InSAR maps peatlands in the Waikato Region of New Zealand

Mark Harvey[a] and Clint Rissmann[b]

[a]*Harvey Geoscience Ltd, New Zealand;* [b]*Land and Water Science Ltd, New Zealand*

Harvey Geoscience Ltd, 29 Ridge Rd, Mahurangi East, Warkworth, New Zealand

mark@harveygeoscience.com

Land and Water Science Ltd, 77 Marama Ave South, Otatara, Southland, New Zealand

This is a pre-print manuscript of an article accepted for publication in The New Zealand Journal of Geology and Geophysics on August 5th, 2025

InSAR maps peatlands in the Waikato Region of New Zealand

We use remote sensing techniques to map the extent of peatland Organic Soils in the Waikato Region of New Zealand based on surface subsidence. Both Interferometric Synthetic Aperture Radar (InSAR) and Digital Elevation Model (DEM) differencing indicate subsidence occurred between 2013 and 2024 within previously mapped Organic Soil boundaries. Both the mapped extent and oscillating surface elevation of Organic Soils derived from InSAR time-series align with ground-based observations. The primary driver of subsidence is the artificial drainage of Organic Soils for agriculture. This has significant environmental implications for soil conservation, climate change mitigation, water quality and flood risk management. Our findings demonstrate that satellite-based approaches offer an efficient and scalable method for mapping Organic Soil that complements ground-based approaches. More moderate subsidence is apparent in low-relief, flood-prone areas beyond mapped Organic Soils in the Hauraki Plains. However, further validation is needed due to possible fading signal effects in vegetated areas. InSAR fading signal or phase bias is known to cause the overestimation of rates on grassland and cropland and additional work is required to determine the accuracy of mean subsidence rates reported in this study.

Keywords: InSAR, subsidence, LiDAR, satellite, DEM, Waikato, Organic Soil, peat, fading, signal, phase, bias.

Introduction

Peatlands cover approximately 3% of the global land surface (400 million hectares) yet hold approximately one-third of the world's soil carbon pool (Joosten, 2009). This is equivalent to twice the amount of carbon stored in all the forests around the globe (Charman, 2002; Kaat and Joosten, 2009; Pronger et al., 2014). Draining peat or Organic Soil enables the development of highly productive agricultural land (Stephens et al., 1984; Pronger et al., 2014) but comes with significant economic and environmental cost. This includes maintenance costs associated with managing the water table and acidity of drained farmland, increased risk of coastal inundation and saline intrusion (Zanello et al., 2011), loss of ecosystem services (Verhoeven and Setter, 2010), and the ongoing oxidation of a large carbon store, which impacts global climate stability (Parish et al., 2008; Pronger et al., 2014).

Subsidence caused by drainage initiates a drainage–subsidence cycle whereby ongoing drain deepening is required to keep pace with subsidence (Pronger et al., 2014). The economic value of farmed peatland may be reduced or completely lost if it falls below sea level (Ingebritsen et al., 1999) or if the underlying mineral soils are not productive (Wösten et al., 1997). The main environmental impacts of drainage are soil shrinkage and subsidence, the acceleration of lateral subsurface contaminant flow from land to water (Pearson, 2015), and oxidation of organic matter resulting in soil nutrient loss and increased CO_2 emissions to the atmosphere (Schipper and McLeod, 2002; Pronger et al., 2014, Glover-Clark, 2020; Layton, 2022).

In New Zealand, previous studies of Organic Soil surface motion have focused on the impacts of drainage on physical soil properties (McLay et al., 1992), mean annual subsidence rates and associated carbon loss (Thompson, 1980; Bowler, 1980; Schipper and McLeod, 2002; Pronger et al., 2014), Peat Surface Oscillation (PSO) (Fritz et al., 2008; Glover-Clark, 2020; Layton, 2022), nitrous oxide emissions (Kelliher et al., 2016), and annual CO_2 exchange (Nieveen et al., 2005; Campbell et al., 2015). In the Waikato Region, previous surveys of peat or Organic Soils used ground based methods (Grange et al., 1939; Wilson, 1980; Davoren, 1978; Bruce, 1979 and Orbell, 1992), quantified the rate of subsidence using Global Positioning Systems (GPS) (Pronger et al., 2014), and assessed PSO in response to hydrology and soil properties (Glover-Clark, 2020; Layton, 2022). Subsidence associated with drained Organic Soils has been documented worldwide, including in North America, Europe, Asia, and the Middle East (Deverel et al., 2016; Erkens et al., 2016; Hooijer et al., 2012; Hoyt et al., 2020; Huning et al., 2024).

Recently, Interferometric Synthetic Aperture Radar (InSAR), a remote sensing method that utilises satellite-based radar has been used to assess subsidence and surface deformation rates of drained Organic Soils (Alshammari et al., 2020; Hoyt et al., 2020; Umarhadi et al., 2022; Tampuu et al., 2023; Hrysiewicz et al., 2024). In New Zealand InSAR has been used to evaluate deformation related to hydrothermal activity and magmatism (Hamling et al., 2016; Hamling, 2020; Harvey, 2021), tectonic processes (Hamling et al., 2022; Kearse, 2024) and slope creep in steep rural terrain caused by seasonal shrink/swell of clay rich soil (Cook et al., 2023). However, InSAR has not been used in New Zealand to assess peat subsidence, thereby limiting our ability to accurately account for GHG emissions.

Here, we address this gap by using LiCSBAS, an open-source package to carry out InSAR time-series analysis using LiCSAR products (July 2018 to July 2022) across 8,000 km^2 of the Waikato Region in New Zealand (*Figure 1*). The primary objective of the study is to determine if InSAR can map Organic Soils in the Waikato Region based on surface subsidence. We also use digital elevation model (DEM) differencing (Harvey et al., 2019), comparing older and newer DEMs to validate LiCSBAS results.

This work informs our understanding of Green House Gas (GHG) emissions and enables more accurate GHG inventories according to the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006) and the 2013 Wetland Supplement (Hiraishi et al., 2014).

Study area

New Zealand has approximately 1,660 km^2 of peatland (0.7% of the total land surface), with approximately 940 km^2 located in the Waikato Region (Davoren, 1978). Peatland soils are dominantly classified as Organic Soils using the New Zealand Soil Classification (Hewitt, 2010), where they contain at least 30 cm of peat or organic soil material (at least 18% total carbon or approximately 30% organic matter) within 60 cm of the surface. Organic Soils in the Waikato Region are commonly associated with raised peat domes and can grade into and interfinger with Gley Soils to form complex associations where the original peat has broken down following artificial drainage (Molloy, 1988; Hewitt et al., 2021) or where mineral material dominates due to fluvial deposition. Soils in the Waikato Region have been mapped at 1:50,000 by the Manaaki Whenua S-Map project, which builds on previous work by Grange et al. (1939), Wilson (1980), Davoren (1978), Bruce (1979) and Orbell (1992).

Approximately 80% of Organic Soils have been drained in the Waikato Region since the early 1900s (Pronger et al., 2014). This has resulted in widespread, ongoing subsidence from soil shrinkage above the water table, consolidation below the water table and loss of carbon through oxidation of organic matter (Schipper and McLeod, 2002; Ewing and Vepraskas, 2006; Pronger et al., 2014; Nusantra et al., 2018; Glover-Clark, 2020; Layton, 2022). Loss of peat over time has resulted in some Organic Soils being reclassified as Gley Soils. Subsidence is also associated with Gley Soils, which can contain lenses of peat and organic soil material (Dresser et al., 2011). Subsidence across the Hauraki plains can also be partly attributed to tectonic activity associated with rifting of the Hauraki Graben (Persaud et al., 2016).

