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Abstract

Drained peatlands are associated with major environmental and land management issues, such as the long-term irreversible subsidence of the peatland surface. Shrinkage, a mechanism of subsidence caused by a shrinking of the peat matrix during dry conditions, is partially reversible upon rewetting, leading to seasonal oscillations of the peat surface height. However, rates of subsidence of drained peatlands have rarely been measured using high-frequency measurements able to discern peat surface oscillations, despite its potential to bias long-term subsidence estimates. We measured the temporal variability of peat surface oscillation using paired pressure transducers at two adjacent dairy farms on Moanatatua drained peatland over a 17-month period, extending a previously reported 10-month dataset at the same study sites. Reversible oscillations were 65.2 and 103.6 mm at the two sites, these exceeded most other published values in the international literature. Furthermore, oscillations were between 3.4 and 5.4 times greater than the average annual irreversible subsidence rate for the Waikato region, highlighting the importance of high-frequency measurements to separately consider reversible and irreversible subsidence processes.

1. Introduction

Peatlands are dense carbon stores, containing 30% of the global soil carbon stock (Blodau, 2002) on less than 3% of Earth's land surface area (Xu et al., 2018). Globally widespread drainage of peatlands has occurred in recent centuries for agricultural and urban expansion, amounting to an estimated 65 million hectares (Kaat & Joosten, 2009). Among the many effects of drainage, surface subsidence is a major environmental and land management issue that affects drained peatlands globally (Deverel & Rojstaczer, 1996). Initiated as soon as peatlands are artificially drained for land uses such as agriculture and forestry (Petersen & Madsen, 1978), subsidence is comprised of three main volume change mechanisms; consolidation of saturated peat, biochemical oxidation of organic matter, and shrinkage of peat in the unsaturated zone (Zanello et al., 2011; Hooijer et al., 2012; Pronger et al., 2014). Consolidation and oxidation are irreversible processes, however, shrinkage is partially reversible with the onset of wetter hydrological conditions (Nieuwenhuis & Schokking, 1997). Consequently, the surface of drained peatlands will shrink and swell in response to variable hydro-climatic conditions (Egglesmann, 1984), a phenomenon known as peatland surface oscillation (PSO; Fritz et al., 2008).

When water tables recede during dry periods, pore water pressures reduce and effective stresses on the peat matrix increase, causing large pore spaces to collapse (Waddington et al., 2010) and a reduction in peat surface elevation. Following precipitation events, effective stresses are reduced as water tables rise closer to the peat surface, causing swelling of the peat matrix (Howie & Hebda, 2018) and an increase in peat surface elevation. This seasonal shrinking and swelling behaviour of drained peatlands causes changes to hydraulic and physical properties, where, for example, the collapse of macropores during a shrinking cycle leads to increased bulk density and water retention, as well as reduced hydraulic conductivity (Price, 2003).

In the Waikato Region of Aotearoa New Zealand, approximately 67,000 ha of a total 90 000 ha peatland area has been drained (Pronger et al., 2020) and developed for agriculture over the past 150 years (Clarkson et al., 2004); all of which is affected by subsidence. A recent study by Glover-Clark (2020) at two dairy farms on Moanatuatua drained peatland used paired pressure transducers (one fixed in place and one free to move with the peat surface) to indirectly quantify PSO by using water level as a mobile benchmark, a methodology adapted from Fritz et al. (2008). PSO of magnitudes 46 and 66 mm over a ten-month period were found; 2.5 and 3.5 times the annual average subsidence rate for the Waikato Region of 19 mm yr^{-1} (Pronger et al., 2014), respectively. Previously not known to affect drained peatlands in Aotearoa, these findings highlighted the importance of separately considering the reversible and irreversible components of subsidence, to prevent the estimation of subsidence rates from being aliased[1] by PSO (Glover-Clark, 2020).

[1] Aliasing refers to misidentifying a signal (e.g. peat surface elevation change) at one frequency (e.g. seasonal reversible shrinkage) as another frequency (long-term irreversible subsidence), leading to error. At its worse manifestation, long-term spot measurements of subsidence rates might appear to indicate that the peat surface is rising.

