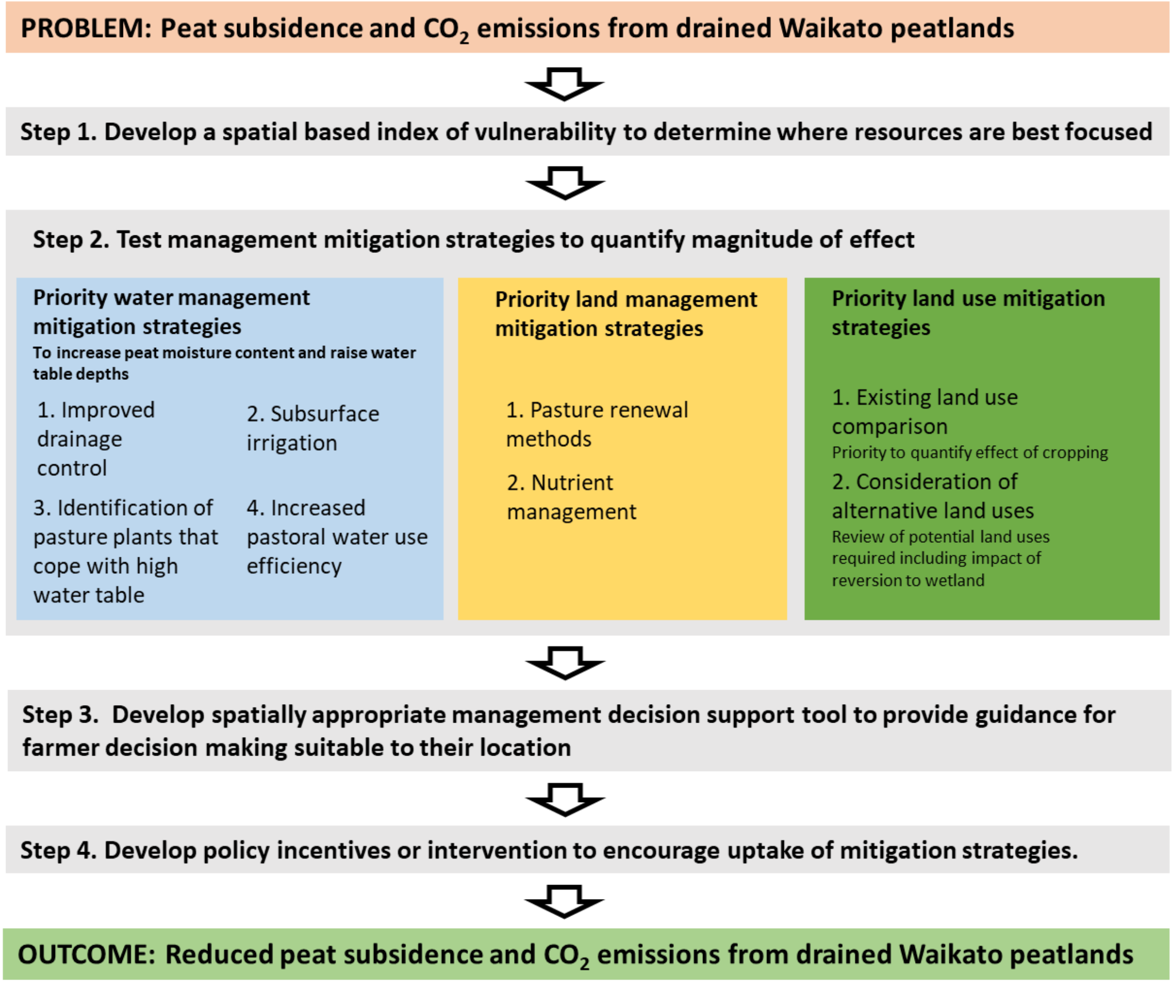


Figure 18. Approach to reduce subsidence and CO_2 emissions from Waikato peatlands.

10.1 Step 1. Develop a spatially based index of vulnerability

A vulnerability index will help identify where the most severe consequences of peat subsidence and CO_2 emissions will occur and, based on this, prioritisation of resources and research. The index should include physical factors that affect vulnerability to subsidence and CO_2 emissions (e.g. peat depth, organic matter content and recalcitrance, time since drainage), elevation with respect to river and sea level, and the impacts of continued peat loss on adjacent reserves and peat lakes. It should also include the changing impact of some factors overtime, for example sea level rise and continued subsidence. Additionally, the social, cultural, and economic vulnerability of stakeholders must be considered. Factors could be weighted before being combined to calculate a spatial vulnerability index.