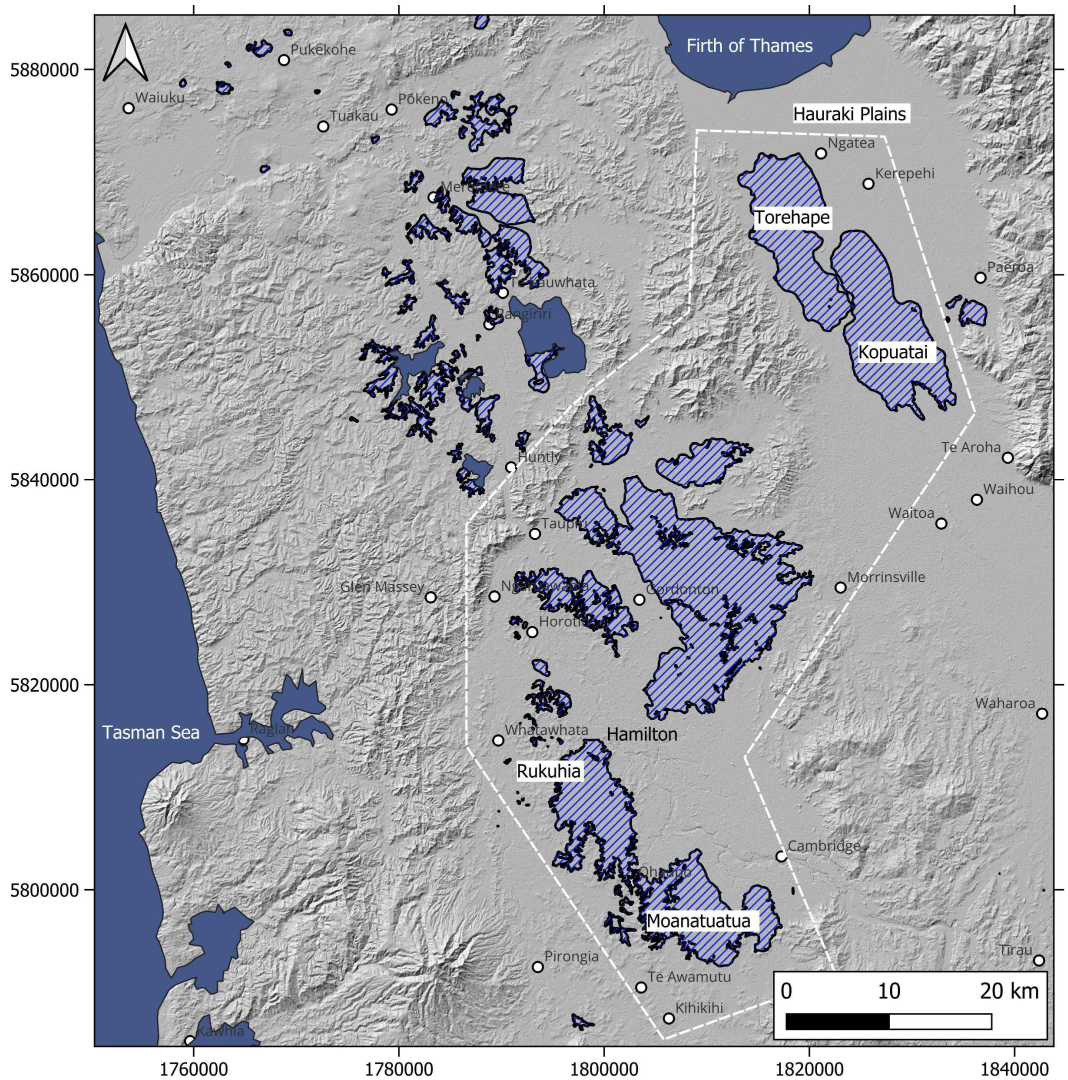


Figure 1. Waikato study area overlaid on SRTM DEM (Farr and Kobrick, 2000). Cross hatching indicates the current mapped extent of Organic Soils derived from the Manaaki Whenua S-Map project with a nominal scale of 1:50,000 (Landcare Research, 2024). White dash boundary shows Organic Soil areas used to estimate mean annual subsidence. Peatlands are labelled with white background.

Methods

For subsidence mapping and time-series plotting we use LiCSBAS, a semi-automated InSAR time-series analysis package that interfaces with the automated Sentinel-1 InSAR processor (LiCSAR) (Morishita et al., 2020). LiSCAR data products are made available by the Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET), and their suitability for measurement of soil deformation in grasslands has been previously demonstrated (Xu et al., 2022; Orhan et al., 2023). LiCSBAS processes publicly available LiCSAR data to undertake InSAR time-series processing. An advantage of LiCSBAS is loop closure, a quality control process whereby interferograms with many unwrapping errors are automatically identified and discarded. LiCSBAS was run using masking parameters chosen by trial and error to provide a balance between good coverage in grassland areas, while masking dense forest with low coherence (*Figure 2*).

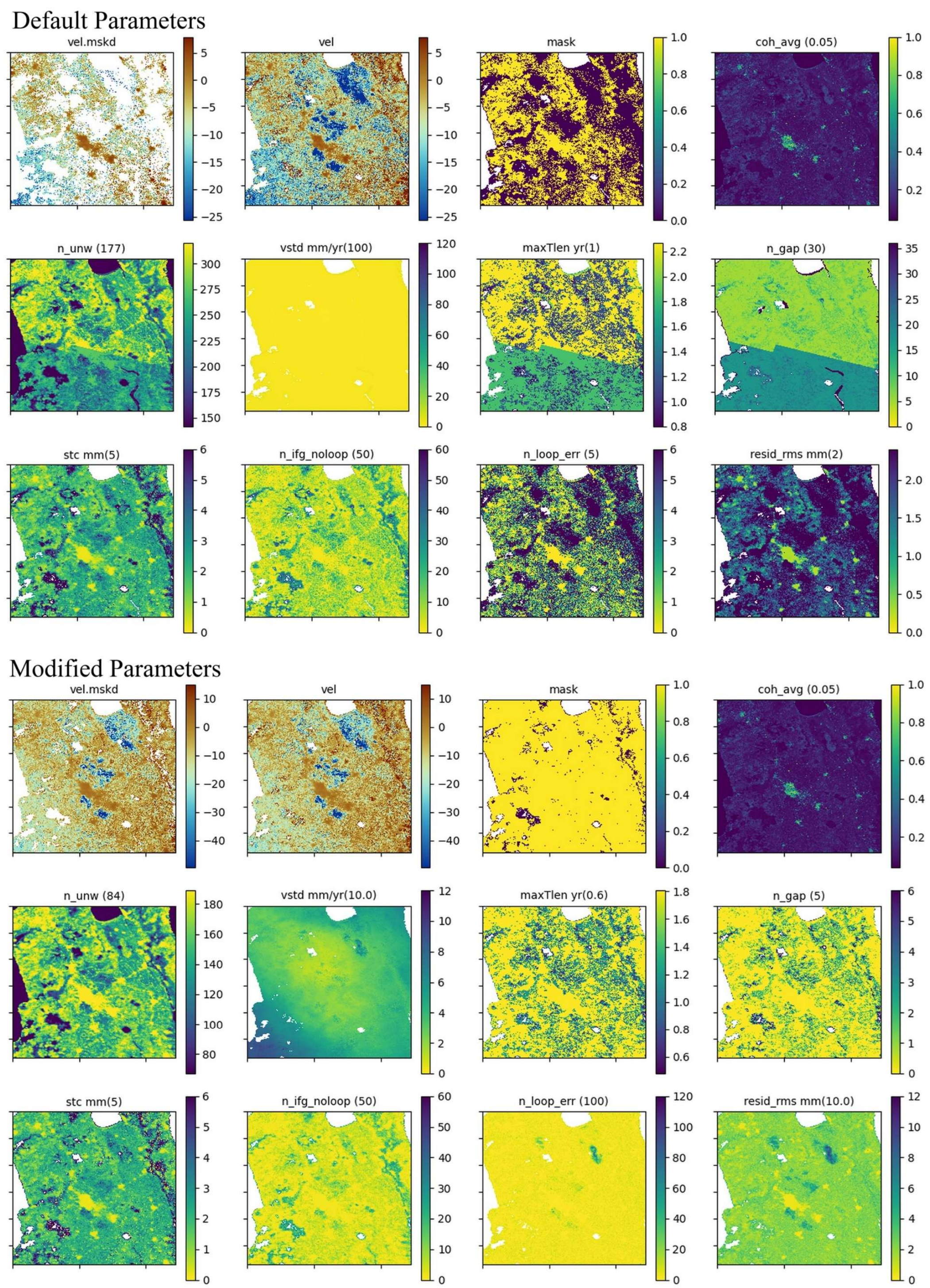


Figure 2. LiCSBAS masking parameters. Masking of velocity pixels using default parameters (top) and modified parameters (bottom). Numbers shown in the parentheses next to the titles of each noise index are the applied threshold value. See Morishita et al. (2020) for a full explanation of masking thresholds.

Time-series for Line-Of-Sight (LOS) results were obtained using the LiCSBAS interactive time-series viewer that provides both filtered and unfiltered series for any selected pixel. Sites 1 – 8 were selected for time-series plotting because they provide clear evidence for seasonal oscillation and/or a multiyear subsidence trend (*Figure 3*). Site 8 is located within mapped Gley Soils, while all other sites are located within mapped Organic Soils. For time-series in this report, red cumulative displacement points and curves represent unfiltered results, whilst those shown in blue have a spatial filter of 2 km and a temporal filter of ~40 days applied. Filtering helps to reduce noise and highlight seasonal patterns. The viewer automatically fits sinusoidal curves to the time-series to show seasonal cycles.

For the Waikato Region, the LiCSBAS dataset was limited to the descending orbit only as complete ascending data were not available for the area or time of interest. This is a limitation that can introduce possible error, and future work may integrate ascending data.

Deformation is described as subsidence in Organic Soil areas (Layton, 2022; Pronger et al., 2014; Schipper and McLeod, 2002), which is assumed to be predominantly vertical motion in this study. Estimation of vertical motion uses the approach of Manzo (2006) (*eq. 2*), simplified for the LOS viewing geometry:

$$dz \approx \ dLOS / \cos\theta \qquad (1)$$

Where dLOS is LOS motion from the descending pass, and θ is local incidence angle (radians).

The period 9th of July 2018 to 30th June 2022 included 111 Sentinel-1 acquisitions, with 466 interferograms available from the COMET-LiCS portal for approximately 8,000 km^2 of the Waikato Region study area (*Figure 1*). Of these 146 were automatically discarded from further processing by the LiCSBAS loop closure quality control process, leaving a network of 320 interferograms.

Small temporal baseline methods including LiCSBAS may be subject to fading signal, also known as ‘phase bias’, which can confound results by mimicking and amplifying subsidence under grassland and cropland (Maghsoudi et al., 2022). The uncertainty introduced by phase bias and the single orbit viewing perspective means that deformation rates mapped in this study have unknown precision and may be exaggerated in areas under pasture or crops. Despite these uncertainties, LiCSBAS may still permit useful mapping of relative rates and can be used to determine if elevated subsidence is associated with known Organic Soil areas.

An additional deformation map was obtained using an independent method and dataset. DEM differencing was undertaken using the following:

i) 2013 Copernicus satellite based 30m DEM (average elevation 2011-2015 with vertical accuracy <2m for slopes below 20%).

ii) 2017 Waikato-Hunty LiDAR 1m DEM of unknown vertical accuracy captured between 8 February 2015 and 24 January 2019.

iii) 2021 Waikato LiDAR 1m DEM with a vertical accuracy of ± 0.2m captured between 5 January and 26 March 2021.

iv) 2024 Waikato LiDAR 1m DEM with a vertical accuracy of ± 0.06m captured between 21 January 2024 – 17 May 2024.

The Copernicus and LiDAR DEMs utilise different vertical datums for elevations (LiDAR uses NZVD 2016, Copernicus uses EGM2008), so the Copernicus DEM was first converted to NZVD using a custom python script. LiDAR DEM’s were downsampled to 10m pixel size prior to differencing to improve processing speed. Note that the differencing process does not require the DEM’s to have the same pixel size.

The DEM's capture the surface at different times, cover different areas and were differenced according to the pairings shown in *Table 1*. Differencing produces displacement maps with units of meters, but time intervals vary for different pairings. To normalize and allow formation of a composite map we divide displacement by the time interval (years) between acquisitions, giving units comparable to InSAR maps (mm yr^{-1}) (*Table 1*).