To meet obligations to reduce subsidence rates and carbon losses set out in the Waikato Regional Policy Statement, Waikato Regional Council contracted Manaaki Whenua – Landcare Research to establish a regional subsidence monitoring programme. Primarily consisting of five-yearly airborne lidar surveys over drained peatlands throughout the Waikato Region, the programme includes the establishment of a number of paired pressure transducer sites to provide lidar ground truthing and continuous measurements of peat surface elevation (Pronger et al., 2020). Thus, the purpose of this report was to extend the PSO dataset described in Glover-Clark (2020) from 10 months to 17 months of data, with a particular focus on capturing changes in surface elevation occurring between January and August 2020, and to provide recommendations on methodological improvements to be incorporated into the design of the regional PSO sites.

2. Methodology

At Moanatuatua drained peatland, we established two research sites situated on adjacent dairy farms, 2.7 km apart. The sites were selected based on having similar grazing and land management practices, but different drainage design and drainage histories. One site (referred to as "surface-drained" or Site SD; peat depth ~7 m) had hump and hollow drainage, characterized by unfenced shallow drains (0.3 m wide × 0.3 m deep) spaced approximately every 30 m within each paddock to create humped profiles (humps). Deep secondary drains (0.8 m × 1.0 m) bordered each pair of paddocks. The other site ("border-drained" or Site BD; peat depth ~5 m), had border-ditch drainage, where fenced drains (0.8 m × 1.0 m) bordered each paddock. Site BD was recontoured in October 2016 from hump and hollow drainage to its current design, by removing soil from the top of each hump to fill in the shallow surface drains, creating a domed profile in each paddock. Site SD was developed for agricultural use around 1975 and Site BD was developed around 1960.

At each site, a transect line extending perpendicular to drains was established, consisting of multiple dipwells used to measure water table depth below the peat surface. Dipwells were each comprised of a 2 m length of slotted closed-bottom polyvinyl-chloride (PVC) tube with diameter 50 mm, encased in a geotextile filter sleeve to prevent the entry of peat. Dipwells were inserted vertically into the peat, recessed below surface level, and covered with removable wooden boards to prevent livestock or machinery impacting dipwell positions. Within two dipwells at each site in representative high and mid-slope topographic positions, paired pressure transducer systems were established, using methodology adapted from Fritz et al. (2008). System design consisted of two pressure transducer probes (INW LevelSCOUT, Seametrics, Kent WA USA) deployed within a single dipwell. One probe, measuring water table depth below the peat surface (relative water level, RWL), was suspended on a braided stainless-steel wire from a steel rod bridging two 30 cm long sections of aluminium channel affixed to the peat just below the surface, therefore free to move with the peat surface. The other probe, measuring water table depth above a given datum (absolute water level, AWL), was suspended from a steel benchmark rod anchored in the substratum adjacent to the dipwell, (Figure 1). The upper 2 m sections of the benchmark rods ran inside 30 mm diameter PVC pipe to prevent any friction between the peat and the rods, further insuring their stability. Following the approach of Fritz et al. (2008), the water table acted as a mobile benchmark, where changes in peat surface elevation were calculated by subtracting RWL from AWL. For further methodologies related to hydrology, soil physical properties and micrometeorological measurements of evaporation rates, refer to Glover-Clark (2020) and Burba (2013).