Knowledge gaps:

- A clear understanding of the consequences of peat subsidence and CO_2 emissions and a ranking of their importance. A workshop with stakeholders is likely a good starting point identify consequences and rank their importance.
- A current regional peat depth layer. This can probably be modelled from Daveron (1978) data, and preliminary peat depth re-probing could be incorporated as part of the regional peat subsidence monitoring programme.

- Elevation data for regional peatlands. This could be informed by lidar measurements as part of the regional peat subsidence monitoring programme and these data could be combined with existing regional scale lidar data held by WRC.
- Regional variation in organic matter content. Time since drainage and peat forming vegetation type could be used as proxies for recalcitrance of organic matter. Time since drainage is known for some peatland areas from examination of historic photography and land development maps and this work could be extended. Local knowledge could also be used to fill in gaps, as could soil survey information. Further insight into stratigraphy of each bog may be gleaned from stratigraphy contained in Daveron (1978) and more recent localised stratigraphy done by Joss Ratcliffe (S. Lambie, Manaaki Whenua – Landcare Research, pers. comm.).

Resources required:

- Spatial modelling expertise.
- Environmental, social, cultural, historical, and economic expertise.
- Combine all existing sources of regional lidar in addition to new sources (e.g. Provincial Growth Fund lidar).
- Historical imagery.

10.2 Step 2. Testing of mitigation strategies

Mitigation strategies to reduce peat subsidence and CO_2 emissions identified in this review need experimental testing in the Waikato region. Here, potential mitigation strategies have been divided into priority water and priority land management strategies. We also suggest it is important to compare existing land uses to quantify the impact of continuous maize cropping on peat subsidence and to highlight that in the future alternative land uses will need to be considered. Within each research area (Fig. 18, step 2) we have suggested recommendations in order of priority based on our current understanding, but this may change following the development of the index of vulnerability.

Experiments detailed below require the effects on both subsidence and CO_2 emissions to be measured. Subsidence rates, peat surface oscillation, and water table depths can be measured continuously at multiple point locations using paired pressure transducers or by repeat measurement over larger spatial scales using surface survey approaches, ground based or airborne lidar (potentially from a drone). CO_2 exchange measurements (respiration, photosynthesis) can be measured at paddock scale using eddy covariance or at plot scale using replicated auto chambers. Equipment to measure CO_2 exchange continuously is expensive (eddy covariance and automated chambers) and requires significant ongoing technical expertise to monitor sites and maintain equipment.

10.2.1 Priority water management strategies to reduce subsidence and CO_2 emissions

1 Water table manipulation through drainage management optimisation

There is a strong consensus that decreasing depth to the water table will reduce subsidence rates and possibly CO_2 emissions. However, maintaining the water table at a specific level is challenging and manipulation of drainage outflow depth may not affect water table levels and peat moisture content during dry periods. Furthermore, decreasing the depth to the water table may increase CH_4 (especially if water tables are at or very near the surface) and N_2O emissions. We recommend establishing paddock-scale experiments at multiple locations, across different drainage management approaches and scales and manipulating drain and water table depths while monitoring subsidence and CO_2 emissions continuously over multiple years.

Knowledge gaps:

- There is a need to better understand regional water table regimes in the Waikato Region. This could be addressed by implementing a network of continuous monitoring sites and developing metrics that could be used to characterise water table regimes more quantitatively.
- Is it practical to manage water table depths at catchment and farm scale and what information is needed to do this? A first step in scoping the feasibility of managing for shallower water table regimes should be a water balance desktop study utilising currently available datasets. Maintaining a shallower water table in summer means offsetting losses caused by the imbalance between rainfall and evaporation. Existing measurements of these water balance components could be used to estimate the volumes of water that would be required to maintain shallower water tables.
- The experiment will help us understand the practical limitations for controlling water table depth at multiple scales. The development of drainage management decision support tools for both drainage and land managers would ultimately be used as a guide towards the optimisation of drainage to reduce peat subsidence and CO_2 emissions.
- What role could other mitigation options play? For example, sub-surface irrigation, more water-efficient pasture plants, pasture plants that cope with higher water tables. More information could be available through the European PEATWISE project which is testing subsurface irrigation techniques.
- What is the optimum water table level for pasture plants and which plants perform comparatively better at higher water table levels?
- What are the trade-offs of increased water tables?
    - What is the likely effect on pasture productivity and trafficability?
    - What is the effect on other GHGs (e.g. methane and nitrous oxide)? Research in this area would require full GHG quantification.
- Can changing the farm system help manage some of the negative consequences of raising water tables. For example, cut and carry systems compared with traditional paddock grazing.