Table 1 DEM differencing pairings

DEM	Area	Vert Accuracy	Differenced Against
2013	Copernicus Global 30m	< 2m	2021 LiDAR
2017 LiDAR	Kopuatai Organic Soils	unknown	2024 LiDAR
2021 LiDAR	Waikato excl. Kopuatai	+/- 0.2m	2013 Cop., 2024 LiDAR
2024 LiDAR	Hauraki incl. Kopuatai	+/- 0.06m	2021 LiDAR, 2017 LiDAR

The vertical precision of the Copernicus DEM (<2m) is relatively large compared to the expected annual rates of deformation (10's of mm yr^{-1}), and the acquisition date (2011 – 2015) means the DEM provides an average of elevations in that time period. However, we suggest our approach may still permit useful mapping of relative rates, despite this possible source of error.

All reported motions are relative to a reference location in the town of Cambridge that is assumed to be stable. All towns in the Waikato Region are observed to be stable, and the choice of Cambridge is arbitrary. Summary statistics (mean and standard deviation) were extracted from the vertical velocity map using QGIS Zonal Statistics. Map grid units are meters (NZTM 2000).

Results

Of the total mapped area (8,000 km^2), InSAR results show relatively strong subsidence within 708 km^2 of Organic Soil boundaries (black boundaries in *Figure 3*). Pixels selected from within these boundaries ($n = 6.4 \times 10^4$) averaged -31 mm yr^{-1} (LOS) for the 2018 – 2022 period. Assuming the LOS measurements result from vertical subsidence provides an average rate of approximately -40 mm yr^{-1} (*Eq. 1*) for Organic Soil areas, and approximately -25 mm yr^{-1} for surrounding low-elevation farmland dominated by Gley Soils on the Hauraki Plains (excluding the Kopuatai and Torehape peat domes). It is important to note that InSAR results here may be subject to the fading signal processing artifact, which can mimic and exaggerate subsidence under grassland and cropland (Maghsoudi et al., 2022). Accordingly, these rates have unknown precision and may be overestimated.

DEM differencing confirms the subsidence within all Organic Soil boundaries in the study area, and widespread subsidence in surrounding low-elevation farmland, including the Hauraki Plains (*Figure 4*).

Time-series for selected Organic Soil locations (Sites 1 - 7 in *Figure 3*) and a non-Organic Soil site on the Hauraki Plains (Site 8 in *Figure 3*) show well-defined seasonal surface oscillations superimposed on a longer-term subsidence trend (*Figure 5*). Additional time-series for Gley Soils on the Hauraki Plains are provided in *Appendix A*.

Waikato Region time-series were observed to contain multiple gaps after mid-2020 (see vertical lines in *Figure 5* time-series). These gaps divide the series into discrete segments that LiCSBAS aligns by assuming an overall linear displacement trend (Morishita et al., 2020). This process appears to provide satisfactory alignment, at least for the selected time-series in *Figure 5*.

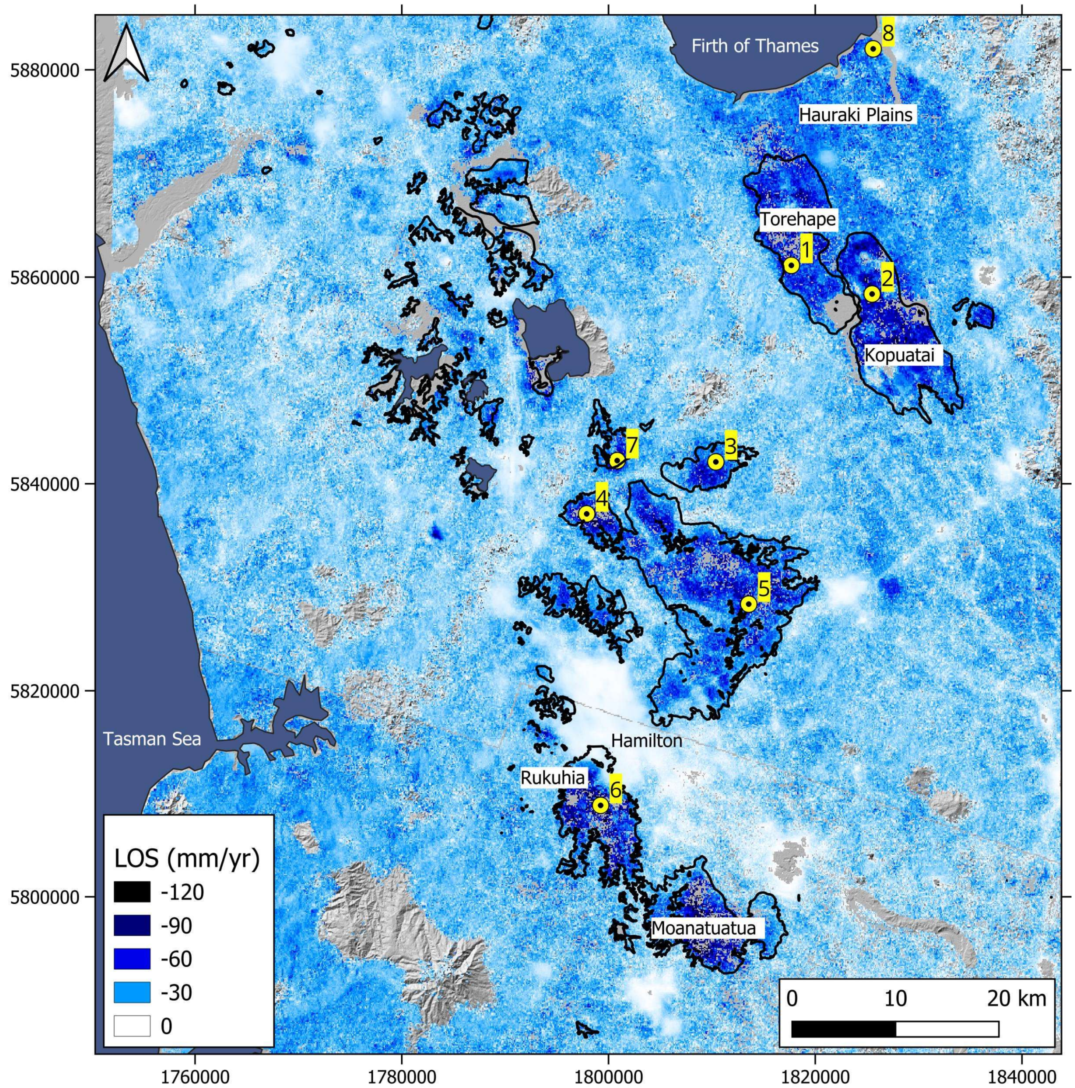


Figure 3. InSAR Line of Sight (LOS) velocity map showing subsidence associated with Organic Soils (black boundaries) and Hauraki Plains (predominantly Gley Soil). Numbers show the time-series Sites 1-8 (*Figure 5*).

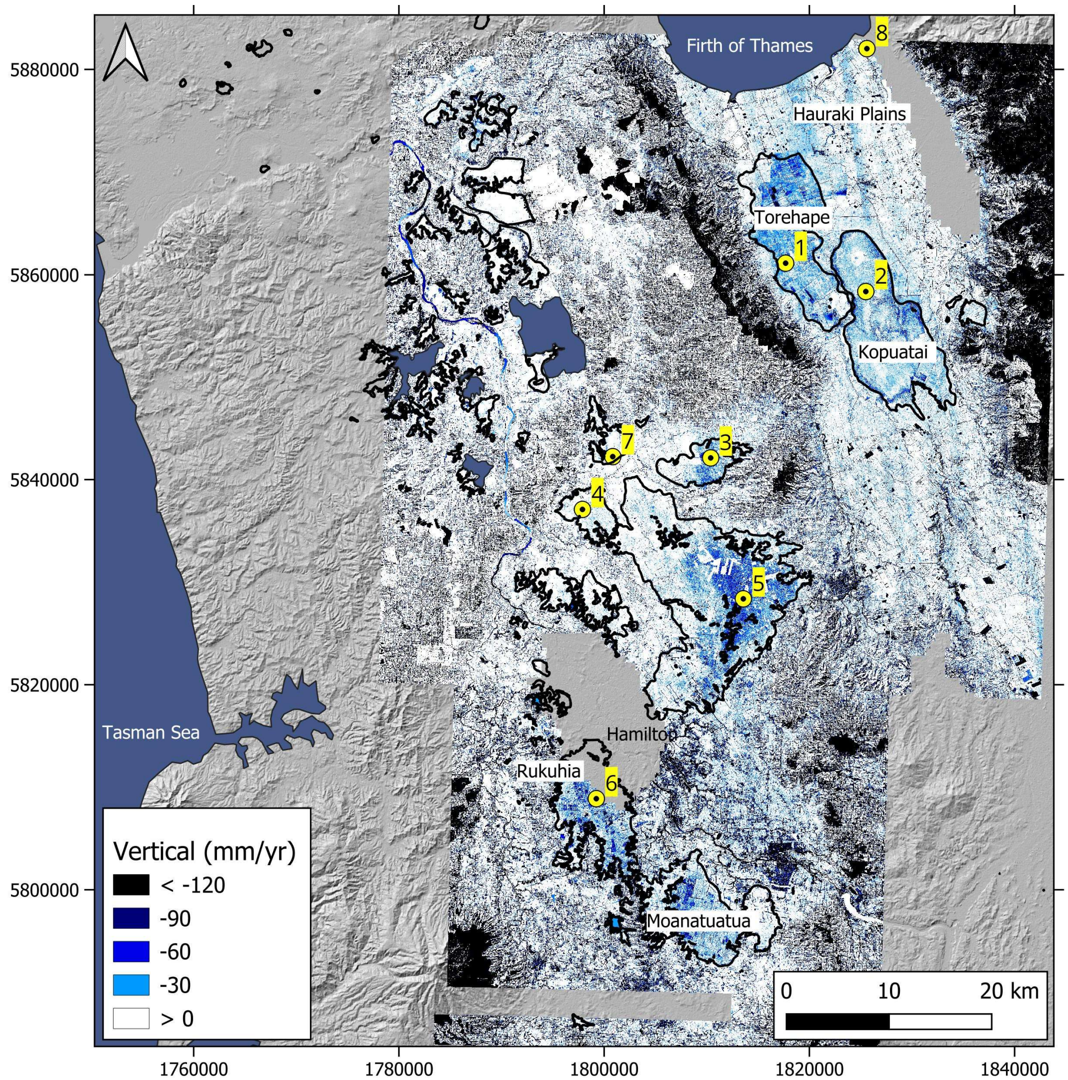


Figure 4. DEM difference map expressed as mean annual motion (mm yr^{-1}), showing the strongest subsidence associated with Organic Soils (black boundaries), which provides independent support of InSAR results (*Figure 3*).