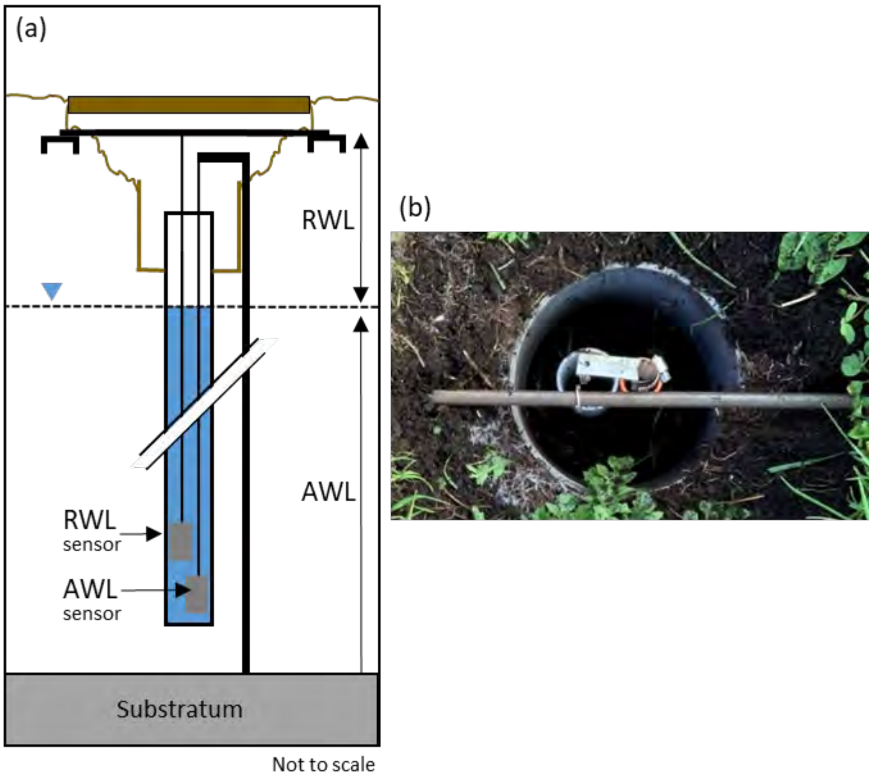

Figure 1 (a) Cross-sectional diagram of the paired pressure transducer method, showing the steel rod bridging the aluminium channels either side of the dipwell, from which the RWL probe is suspended, and the vertical benchmark rod from which the AWL probe hangs, (b) vertical photograph of a dipwell containing paired pressure transducers.

3. Results

Rainfall between 1 March 2019 and 1 August 2020 totalled 1257 mm at Site SD and 1269 mm at Site BD; 75% and 76% of the long term average rainfall total of 1667 mm in Cambridge (NIWA, 2019) for these months, respectively. January and February 2020 were particularly dry, receiving only 11% and 9% of normal rainfall (Figure 2a) and initiating a severe drought. The water balances of each site, shown as rainfall (P) less evaporation (E; $P - E$) due to assumed negligible lateral flows, revealed very small differences between sites[2] over the measurement period (Figure 2b). Both sites had near-zero water balances from March to June 2019, reflecting little change of stored water from evaporation between intermittent rainfall events. During this time, relative water level (RWL) at Site

[2] Note that evaporation data for Site BD was not available at the time of writing this report, and has been replaced with Site SD evaporation data from 16 January 2020 onwards.

SD remained fairly constant, yet RWL at Site BD continued to recede (Figure 2c). Shallow soil moisture content (volumetric moisture content; VMC) increased at both sites during this period, particularly at 50 mm depth (Figure 2d). Considerable rainfall coupled with lower evaporation rates in June, July and August 2019 resulted in a net increase in water storage at both sites, recharging both RWL and VMC.