Resources required:

- A desktop study using presently available data sets to examine the feasibility of managing for shallower water tables.
- A network of water table monitoring sites, using pressure transducers.

- Engineering solutions to manage water levels in catchments and drain outflows
- Farmers prepared to participate in experimental work.
- Equipment to monitor subsidence and GHG emissions continuously.
- Spatial mapping of underlying mineralogy to identify areas where peat is underlain by clay layers to aid control of water tables (limits vertical water flow).

2 Subsurface irrigation and drainage

Subsurface irrigation and drainage can be used to keep peat wetter in summer and improve drainage during winter, which may be attractive for farmers to improve both summer pasture production and winter trafficability. Despite the potential for this technique to reduce both CO_2 emissions and subsidence, there are potential barriers and trade-offs. These include the limited availability of water, especially during dry summer periods, the cost of construction and maintenance of infrastructure and the cost of pumping water. Additionally, there will likely be GHG trade-offs where reductions in CO_2 emissions may come at the expense of increased emissions of N_2O and/or CH_4. We recommend setting up paddock-scale experiments at multiple locations over successive years to test the effectiveness and economic impacts of subsurface irrigation.

Knowledge gaps:

- Improved information on the amount of water required for subsurface irrigation and drainage and availability of water during dry periods. This would require collating information on peatland water balances and external water sources and potential for extraction across a range of climatic scenarios. Existing river flow and regional drainage information may be supported by additional targeted data collection in combination with scenario modelling.
- More detailed information on existing subsurface irrigation and drainage approaches trialled overseas, including detail on subsurface drainage design and pumping. This information may be obtained by contacting researchers and organisations involved in past and current subsurface irrigation trials in the Netherlands (e.g. PEATWISE).
- Improved information on the cost of infrastructure and pumping which could be estimated by a suitably experienced drainage and irrigation specialist.

Resources required:

- Subsurface drainage and pumping infrastructure and expertise.
- Equipment to monitor subsidence and GHG emissions continuously.

3 Identification of pasture species tolerant of high-water tables

Plant roots require oxygen to function and consequently wet soils are drained to increase productivity (McLaren & Cameron 1996). Currently there is a dearth of information on pasture species that can tolerate high-water tables and consequently this has not been reviewed in this report. However, given the likely benefits of maintaining high water tables in peatlands to reduce subsidence and CO_2 emissions, pasture species (or other types of plants) that can tolerate wet conditions should be identified together with production trade-offs. Research could be done in barrel lysimeters where water tables can be set at a range of specified depths (between about 0.6 and 0.2 m of the surface). The experiment should include fibric, humic and mesic Organic Soil Groups.

Knowledge gaps:

- What crops are suitable in peat soils with a shallow water table?
    - Farmers may be able to provide suggestions on plant species that typically cope better in wetter conditions, and tolerable water table depths for common pasture species.
    - A pasture plant physiologist or wetland ecologist maybe able to guide species to trial.
    - Review of rooting preferences of range of possible plants including grasses, herbs and legumes (e.g. https://extension.psu.edu/trees-shrubs-and-groundcovers-tolerant-of-wet-sites).

Resources required:

- Collaboration with a plant physiologist with experience in grazed pasture and/or wetland systems.
- Lysimeters designed to control water table depth and facility to run lysimeters.
- Sites to collect peat soils for lysimeters

4 Identification of pasture species that are more water efficient

Evaporation of water through plant transpiration and directly from the soil surface is a large component of the water balance output from a grazed peatland that could be reduced by optimising plant species selection. For example, plant species that are productive and palatable and more efficiently use water during critical time periods such as chicory in spring (Pronger et al. 2019). Water use efficiency of a range of pasture plants at different water table depths could be measured using barrel lysimeters. Weighing lysimeters may be required to provide higher frequency data. Instrumentation with soil moisture probes would also be informative. Leaf water use efficiency could also be measured using carbon isotope discrimination approaches (this can be very cost effective depending on the approach). The contribution of soil water evaporation from different species and mixtures will also need to be quantified and separated from leaf transpiration.