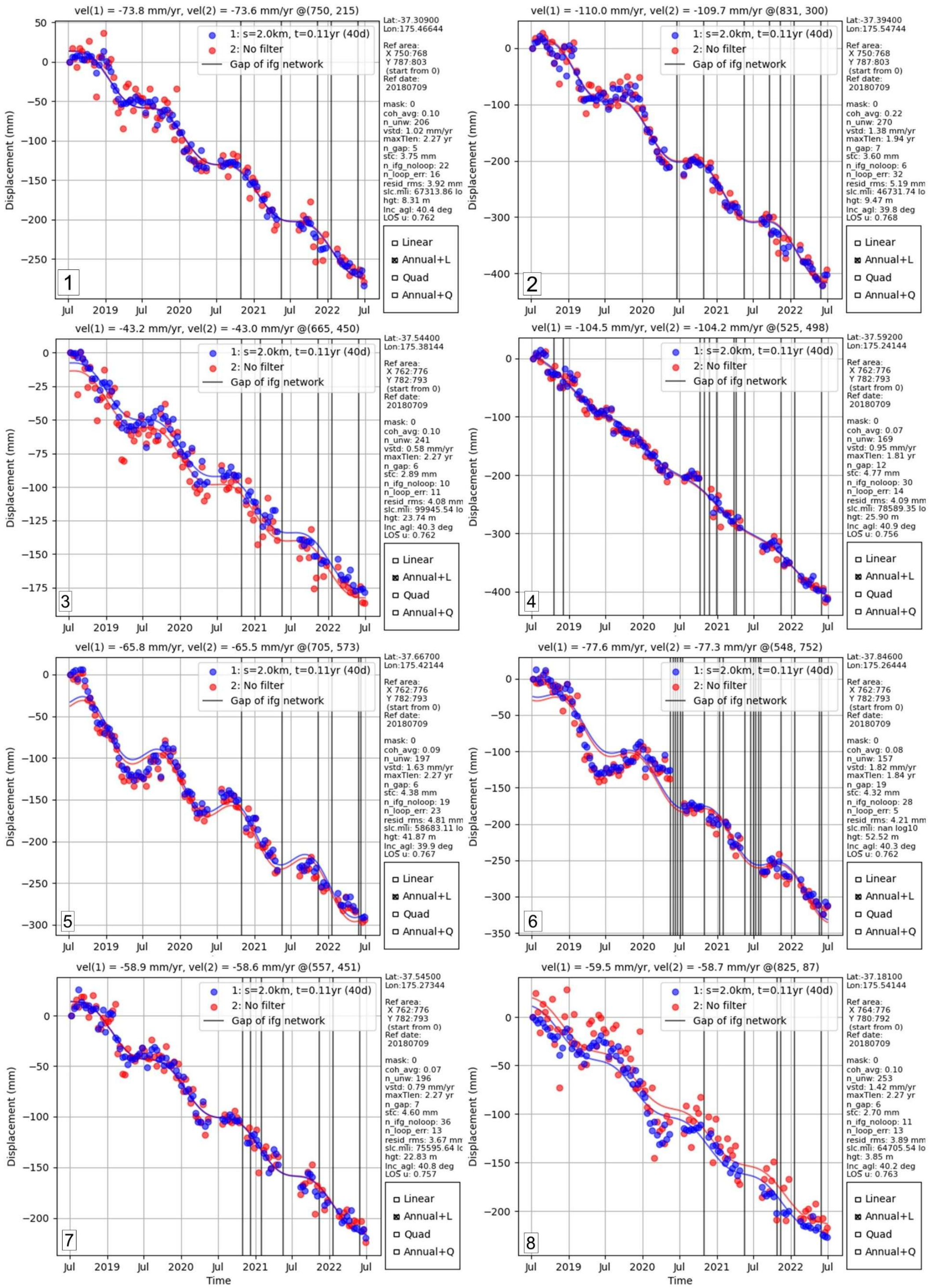


Figure 5. InSAR time-series showing seasonal surface oscillation superimposed on longer term subsidence trend. Numbers correspond to time-series Sites 1-8 shown in *Figure 3*. Note: Site 2 is located on the Kopuatai raised peat dome, Site 8 is located within a mapped Gley Soil area on the Hauraki Plains (see top right of *Figure 3*).

Discussion

Results here show the value of using remote sensing methods (LiCSBAS and DEM differencing) to map Organic Soils at a regional scale using freely available datasets (Sentinel-1 and LiDAR) processed by open-source software (LiCSBAS and QGIS). Accurate delineation of Organic Soil boundaries in the Waikato Region is problematic due to their extensive modification and the way they form complex associations with neighbouring soil orders. Our work demonstrates that remote sensing methods have the potential to be important tools to support traditional field-based soil surveys and refine our ability to map the distribution of Organic Soils across the landscape.

Neither LiCSBAS nor DEM differencing requires high-performance computing infrastructure, making the approach highly accessible for large-area and long time-series analysis. LiCSBAS includes built-in tools that allow users to automatically mask deformation maps based on customizable data quality criteria. Additionally, the software offers automated time-series plotting, with support for user-defined spatial and temporal filters. Here, the resulting series successfully captured the seasonal surface oscillations of Organic and Gley Soils, which are driven by fluctuations in groundwater levels.

Areas of elevated subsidence mapped by InSAR and DEM differencing generally agree with Organic Soil areas mapped by previous field-based soil surveys. However, the average rates of subsidence provided in this paper from LiCSBAS (~ -40 mm yr^{-1}) are higher than those estimated in previous work at between -19 mm yr^{-1} (Pronger et al., 2014) and -34 mm yr^{-1} (Schipper and McLeod, 2002), which is likely due to the fading signal effect under grassland and cropland (Maghsoudi et al., 2022).

Fading signal error is an emerging area of research with several algorithmic approaches proposed to correct or mitigate it. For example, Hrysiewicz at al. (2024) used a combination of interferometric networks with long and short temporal baselines to correct for fading signal, while Ma et al. (2025) used triplet phase closure-based stacking. However, both approaches are subject to physical limitations, e.g. unwrapping errors caused by long temporal baseline interferograms, low coherence from changes in vegetation cover, and a limited number of interferograms or rainfall events (Ma et al., 2025). Ansari (2020) notes the sign, magnitude, and temporal behaviour of the fading signal varies across different regions and land covers, complicating any potential correction.

Algorithmic approaches to correct for fading signal are environment specific and may require ground truthing using conventional methods to determine the precision of the corrected InSAR deformation measurements. These limitations apply to Organic Soil areas in the Waikato Region, which have vegetation cover and soil moisture that are spatially and seasonally variable. Algorithmic correction of fading signal with ground truthing of the corrected rates (e.g. repeat levelling surveys, repeat LiDAR surveys and DEM differencing) is beyond the scope of this study but is a recommendation for future work.

When discussing the precision of mean annual rates estimated by InSAR, or any other method, it is important to consider that the surface motions of Organic Soils may be non-linear. Seasonal oscillation is one example of non-linear motion. Hrysiewicz et al. (2024) suggests long term rates of peatland surface motion derived by InSAR should be based on datasets of at least 3 years duration.

But even for monitoring periods exceeding three years, deformation trajectories may not follow linear trends; subsidence rates may accelerate, decelerate, or exhibit episodic behavior in response to land use, drainage, or hydrological variability. For example, an early study of Waikato restiad peatlands reported subsidence rates were initially 200 mm yr^{-1}, reducing to about 70 mm yr^{-1} under cropping, then finally 20 mm yr^{-1} under pastoral management (Thompson, 1980). Other studies reported high initial rates (330 mm yr^{-1}) during peatland development in the Waikato Region (Bowler, 1980), and rates averaging 34 mm yr^{-1} over a 40-yr period for a single site in the Waikato Region (Schipper and McLeod, 2002).

Schipper and McLeod (2002) used drained and undisturbed Organic Soil depths at the Moanatuatua peatland (*Figure 3* and *Figure 4*) to estimate mean subsidence (-34 mm yr^{-1}), which they attributed partly to densification (63%), and partly to oxidation of organic matter and CO_2 degassing (37%) (2.5 to 5.0 ton C ha^{-1} $year^{-1}$) to the atmosphere. A more recent study based on repeated GPS measurements (2000 – 2012) provided subsidence rates at the Moanatuatua (-21 mm yr^{-1}), Rukuhia (-17 mm yr^{-1}) and Hauraki (-19 mm yr^{-1}) Organic Soil areas (Pronger et al., 2014). Possibly because of the fading signal effect, InSAR provides a higher mean subsidence (~ -40 mm yr^{-1} vertical) for all Organic Soil areas (2018 – 2022), and the DEM differencing estimate is even higher (~ -60 mm yr^{-1}) (2013 – 2024).

Mean subsidence rates calculated using LiCSBAS and DEM differencing in this study should be regarded with caution due to possible sources of error. However, the overall pattern of subsidence displayed by the LiCSBAS and DEM differencing methods provides a good match for known areas of Organic Soils based on S-Map data. This provides support that remote sensing has the potential to be an important tool to support the delineation of Organic Soils in the Waikato Region and elsewhere.