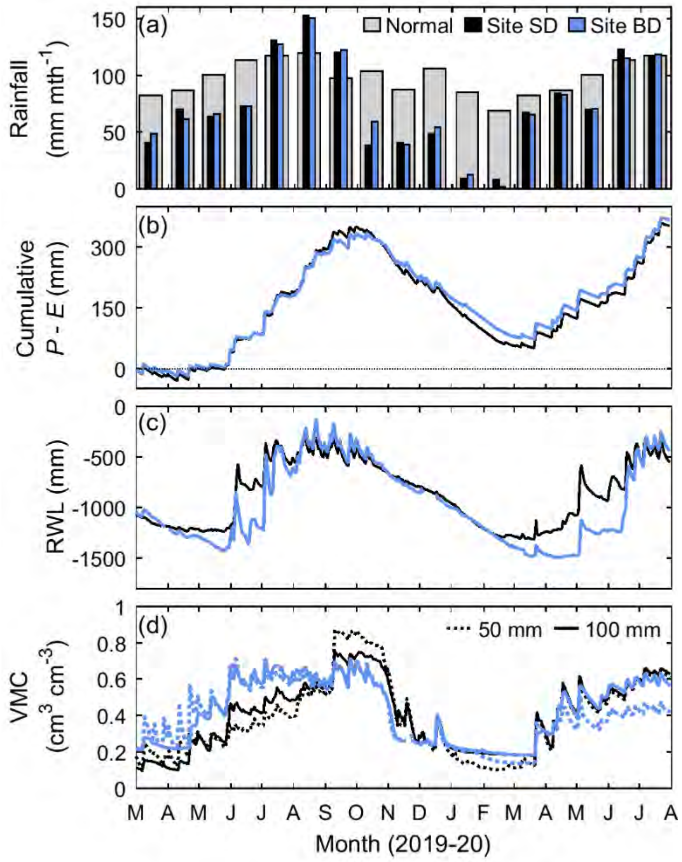

Figure 2 Hydro-climatic conditions at the study sites during the period 1 March 2019 and 1 August 2020, showing (a) monthly total rainfall at Sites SD (black) and BD (blue) compared to 1981-2010 normal rainfall (grey), (b) cumulative precipitation minus evaporation ($P - E$), (c) relative water level (RWL) measured at the hump PSO sites (0 mm represents the peat surface), and (d) soil volumetric moisture content (VMC) measured at 50 mm (dotted lines) and 100 mm (solid lines) depths. Rainfall, evaporation and VMC were all measured at the EC sites. Colour coding is black for Site SD and blue for Site BD.

Sites SD and BD began losing stored water from mid-October 2019, which caused a rapid decline in VMC at both sites, and a more gradual decrease in RWL that persisted until March 2020 at Site SD and May 2020 at Site BD. Towards the end of April 2020, rainfall increased VMC at both sites, where VMC at 100 mm depth at both sites and 50 mm depth at Site SD were similar. VMC at 50 mm depth at Site BD remained lower for the remainder of the measurement period, likely due to poor contact between soil and the probe from shrinkage of the peat matrix over the preceding dry period.

PSO measured at all four monitoring locations across Sites SD and BD between March 2019 and August 2020 (Figure 3), exhibited a strong seasonal pattern largely reflecting the water balance; shrinking during periods of net water loss and swelling during periods of net water gain (Figure 2c). Irrespective of the magnitude of PSO, changes in surface elevation appeared remarkably similar between sites, despite their geographical separation. Clear malfunctions with the paired pressure transducer system at Site BD mid-slope position in June and August 2019 and from March 2020 onwards meant that changes in SE were recorded that could not have been real. Inspection of water level data (data not shown) indicated that this was likely a result of the RWL and AWL probes measuring changes in water table depth at slightly different times, despite calibration of probes prior to deployment in the field and quarterly syncing of sensor clocks.