Knowledge gaps and resources required:

- Improved knowledge of production and water use of a range of pasture grasses, herbs and legumes on peat soils. Plant transpiration and the contribution of soil water evaporation from different species and mixtures will need to be quantified and would likely require a multiyear experiment at several sites across the region.

Resources required:

- Collaboration with a plant physiologist with experience in grazed pasture systems and water use efficiency.
- Lysimeters designed to control water table depth and facility to run lysimeters.
- Site to collect peat soil groups.
- Align with water table depth tolerance work (see number 3 above).

10.2.2 Priority land management strategies to reduce subsidence and CO_2 emissions

5 Quantify effect of pasture renewal methods on subsidence and CO_2 emissions

Pastures are often renewed on a 5–10-year rotation because productivity typically declines as subsidence continues and pasture roots are exposed to more acidic conditions lower in the peat soil profile. Farmers often include a crop rotation during pasture renewal where the old pasture is killed with herbicide, fields are ploughed, lime is worked into depth and then a crop is sown (common crops include maize, rape, fodder beet). Following harvest, ploughing may occur again or spray and direct drill of pasture if further lime is not required. Lime injection to depth may negate the need for regular pasture renewal. The effect of this new technology on subsidence, CO_2 emissions, and pasture productivity needs to be quantified. Treatments should include lime injection into existing pasture (no pasture renewal), lime injection and direct drill pasture renewal and pasture renewal with deep ploughing. We recommend experiments are set up at several locations.

Knowledge gaps:

- Approaches and sequences of cultivation, liming and sowing being used by peatland farmers.
- What are the range of crops and crop systems used?

Resources required:

- Workshop with farmers to fill knowledge gaps.
- Equipment to measure subsidence continuously at several points and spatially on occasion.
- Equipment to measure carbon exchange continuously at paddock and plot scale.

6 Nutrient budgets and selection of pasture species for nutrient-poor and acidic peat soils

N and P are commonly applied to pasture systems to enhance plant productivity but also act to promote soil microbial activity and thereby decomposition of peat (Kechavarzi et al. 2010). Careful use of nutrients may reduce subsidence and CO_2 emissions but research to quantify the magnitude of the effect is required.

Knowledge gaps:

- What fertilisers are commonly applied by peat farmers and at what rates? How do typical application rates compare to good practise for reducing nutrient losses and optimal pasture production on peat soils?
- If nutrient application were reduced, what would the impact on productivity be? This would require examination of peatland agronomic literature and likely some research trials.
- Liming may stimulate microbial activity in peatlands but requires assessment.

Resources required:

- Workshop with farmers to fill knowledge gaps or work closely with dairy NZ farm advisors.
- Review of peatland agronomic literature and research trials to determine fertiliser and lime requirements.
- Equipment to measure subsidence continuously at several points and spatially on occasion.
- Equipment to measure CO_2 exchange continuously at paddock and plot scale.

10.2.3 Priority land use strategies to reduce subsidence and CO_2 emissions

7 Quantify effect of current land uses on peat soil subsidence and CO_2 emissions

Land use on Waikato peatlands is mostly pasture grazing for dairy cattle; however, other land uses, including continuous cropping, blueberry orchards, and drystock grazing, also occur on a smaller scale. Cultivation of peat soils associated with cropping likely accelerates peat subsidence and CO_2 emissions by enhancing the rate of oxidation (Fell et al. 2016). On grazed peat soils in the Waikato a cropping rotation often occurs with pasture renewal (maize, rape, fodder beet). We recommend implementing paired monitoring sites to examine the long-term effect of different land uses on peat subsidence. Of most interest would be the comparison of an intensity spectrum (e.g. blueberry orchards, continuous grazing, and continuous maize cropping). Rotational cropping as part of the pasture renewal process would also be of interest but due to the transient nature of these activities careful consideration would have to be given to experimental design. Findings could be integrated into management decision support tools. This work should be aligned with examination of pasture renewal methods (number 5 above).

Knowledge gaps:

- Effect of different cultivation techniques and pasture renewal methods.
- Overall effect of different land use practises on peat subsidence and CO_2 emissions.