Subsidence in the Waikato Region is mostly concentrated within Organic Soil areas, with subsidence generally higher toward the centre, grading to lower values at the periphery. InSAR indicates there is also moderate subsidence (~ -25 mm yr^{-1}) in soils with lower organic carbon content, i.e. partly mineralised Gley Soils of the Hauraki Plains near Ngatea and Kerepehi (*Figure 3*). However, this needs to be confirmed by future ground truthing.

As the peat breaks down due to lowering of the water table and cultivation, Organic Soils continue to lose organic matter and can eventually fall into a Gley Soil classification (<30 cm peat or organic soil material within 60 cm of the surface). The InSAR results in the Hauraki Plains area may be capturing this process (see *Figures 3 and 5,* and *Appendix A*). Subsidence of Gley Soils indicated in this study could result from organic matter loss, densification/water loss in the underlying sediment, tectonic activity, or artifacts and fading signal effect in the data.

Interestingly, the time-series for both Organic Soils and Gley Soils (see Site 8 and *Appendix A*) show seasonal PSO superimposed on a longer-term subsidence trend (*Figure 5*). Note that additional time series for Hauraki Plains Gley Soils are provided in *Appendix A* to support this observation.

The low-lying Hauraki Plains are already subject to major flood risk due to tectonic subsidence, rising sea level and more frequent and intense storm events (Munro, 2007). This risk is exacerbated by any subsidence caused by the loss of soil organic matter or other processes and requires further work to quantify using ground truthing.

Most series show PSO with displacement maxima occurring after July, which is consistent with recent PSO studies for the same Organic Soils and period (Glover-Clark, 2020; Layton, 2022). These studies measured the oscillation using onsite field methods and correlated shrinking/swelling of soils to seasonal dry/wet conditions. Both studies concluded that oscillation could confound longer-term subsidence rates based on a limited number of repeat field-based measurements. InSAR provides an advantage in this respect as mean subsidence rates are based on time-series of many measurements (~12-day frequency) acquired over multiple years. Site 4 is an exception, located on a mapped Organic Soil area (*Figure 3*), yet showing no PSO (*Figure 5*). This could result from soil type variability or other site-specific hydrological factors that require field-based investigations to determine.

Surface drainage channels across the Waikato Region show a strong association with low lying areas characterised by high groundwater tables, Organic Soils and subsidence (*Figure 6*). The surface channel map (*Figure 6*) is potentially useful, as at a finer scale the distribution and density of channels might be related to measured subsidence. The value of up-to-date drainage maps to wetland conservation was the subject of a recent study, which found that the Land Information New Zealand (LINZ) sourced channels may underestimate the true density and extent of drainage channels (Burge et al., 2023). Furthermore, there is limited information on the extent of subsurface drains. Given this potential correlation, updating drainage channel maps and comparing them with InSAR-derived subsidence patterns is recommended for future research.

InSAR subsidence at the protected Kopuatai raised peat dome is anomalous as it lacks agricultural drainage (Maggs, 1997) (*Figure 6*). DEM differencing also shows subsidence at Kopuatai, though weaker than drained Organic Soil areas (*Figure 4*). One possible explanation is the relatively shallow and stable water table compared to nearby drained peatlands (Daws, 2018), essentially a large mass of water contained within peat and elevated above the surrounding Hauraki Plains. It is possible that subsidence at Kopuatai results from a hydrological connection to the surrounding lowlands that are heavily drained. The raised mass of water at Kopuatai is likely associated with a local piezometric gradient, causing outflow to the surrounding drained soils and drainage network. However, this explanation is speculative, and it is also possible that the apparently strong subsidence at Kopuatai is an artifact of fading signal. Certainly, LiCSBAS noise indexes are very high in the area, as shown in n_loop_err and resid_rms in *Figure 2*.

Deformation Mechanisms

In drained Organic Soils, the primary subsidence mechanisms are likely to be soil densification (shrinkage and consolidation) and oxidation. Densification may occur in surface soils where pore volumes are reduced by cycles of wetting and drying, where re-saturation after drying does not restore the soil to its original volume (hysteresis) (Elsaidy, 2021). Drainage has resulted in the shrink/swell cycling of Organic Soils that were previously saturated throughout the year (Schipper and McLeod, 2002; Pronger et al., 2014; Glover-Clark, 2020; Layton, 2022). To a lesser extent, some soil compaction may occur via a volume-loss process occurring beneath surface soils in the aquifers that underlie low-relief farmland in the Waikato Region (Griffiths et al., 2023). When groundwater is extracted for irrigation or recharge is reduced by drainage or drought, it causes poroelastic compression of an aquifer's coarse-grained sand and gravel deposits, resulting in subsidence of the overlying surface (Murray and Lohman, 2018).

Numerous InSAR studies have correlated subsidence with aquifer compaction caused by abstraction of groundwater for agriculture in arid areas (Castellazzi et al., 2016; Motagh et al., 2017; Navarro-Hernández et al., 2020; Cigna and Tapete, 2021; Peng et al., 2022; Orhan et al., 2023; Lees and Knight, 2024). However, aquifer compression and subsidence in the Waikato Region may be more likely to result from drainage (reduced recharge to underlying aquifers) than from groundwater abstraction.

Physical pressure applied by heavy agricultural equipment or high stocking rates is another mechanism that may cause soil densification and contribute to the observed subsidence (Batey, 2009; Hooijer et al., 2012; Pronger et al., 2014; Nusantra et al., 2018; Keller et al., 2019).

Oxidation of soil organic carbon (CO_2 release) and associated subsidence is an active area of research in drained Waikato Region Organic Soils (Schipper and McLeod, 2002; Pronger et al., 2014; Glover-Clark, 2020; Campbell et al., 2021; Layton, 2022; Pronger et al., 2022) and globally (Dawson et al., 2010; Elsgaard et al., 2012; Hooijer et al., 2012; Hoogland et al., 2012; Tiemeyer et al., 2016; Nusantra et al., 2018; Hoyt et al., 2020; Qiu et al., 2021; Liang et al., 2024). Drainage lowers the water table, exposing organic material to oxidation. The organic material is then oxidized into carbon dioxide via microbial processes, which causes subsidence (Kellner, 2003; Dawson et al., 2010; Hoyt et al., 2020). Soil organic carbon may also be dissolved and mobilised by drainage after rainfall, which provides another subsidence mechanism via mass outflow (Freeman et al., 2004; Guimarães et al., 2013; Rosset et al., 2022).

Greenhouse Gas Emissions (GHG)

Soil is the largest terrestrial reservoir of organic carbon, and understanding net inflows/outflows is critical for mitigation efforts (Oertel et al., 2016; Georgiou et al., 2022). Drained Organic Soils are a particularly concentrated CO_2 source (Hoyt et al., 2020; Huang et al., 2021). In New Zealand, by adopting the 2013 Wetlands Supplement (Hiraishi et al., 2014) and using the default temperate climate zone assumptions, drained Organic Soils under grassland and cropland contribute 9.8% of net GHG (Pronger et al., 2022). Further, Pronger et al. (2022) recommended InSAR as a method to map subsidence of Organic Soils. The magnitude of GHG emissions and the uncertainties of current methods mean that it is critical to refine the areal extent of affected soils and associated emission factors. Where oxidation contributes to soil subsidence, InSAR-derived subsidence maps may provide a proxy for GHG emissions, allowing for improved quantification and mitigation efforts.

New Zealand currently lacks full national coverage of 1:50,000 S-Map data and uses 1:63,360 (inch to the mile) Fundamental Soil Layer (FSL) information to determine the extent of Organic Soils and calculate emissions (Pronger et al., 2022). FSL has poor spatial control but has national coverage. Remote sensing tools such as InSAR could be used to help improve the spatial accuracy of FSL and refine national Organic Soil and emissions estimates.

Water Quality

The health impacts of nitrate in drinking water are an active area of research in New Zealand (Richards et al., 2022; Rogers et al., 2023). Accordingly, agricultural drainage and associated contamination, especially nitrate from animal urine and mineralisation of highly productive grazing pastures, is a major issue in New Zealand (Monaghan, 2005; Collins et al., 2007; Dench and Morgan, 2021). Both surface and subsurface artificial drainage on farms are widespread in New Zealand (Collins et al., 2007). InSAR-derived subsidence maps may help provide an indication of contamination source areas through the correlation between drainage and/or irrigation and soil subsidence.

Flooding

Flooding is the most frequent damaging natural hazard in New Zealand (Craig et al., 2021), and climate change is expected to further increase the frequency of extreme rainfall events in New Zealand (Hughes et al., 2021; Paulik et al., 2021). This is a major issue in low-elevation coastal agricultural areas simultaneously impacted by sea level rise (Craig et al., 2023) and low-relief inland areas subject to inundation from overflowing rivers (Paulik et al., 2021; Griffin et al., 2023). Our results show relatively moderate (~ -25 mm yr^{-1}) subsidence in low-lying coastal areas of the Hauraki District. Confirming subsidence in these areas should be undertaken as soon as possible to allow timely mitigation measures. The situation may be analogous to the Netherlands, where a large part of the western coastal region is covered by organic soils that were historically drained for agriculture. These areas subsided below sea level and now require extensive flood prevention measures (Hoogland et al., 2012).