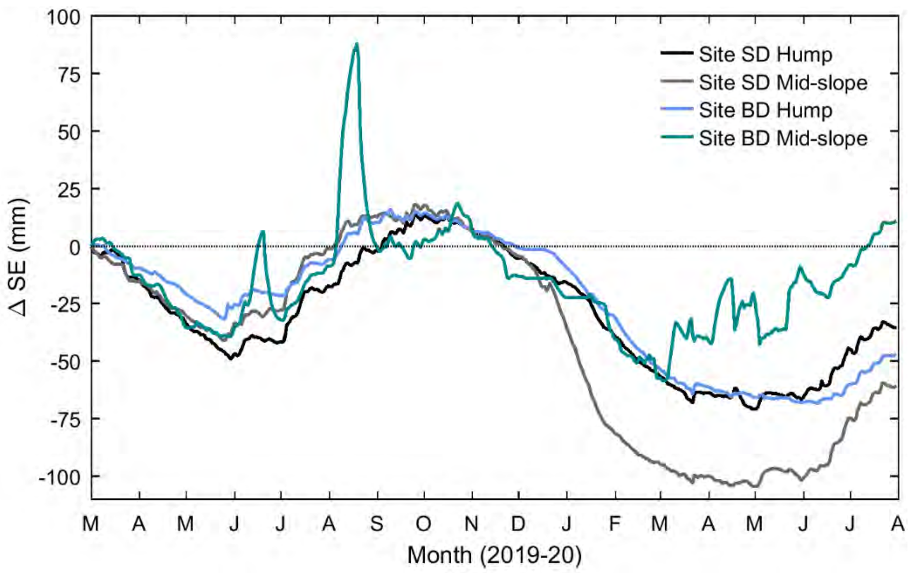

Figure 3 Total changes in peat surface elevation (Δ SE) based on mean daily data from hump and mid-slope paired pressure transducer systems at Sites SD and BD during the time period 1 March 2019 and 1 August 2020.

Focusing on the second shrinkage cycle initiated in October 2019, shrinkage rates at Sites SD hump, SD mid-slope and BD hump were initially relatively slow until 1 January 2020 (Figure 4). During this time, shrinkage rates at the hump positions at Sites SD and BD were the most similar, averaging 0.29 and 0.26 mm day^{-1}, respectively. In contrast, Site SD mid-slope had a shrinkage rate close to double, with the peat surface elevation decreasing by approximately 0.55 mm day^{-1}. Coinciding with extremely low rainfall in January, February and March (35% of normal rainfall), shrinkage rates increased at all three paired transducer locations, consistent with a slight increase in the rate of water table decline (Figure 4b). Again, shrinkage rates at Sites SD and BD hump were very similar, averaging 0.55 and 0.56 mm day^{-1}, respectively, whilst Site SD mid-slope shrank considerably faster, averaging 0.71 mm day^{-1}. The steep linear pattern of the shrinkage at Site SD mid-slope during December and January raised concerns that an instrumental problem may have occurred, however, careful inspection of the data revealed no discrepancies between RWL and AWL, suggesting this shrinkage was real. Manual measurements taken on 17 December 2019 and 16 January 2020 indicated shrinkage of 39 mm at the mid-slope site , and 12 mm at the hump site, consistent with both sets of paired transducers. Time did not permit manual measurements to be taken past January to confirm further shrinkage rate measurements.

Minimum SE was reached at Site SD hump and mid-slope locations at the beginning of May 2020, with total shrinkage since October 2019 of 84.3 and 122.6 mm, respectively (Figure 4 and Table 1). Minimum SE occurred slightly after deepest RWL was reached in mid-March 2020 for both these sites. Shrinkage persisted at Site BD hump until the middle of June 2020, totalling 84.2 mm, and similarly occurred approximately a month and a half after deepest RWL in early May 2020. As RWL came within 800 mm of the peat surface in June 2020, the peat matrix at all three sites began to swell. Small oscillations in SE of magnitude 2-4 mm occurred between 16 June and 1 August 2020, correlating with fluctuating RWL and reflecting intermittent but sizeable rainfall events. Total swelling during this time amounted to 37.7 mm, 45.0 mm, and 21.4 mm at SD hump, mid-slope and BD hump, representing SE recovery since October 2019 of 45%, 37% and 25%, respectively.