Resources required:

- Up-to-date land use information; Agribase is currently the best source of information. In the future information from farm environment plans may also be useful, if available and representative.
- A network of paired pressure transducers and associated infrastructure to monitor water tables, peat surface oscillation and subsidence rates.

8 Consideration of alternative land uses

This review has focused on water and land management strategies to reduce peatland subsidence. However, under continued drainage these will at best only slow the rate of subsidence and CO_2 emissions. The effect of changing land use should also be examined. A range of alternative land uses could be considered including expansion of blueberry production, which may reduce subsidence relative to pastoral land use (Fitzgerald et al. 2005), paludiculture, and reversion of some areas to natural water regimes and vegetation. Such options require community and stakeholder engagement along with further science led research and consideration of the wider environmental, social-economic and cultural impacts. We recommend a standalone review is carried out to examine the range of potential options and such a review should include consideration of these wider agronomic and socio-economic impacts.

10.3 Step 3. Development of spatial catchment-scale management decision support tools

A spatially based management decision support tool will be required to facilitate regional authorities, farmers and consultants to assess scenarios based on anticipated management interventions. This model should include catchment modelling of water tables and expected response to antecedent weather condition and finer control of water tables by drainage control structures and link to changes in rainfall and evaporation associated with climate change. The model could initially be informed by international research on the effectiveness of mitigation options, and as research in the Waikato is completed, the model improved.

Knowledge gaps:

- Spatial drainage layout and management including drain depths. Some of these data will be available (e.g. Manderson (2020) Hauraki Plains drainage mapping) but further surveying and spatial work will be required.
- Detailed land surface elevation data for regional peatlands. This could be informed by the first round of regional monitoring and these data used to adjust LINZ regional lowland lidar.
- Improved spatial information on hydrological behaviour of peat soils. This is challenging, and collating peat soil hydrological data currently held by MWLR and WRC and examining spatial and depth variation could inform a sampling and monitoring plan to improve data coverage.
- Prediction of upcoming seasonal rainfall. This will depend on accuracy of medium term whether forecasting by NIWA and will also be challenging.

- Knowledge of effectiveness of a range of potential water and land management strategies to reduce peat subsidence and CO_2 emissions. Could be informed by international research and model improved as Waikato based experiments are progressed.

Resources required:

- Spatial modelling expertise.
- Regional lidar.
- Historic aerial imagery.

10.4 Step 4. Policy incentives or interventions to reduce peat subsidence and CO_2 emissions

Recognising that short-term economic gains are often prioritised over environmental impacts, there is likely a need for policy intervention to promote sustainable use of organic soils and require farmers to make management changes. Significant shifts in land management approaches may impact on productivity, therefore policy incentives may also be needed. A review on sustainable drained peatland management in Switzerland by Ferré et al. (2019) concluded that the main challenges for adopting change were current land use profitability and the difficulty of integrating new management practices that reduce subsidence and CO_2 emissions, particularly in smaller farming operations. Similar challenges to widespread adoption of management approaches may emerge in the Waikato Region, especially where agricultural productivity may need to be compromised over environmental benefits, and so a top-down approach may have to be considered.

Knowledge gaps:

- Improved information on the effectiveness of possible management and land use change interventions on peat subsidence and CO_2 emissions.
- Knowledge of international policy interventions and incentives and their effectiveness.
- Improve knowledge exchange with land and drainage managers on the consequences of peat subsidence and CO_2 emissions and assess landowner impetus for change.

Resources required:

- Funding for review of international policy for sustainable management of peatlands.
- Funding for experimental investigation of management practices to reduce peat subsidence and CO_2 emissions in the Waikato region.
- Facilitation of a workshop with land managers to capture awareness of peat subsidence and CO_2 emissions from drained peat soils and suggestions for change.

10.5 Future international research and policy advice

While it is important that mitigation options are evaluated in a New Zealand context, we must continue to watch developments from ongoing international research. For example, the PEATWISE programme has tested a range of mitigation options including water table manipulations (multiple sites across Europe), submerged drains (Netherlands), management intensity (Norway, Germany), sand addition (Sweden), and paludiculture (Netherlands and Denmark). Findings from PEATWISE were not available at the time of writing this review but should be available 2021. PEATWISE project findings will be used to make recommendations and inform policy in Europe and it is likely their experience will help guide our research priorities and development of management decision support tools and policy incentives or intervention.

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