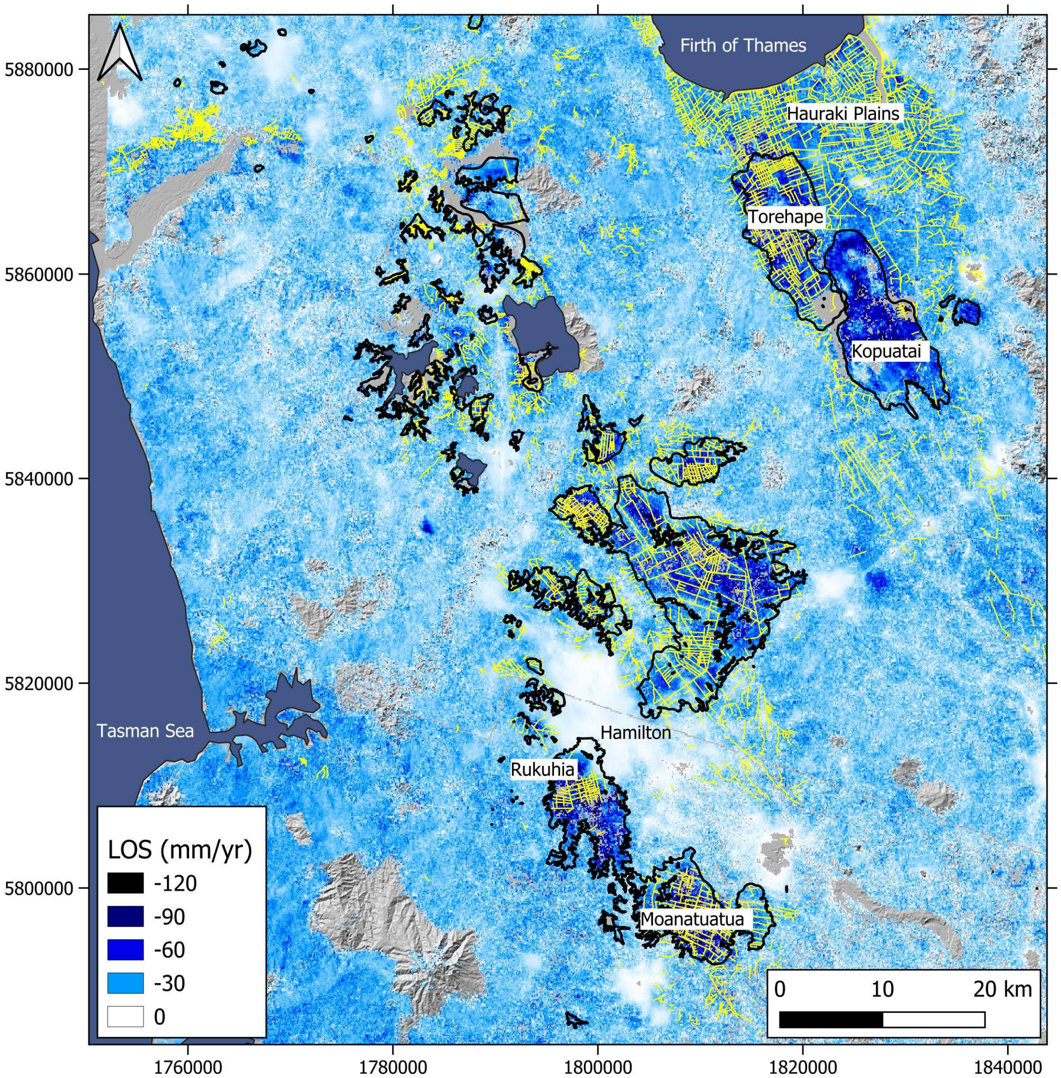


Figure 6. InSAR velocity map with Organic Soils (black boundaries) and agricultural surface drainage channels (thin yellow lines). Agricultural surface drainage channels derived from Land Information New Zealand. Note: Kopuatai raised peat dome is protected and lacks drainage.

Summary

The primary objective of this study was to determine if InSAR and DEM differencing could map Organic Soils in the Waikato Region based on subsidence rates. Results show that InSAR analysis (2018-2022) and DEM differencing (2013 – 2021) met this objective by providing subsidence maps that agree with previously mapped Organic Soil boundaries. InSAR time-series show Organic and Gley Soils (Hauraki Plains) undergo seasonal elevation changes (oscillations) from rainfall absorption and consequent changes in groundwater levels. This result is consistent with previous ground-based studies of Organic Soils but is unexpected for Gley Soils.

The InSAR analysis in this study provides an average rate of subsidence for Organic Soil areas of ~ -40 mm yr^{-1}. This is higher than estimates in previous work at between -19 mm yr^{-1} (Pronger et al., 2014) and -34 mm yr^{-1} (Schipper and McLeod, 2002). This difference is likely due to the fading signal effect under grassland and cropland, which can cause overestimation of rates (Maghsoudi et al., 2022). Ongoing work could investigate this effect by using repeat levelling surveys, repeat LiDAR surveys, DEM differencing and refining InSAR processing.

Potential subsidence identified across the Hauraki Plains requires confirmation through additional investigation, with important implications for flood risk. Sea level rise and increasingly frequent and intense storm events have the potential to be exacerbated by subsidence from agricultural drainage, potentially rendering parts of the Hauraki Plains unsuitable for agricultural or residential use.

Current emission estimates related to Organic Soils in New Zealand are limited by the poor spatial quality of historic soil information. Remote sensing tools such as InSAR represent a cost effective opportunity to help improve spatial accuracy and refine estimates. Our findings demonstrate that satellite-based approaches have the potential to

be important tools to support traditional field-based soil surveys and refine our ability to map the distribution of Organic Soils across the landscape.

Acknowledgments

The authors wish to acknowledge Dr. Yu Morishita for developing the LiCSBAS tool. It is astonishing software, and this work would not have been possible without it. This paper contains modified Copernicus Sentinel data (2018–2022) downloaded from the Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) web portal. The authors wish to acknowledge Waikato Regional Council for their ongoing funding of InSAR studies in the Waikato, Dr Callum Rees and the anonymous referees for their useful input during the review process.

References

Alshammari, L., Boyd, D. S., Sowter, A., Marshall, C., Andersen, R., Gilbert, P., ... & Large, D. J. (2020). Use of surface motion characteristics determined by InSAR to assess peatland conditions. Journal of Geophysical Research: Biogeosciences, 125(1), e2018JG004953.

Ansari, H., De Zan, F., & Parizzi, A. (2020). Study of systematic bias in measuring surface deformation with SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, 59(2), 1285-1301.

Batey, T. (2009). Soil compaction and soil management – a review. Soil Use and Management, 25(3), 335-345. https://doi.org/10.1111/j.1475-2743.2009.00236.x

Bowler, D.G. 1980. The drainage of wet soils. Hodder and Stoughton, Auckland, New Zealand.

Bruce, J.G. (1979). Soils of Hamilton City, North Island, New Zealand. New Zealand Soil Survey Report 31. 65p + 1 sheet.

Burge, O. R., Price, R., Wilmshurst, J. M., Blyth, J. M., & Robertson, H. A. (2023). LiDAR reveals drains risks to wetlands have been under-estimated. New Zealand journal of ecology, 47(1), 1-9.

Campbell, D. I., Wall, A. M., Nieveen, J. P., & Schipper, L. A. (2015). Variations in CO2 exchange for dairy farms with year-round rotational grazing on drained peatlands. Agriculture, Ecosystems & Environment, 202, 68-78. https://doi.org/10.1016/j.agee.2014.12.019

Campbell, D. I., Glover-Clark, G. L., Goodrich, J. P., Morcom, C. P., Schipper, L. A., & Wall, A. M. (2021). Large differences in CO2 emissions from two dairy farms on a drained peatland driven by contrasting respiration rates during seasonal dry conditions. Science of the Total Environment, 760, 143410.

Castellazzi, P., Arroyo-Domínguez, N., Martel, R., Calderhead, A. I., Normand, J. C., Gárfias, J., & Rivera, A. (2016). Land subsidence in major cities of Central Mexico: Interpreting InSAR-derived land subsidence mapping with hydrogeological data. International journal of applied earth observation and geoinformation, 47, 102-111.

Charman, D. (2002). Peatlands and environmental change. John Wiley & Sons,West Sussex, UK.

Cigna, F., & Tapete, D. (2021). Satellite InSAR survey of structurally-controlled land subsidence due to groundwater exploitation in the Aguascalientes Valley, Mexico. Remote Sensing of Environment, 254, 112254.

Collins, R., Mcleod, M., Hedley, M., Donnison, A., Close, M., Hanly, J., ... & Matthews, L. (2007). Best management practices to mitigate faecal contamination by livestock of New Zealand waters. New Zealand Journal of Agricultural Research, 50(2), 267-278.

Cook, M. E., Brook, M. S., Hamling, I. J., Cave, M., Tunnicliffe, J. F., & Holley, R. (2023). Investigating slow-moving shallow soil landslides using Sentinel-1 InSAR data in Gisborne, New Zealand. Landslides, 20(2), 427-446.

Craig, H., Paulik, R., Djanibekov, U., Walsh, P., Wild, A., & Popovich, B. (2021). Quantifying national-scale changes in agricultural land exposure to fluvial flooding. Sustainability, 13(22), 12495.

Craig, H., Wild, A., & Paulik, R. (2023). Dairy farming exposure and impacts from coastal flooding and sea level rise in Aotearoa-New Zealand. International Journal of Disaster Risk Reduction, 98, 104079.

Davoren, A. (1978). A Survey of New Zealand Peat Resources. The National Water and Soil Conservation Group. 185p.

Daws, C. M. (2018). Factors contributing to the unnaturally low water table of Moanatuatua Scientific Reserve, Waikato, New Zealand (Doctoral dissertation, The University of Waikato).

Dawson, Q., Kechavarzi, C., Leeds-Harrison, P. B., & Burton, R. G. O. (2010). Subsidence and degradation of agricultural peatlands in the Fenlands of Norfolk, UK. Geoderma, 154(3-4), 181-187.

Dench, W. E., & Morgan, L. K. (2021). Unintended consequences to groundwater from improved irrigation efficiency: Lessons from the Hinds-Rangitata Plain, New Zealand. Agricultural Water Management, 245, 106530.

Deverel, S. J., Ingrum, T., & Leighton, D. (2016). Present-day oxidative subsidence of organic soils and mitigation in the Sacramento-San Joaquin Delta, California, USA. Hydrogeology Journal, 24(3), 569–586. https://doi.org/10.1007/s10040-016-1391-1

Dresser, M., Hewitt, A., Willoughby, J., Belliss, S. (2011). Area of Organic Soils. MAF Technical Paper No: 2012/14. Report prepared for Ministry of Agriculture and Forestry by Landcare Research. Contract: MAF-12273. 37p.

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). 2006 IPCC guidelines for national greenhouse gas inventories. 2000p.

Elsaidy, H. (2021). Effect of Wetting and Drying Cycles on the 3D Hydromechanical Behaviour of Expansive Residual Soils in Auckland (Doctoral dissertation, ResearchSpace@ Auckland).