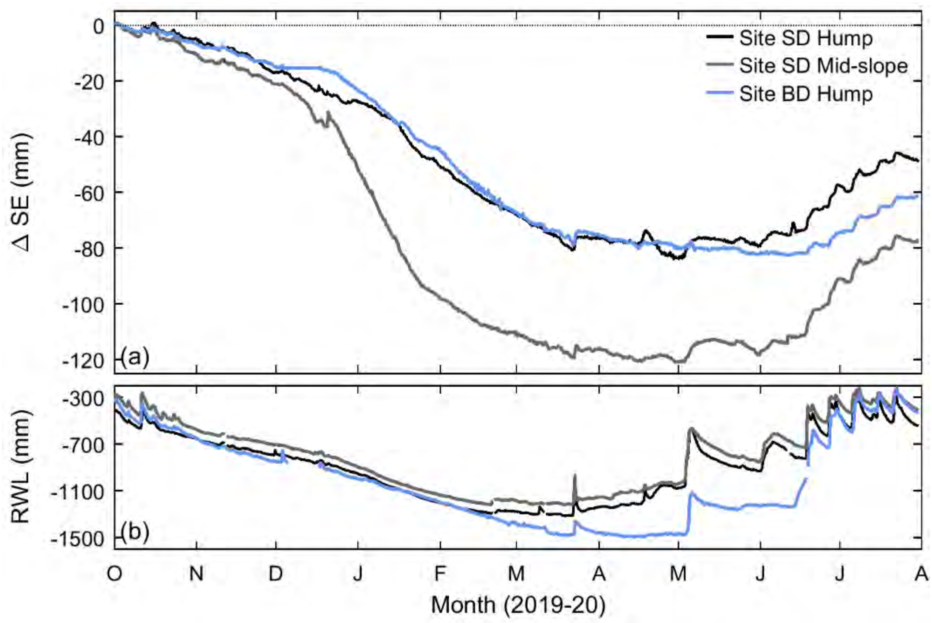

Figure 4 Six-hourly mean changes in (a) total peat surface elevation (Δ SE) based on data from the paired pressure transducers at Sites SD (hump and mid-slope) and BD (hump), and (b) relative water level (RWL) during the period 1 October 2019 and 1 August 2020.

Table 1 Summary of the magnitude of shrinkage and swelling at Site SD hump, Site SD mid-slope, and Site BD hump paired transducer positions for each given time period.

	Site SD mid-slope (mm)	Site SD hump (mm)	Site BD hump (mm)
Shrinkage period 1 (March – June 2019)	-41.1	-49.0	-31.7
Swelling period 1 (June – October 2019)	59.4	62.8	47.7
Shrinkage period 2 (October 2019 – June 2020)	-122.6	-84.3	-84.2
Swelling period 2 (June – August 2020)	45.0	37.7	21.4

Considering the use of paired pressure transducers for long-term subsidence monitoring, Figure 5 shows the relationship between RWL and SE[3] and how these data can be used to estimate irreversible subsidence rates. The vertical distance between the red diamonds show the decrease in SE due to irreversible subsidence, based on the same RWL one year apart (July 2019 and July 2020); being 24 mm yr^{-1} at Site SD hump and 33 mm yr^{-1} at Site BD hump.