Elsgaard, L., Görres, C. M., Hoffmann, C. C., Blicher-Mathiesen, G., Schelde, K., & Petersen, S. O. (2012). Net ecosystem exchange of CO2 and carbon balance for eight temperate organic soils under agricultural management. Agriculture, ecosystems & environment, 162, 52-67.

Erkens, G., van der Meulen, M. J., & Middelkoop, H. (2016). Double trouble: Subsidence and CO 2 respiration due to 1,000 years of Dutch coastal peatlands cultivation. Hydrogeology Journal, 24(3), 551–568. https://doi.org/10.1007/s10040-016-1380-4

Ewing, J., & Vepraskas, M. (2006). Estimating primary and secondary subsidence in an organic soil 15, 20, and 30 years after drainage. Wetlands, 26(1).

Farr, T. G., & Kobrick, M. (2000). Shuttle Radar Topography Mission produces a wealth of data. Eos, Transactions American Geophysical Union, 81(48), 583-585.

Freeman, C., Fenner, N., Ostle, N. J., Kang, H., Dowrick, D. J., Reynolds, B., ... & Hudson, J. (2004). Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature, 430(6996), 195-198.

Fritz, C., Campbell, D. I., & Schipper, L. A. (2008). Oscillating peat surface levels in a restiad peatland, New Zealand-magnitude and spatiotemporal variability. Hydrological Processes, 22(17), 3264-3274.

Georgiou, K., Jackson, R. B., Vindušková, O., Abramoff, R. Z., Ahlström, A., Feng, W., ... & Torn, M. S. (2022). Global stocks and capacity of mineral-associated soil organic carbon. Nature communications, 13(1), 3797.

Glover-Clark, G. (2020). Spatiotemporal variability of hydrology in Moanatuatua drained peatland and its influence on CO_2 emissions and surface oscillations (Masters Thesis, The University of Waikato).

Grange, L. I., Taylor, N. H., Sutherland, C. F., Dixon, J.K., Hodgson, L., Seelye, F. T., Kidson, E., Cranwell, L. M. Smallfield, P. W. (1939). Soils and agriculture of part of Waipa County. New Zealand Soil Bureau publication No. 5. Department of Scientific and Industrial Research. Wellington, New Zealand. 85p +14 map sheets.

Griffin, C., Wreford, A., & Cradock-Henry, N. A. (2023). 'As a farmer you've just got to learn to cope': Understanding dairy farmers' perceptions of climate change and adaptation decisions in the lower South Island of Aotearoa-New Zealand. Journal of Rural Studies, 98, 147-158.

Griffiths, J., Yang, J., Woods, R., Zammit, C., Porhemmat, R., Shankar, U., ... & Howden, N. (2023). Parameterization of a National Groundwater Model for New Zealand. Sustainability, 15(17), 13280.

Guimarães, D. V., Gonzaga, M. I. S., da Silva, T. O., da Silva, T. L., da Silva Dias, N., & Matias, M. I. S. (2013). Soil organic matter pools and carbon fractions in soil under different land uses. Soil and Tillage Research, 126, 177-182.

Hamling, I. J., Williams, C. A., & Hreinsdóttir, S. (2016). Depressurization of a hydrothermal system following the August and November 2012 Te Maari eruptions of Tongariro, New Zealand. Geophysical Research Letters, 43(1), 168-175.

Hamling, I.J. (2020). InSAR observations over the Taupō Volcanic Zone's cone volcanoes: insights and challenges from the New Zealand volcano supersite. New Zealand Journal of Geology and Geophysics, pp.1-11.

Hamling, I. J., Wright, T. J., Hreinsdóttir, S., & Wallace, L. M. (2022). A snapshot of New Zealand's dynamic deformation field from Envisat InSAR and GNSS observations between 2003 and 2011. Geophysical Research Letters, 49 (2), e2021GL096465.

Harvey, M.C., K. M. Luketina, McLeod, J., and Rowland, J.V. (2019). Geothermal Subsidence and Inflation in Taupo: A Comparison of Detection Methods. Proceedings 40th New Zealand Geothermal Workshop.

Harvey, M. (2021). Sentinel-1 InSAR captures 2019 catastrophic White Island eruption. Journal of Volcanology and Geothermal Research, 411, 107124.

Hewitt, A. E., (2010). New Zealand soil classification. 3rd edn. Landcare Research Science Series 1. Lincoln, Manaaki Whenua Press. 136 p.

Hewitt, A. E., Balks, M. R., & Lowe, D. J. (2021). The Soils of Aotearoa New Zealand. Berlin/Heidelberg, Germany: Springer.

Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., and Troxler, T. G. (2014). 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands. IPCC, Switzerland. 354p.

Hoogland, T., Van den Akker, J. J. H., & Brus, D. J. (2012). Modeling the subsidence of peat soils in the Dutch coastal area. Geoderma, 171, 92-97.

Hooijer, A., Page, S., Jauhiainen, J., Lee, W. A., Lu, X. X., Idris, A., & Anshari, G. (2012). Subsidence and carbon loss in drained tropical peatlands. Biogeosciences, 9(3), 1053-1071.

Hoyt, A. M., Chaussard, E., Seppalainen, S. S., and Harvey, C. F. (2020). Widespread subsidence and carbon emissions across Southeast Asian peatlands. Nature Geoscience, 13(6), 435-440.

Hrysiewicz, A., Williamson, J., Evans, C. D., Jovani-Sancho, A. J., Callaghan, N., Lyons, J., ... & Holohan, E. P. (2024). Estimation and validation of InSAR-derived surface displacements at temperate raised peatlands. Remote Sensing of Environment, 311, 114232.

Huang, Y., Ciais, P., Luo, Y., Zhu, D., Wang, Y., Qiu, C., Goll, D.S., Guenet, B., Makowski, D., De Graaf, I. and Leifeld, J. (2021). Tradeoff of CO2 and CH4 emissions from global peatlands under water-table drawdown. Nature Climate Change, 11(7), pp.618-622.

Hughes, J., Cowper-Heays, K., Olesson, E., Bell, R., & Stroombergen, A. (2021). Impacts and implications of climate change on wastewater systems: A New Zealand perspective. Climate Risk Management, 31, 100262.

Huning, L. S., Love, C. A., Anjileli, H., Vahedifard, F., Zhao, Y., Chaffe, P. L., ... & AghaKouchak, A. (2024). Global land subsidence: Impact of climate extremes and human activities. Reviews of Geophysics, 62(4), e2023RG000817.

Ingebritsen, S., C. Mcvoy, B. Glaz, and Park, W. (1999). Florida Everglades: Subsidence threatens agriculture and complicates ecosystem restoration. In: D. Galloway, D. Jones, and S. Ingebritsen, editors, Land subsidence in the United States. USGS, Reston, VA. p. 95–106.

Joosten, H. (2009). The global peatland CO2 picture. Wetlands International, Ede, 33, 431.

Kaat, A., and H. Joosten. (2009). Factbook for UNFCCC policies on peat carbon emissions. Wetlands International, Wageningen, The Netherlands.

Kearse, J. (2024). InSAR Measurement of Vertical Land Motion at Urban and Rural New Zealand Coastal Strips (Doctoral dissertation, Open Access Te Herenga Waka-Victoria University of Wellington).

Keller, T., Sandín, M., Colombi, T., Horn, R., & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil and Tillage Research, 104293. https://doi.org/10.1016/j.still.2019.104293

Kelliher, F. M., van Koten, C., Lindsey, S. B., Wise, B., & Rys, G. (2016). Nitrous oxide emissions from drained peat soil beneath pasture. New Zealand Journal of Agricultural Research, 59, 363-376. https://doi.org/10.1080/00288233.2016.1212382

Kellner, E. (2003). Wetlands-different types, their properties and functions.

Landcare Research (2024). S-Map Soil Classification (Soil Order) August 2024. https://lris.scinfo.org.nz/layer/119585-s-map-soil-classification-soilorder-aug-2024/ (accessed 28 June 2025).

Layton, H. G. (2022). Peat soil properties and seasonal surface elevation changes of drained Waikato peatlands (Master Thesis, The University of Waikato).

Lees, M., & Knight, R. (2024). Quantification of record-breaking subsidence in California's San Joaquin Valley. Communications Earth & Environment, 5(1), 677.

Liang, Z., Hermansen, C., Weber, P. L., Pesch, C., Greve, M. H., de Jonge, L. W., ... & Elsgaard, L. (2024). Underestimation of carbon dioxide emissions from organic-rich agricultural soils. Communications Earth & Environment, 5(1), 286.

Ma, Z., Wang, N., Yang, Y., Aoki, Y., & Wei, S. (2025). Unwrapping error and fading signal correction on multi-looked InSAR data. ISPRS Journal of Photogrammetry and Remote Sensing, 220, 51-63.

Maggs, G. R. (1997). Hydrology of the Kopouatai peat dome. Journal of Hydrology (New Zealand), 147-172.

Maghsoudi, Y., Hooper, A. J., Wright, T. J., Lazecky, M., & Ansari, H. (2022). Characterizing and correcting phase biases in short-term, multilooked interferograms. Remote Sensing of Environment, 275, 113022.

Manzo, M., Ricciardi, G. P., Casu, F., Ventura, G., Zeni, G., Borgström, S., ... & Lanari, R. (2006). Surface deformation analysis in the Ischia Island (Italy) based on spaceborne radar interferometry. Journal of Volcanology and Geothermal Research, 151(4), 399-416.

McLay, C., Allbrook, R., & Thompson, K. (1992). Effect of development and cultivation on physical properties of peat soils in New Zealand. *Geoderma, 54*, 23-37. https://doi.org/10.1016/0016-7061(92)90096-P

Molloy, L., & Hewitt, A. E. (1988). Soils in the New Zealand landscape: the living mantle (pp. 179-181). Wellington: Mallison Rendel.

Monaghan, R. M., Paton, R. J., Smith, L. C., Drewry, J. J., & Littlejohn, R. P. (2005). The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. New Zealand Journal of Agricultural Research, 48(2), 227-240.

Morishita, Y., Lazecky, M., Wright, T. J., Weiss, J. R., Elliott, J. R., & Hooper, A. (2020). LiCSBAS: An open-source InSAR time series analysis package integrated with the LiCSAR automated Sentinel-1 InSAR processor. Remote Sensing, 12(3), 424.

Motagh, M., Shamshiri, R., Haghighi, M. H., Wetzel, H. U., Akbari, B., Nahavandchi, H., ... & Arabi, S. (2017). Quantifying groundwater exploitation induced subsidence in the Rafsanjan plain, southeastern Iran, using InSAR time-series and in situ measurements. Engineering geology, 218, 134-151.

Munro, A. (2007). An overview of Natural Hazards in the Hauraki District, including a qualitative risk assessment. Environment Waikato Technical Report 2006/16. 45p.

Murray, K. D., & Lohman, R. B. (2018). Short-lived pause in Central California subsidence after heavy winter precipitation of 2017. Science Advances, 4(8), eaar8144.

Navarro-Hernández, M. I., Tomás, R., Lopez-Sanchez, J. M., Cárdenas-Tristán, A., & Mallorquí, J. J. (2020). Spatial analysis of land subsidence in the San Luis potosi valley induced by aquifer overexploitation using the coherent pixels technique (CPT) and sentinel-1 insar observation. Remote Sensing, *12*(22), 3822.

Nieveen, J. P., Campbell, D. I., Schipper, L. A., & Blair, I. J. (2005). Carbon exchange of grazed pasture on a drained peat soil. Global Change Biology, 11, 607-618. https://doi.org/10.1111/j.1365-2486.2005.00929.x

Nusantra, R. W., Hazriani, R., & Suryadi, U. S. (2018). Water table depth and peat subsidence due to land use change of peatlands. Presented at the IOP Conference Series: Earth and Environmental Science.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils—A review. Geochemistry, 76(3), 327-352.

Orbell, G. E. (1992). Soil map of Waikato lowlands, North Island, New Zealand. Department of Scientific and Industrial Research Land Resources Map 311/2. 2 map sheets.

Orhan, O., Haghshenas Haghighi, M., Demir, V., Gökkaya, E., Gutiérrez, F., & Al-Halbouni, D. (2023). Spatial and Temporal Patterns of Land Subsidence and Sinkhole Occurrence in the Konya Endorheic Basin, Turkey. Geosciences, 14(1), 5.

Parish, J., A. Sirin, D. Charman, D. Joosten, T. Minayeva, M. Silvius, and L. Stringer. (2008). Assessment on peatlands, biodiversity and climate change: Main report. Global Environment Centre, Selangor, Malaysia.

Paulik, R., Crowley, K., Cradock-Henry, N. A., Wilson, T. M., & McSporran, A. (2021). Flood impacts on dairy farms in the Bay of Plenty Region, New Zealand. Climate, 9(2), 30.

Peng, M., Lu, Z., Zhao, C., Motagh, M., Bai, L., Conway, B. D., & Chen, H. (2022). Mapping land subsidence and aquifer system properties of the Willcox Basin, Arizona, from InSAR observations and independent component analysis. Remote Sensing of Environment, 271, 112894.

Persaud, M., Villamor, P., Berryman, K. R., Ries, W., Cousins, J., Litchfield, N., and Alloway, B. V. (2016). The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and hazard. New Zealand Journal of Geology and Geophysics, 59(1), 117-135.

Pronger, J., Schipper, L. A., Hill, R. B., Campbell, D. I., & McLeod, M. (2014). Subsidence rates of drained aricultural peatlands in New Zealand and the relationship with time since drainage. Journal of Environmental Quality, 43(4), 1442-1449.

Pronger, J., Glover-Clark, G., Price, R., Campbell, D., & Schipper, L. (2022). Improving accounting of emissions from drained organic soils. New Zealand Ministry of Primary Industries Technical Paper No: 2023/16.

Qiu, C., Ciais, P., Zhu, D., Guenet, B., Peng, S., Petrescu, A. M. R., ... & Brewer, S. C. (2021). Large historical carbon emissions from cultivated northern peatlands. Science advances, 7(23), eabf1332.

Richards, J., Chambers, T., Hales, S., Joy, M., Radu, T., Woodward, A., ... & Baker, M. G. (2022). Nitrate contamination in drinking water and colorectal cancer: Exposure assessment and estimated health burden in New Zealand. Environmental research, 204, 112322.

Rogers, K. M., van der Raaij, R., Phillips, A., & Stewart, M. (2023). A national isotope survey to define the sources of nitrate contamination in New Zealand freshwaters. Journal of Hydrology, 617, 129131.

Rosset, T., Binet, S., Rigal, F., & Gandois, L. (2022). Peatland dissolved organic carbon export to surface waters: Global significance and effects of anthropogenic disturbance. Geophysical Research Letters, 49(5), e2021GL096616.

Schipper, L.A., and McLeod, M. (2002). Subsidence rates and carbon loss in peat soils following conversion to pasture in the Waikato Region, New Zealand. Soil Use Manage. 18:91–93. doi:10.1111/j.1475-2743.2002.tb00225.x

Stephens, J., L. Allan, and E. Chen. (1984). Organic soil subsidence. Rev. Eng. Geol. 6:107–122.

Tampuu, T., Praks, J., De Zan, F., Kohv, M., & Kull, A. (2023). Relationship between ground levelling measurements and radar satellite interferometric estimates of bog breathing in ombrotrophic northern bogs. Mires and Peat, 29.

Thompson, K. (1980). Peat and peatlands: Economic and scientific importance. In: F. van der Elst and D.I. Kinloch, editors, Soil groups of New Zealand: Part 4. Organic soils. New Zealand Society of Soil Science, Wellington, New Zealand. p. 17–25.

Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., ... & Zeitz, J. (2016). High emissions of greenhouse gases from grasslands on peat and other organic soils. Global change biology, 22(12), 4134-4149.

Umarhadi, D. A., Widyatmanti, W., Kumar, P., Yunus, A. P., Khedher, K. M., Kharrazi, A., & Avtar, R. (2022). Tropical peat subsidence rates are related to decadal

LULC changes: Insights from InSAR analysis. Science of The Total Environment, 816, 151561.

Verhoeven, J.T.A., and T.L. Setter. (2010). Agricultural use of wetlands: Opportunities and limitations. Ann. Bot. (Lond.) 105:155–163. doi:10.1093/aob/mcp172

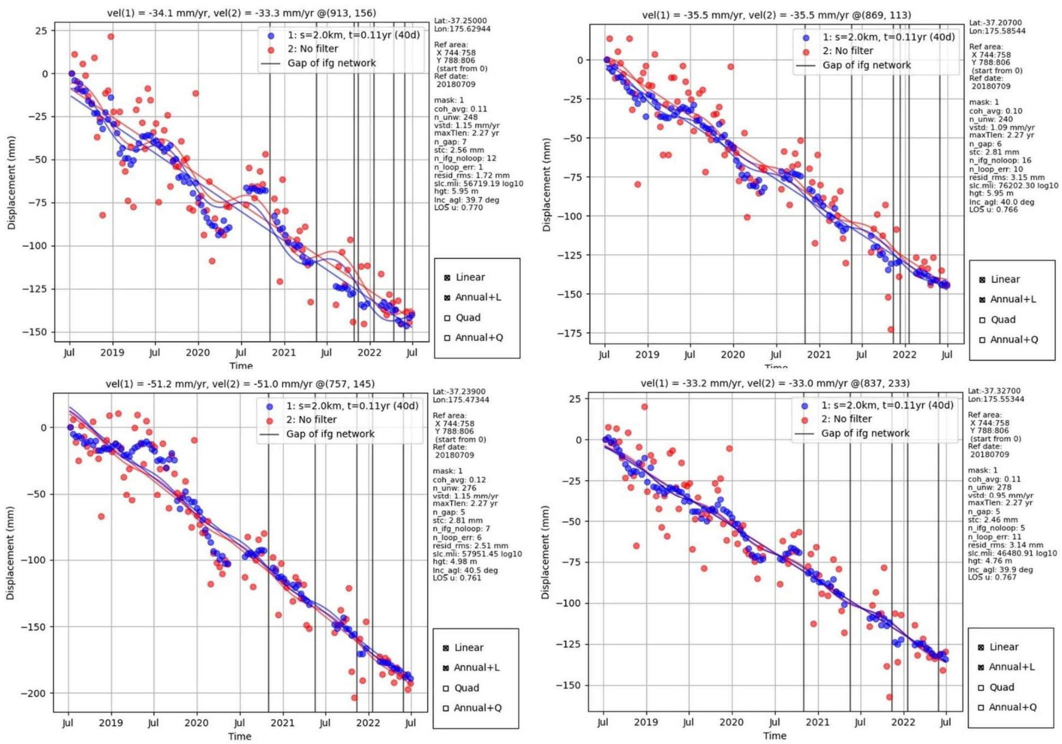
Wilson, A.D. (1980). Soils of Piako County, North Island, New Zealand. New Zealand Soil Survey Report 39. 171 p. + 5 map sheets.

Wösten, J. H. M., Ismail, A. B., & Van Wijk, A. L. M. (1997). Peat subsidence and its practical implications: a case study in Malaysia. Geoderma, *78*(1-2), 25-36.

Xu, Z., Jiang, L., Niu, F., Guo, R., Huang, R., Zhou, Z., & Jiao, Z. (2022). Monitoring regional-scale surface deformation of the continuous permafrost in the qinghai–tibet plateau with time-series InSAR analysis. Remote Sensing, 14(13), 2987.

Zanello, F., P. Teatini, M. Putti, and G. Gambolati. (2011). Long term peatland subsidence: Experimental study and modeling scenarios in the Venice coastland. J. Geophys. Res. Earth Surf. 116:F04002. doi:10.1029/2011jf002010.

Appendix A



InSAR time-series for Gley Soils on the Hauraki Plains. Note: Series show seasonal surface oscillation superimposed on longer term subsidence trend. Series locations are provided as geographic coordinates (top left of each plot).