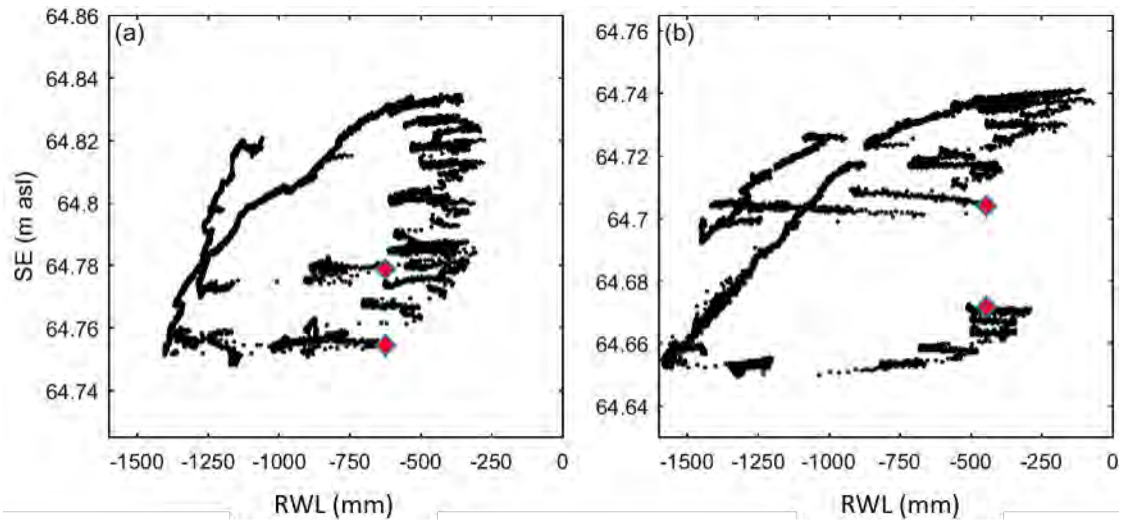

Figure 5 Half-hourly values of peat surface elevation (SE) plotted against relative water level (RWL) at (a) Site SD hump and (b) Site BD hump, for the measurement period (1 March 2019 – 1 August 2020). Red diamonds indicate the same RWL in July 2019 and July 2020, but different SE representing current best estimate of the irreversible subsidence rate. Note that the values on the Y axes differ between sites, but the ranges are the same.

4. Discussion

The maximum ranges of peat surface elevation movement over the measurement period occurred between October 2019 and June 2020 at the three paired transducer sites (Site SD mid-slope, Site SD hump, Site BD hump) were 122.6 mm, 84.3 mm and 84.2 mm, respectively. This period included the severe Waikato drought of 2020. Glover-Clark (2020) noted that annual subsidence rates should be estimated near the end of winter when the peat surface had reached maximum elevation, because high rainfall in spring or summer can act to reset shrinkage processes. The study period did not quite capture two full swelling cycles, preventing accurate estimation of annual irreversible subsidence, however, given that the change in SE from maximum elevation to minimum elevation occurred over just 9 months, the subsidence rate for the Waikato Region of 19 mm yr^{-1} (Pronger et al., 2014) can be applied to the 12 month period August 2019 – August 2020. Thus, by subtracting 19 mm from measured ΔSE at each paired transducer location, total reversible surface oscillations were around 104 mm at Site SD mid-slope, 65 mm at Site SD hump, and 65 mm at Site BD hump. Like Glover-Clark (2020) found, the magnitude of PSO at these sites over the extended time period still exceeds

[3] For a detailed description of this figure, refer to Figure 5.9 and the accompanying text in Glover-Clark (2020).

most other annual PSO values in the published literature, e.g. 40 mm (Egglesmann, 1984), 40-50 mm (Teatini et al., 2004; Zanello et al., 2011), 40-80 mm (Schothorst, 1982), which could be related to the severity of the drought Waikato experienced, or the year-round growing conditions and intensive land use in New Zealand when compared to Europe.

The PSO mechanisms and processes described by Glover-Clark (2020) are applicable to the extended time period described here, however, there are a few additional points to discuss. Unlike the initial study by Glover-Clark (2020), the magnitude of PSO was comparable between Sites SD and BD hump locations from October 2019 to August 2020, indicating that differences between Sites SD and BD hump locations from March to October 2019 that had been previously attributed to soil physical properties, may not have been the cause. An explanation could be the very similar behaviour of VMC at both sites which was not observed in the initial 10 month dataset or, alternatively, shrinkage occurring deeper in the soil profile. Price and Schlotzhauer (1999) found that shrinkage would take place deeper in the soil profile following compression of surface peat, and Glover-Clark (2020) established that soil physical properties below a depth of around 500 mm were very similar at Sites SD and BD. It remains unknown why such large shrinkage occurred at the mid-slope Site SD location, especially considering that both Wosten et al. (1997) and Glover-Clark (2020) found less shrinkage to occur closer to drainage channels, highlighting an area for further investigation.

As described by Glover-Clark (2020) and further evidenced in the extended dataset, PSO appeared most correlated with RWL during dry conditions; attributed to increasing effective stress on the peat matrix from the receding water table and added overburden stress from overlying peat layers (Oleszczuk et al., 2003). This correlation was particularly prominent over the period from the beginning of May to the middle of June 2020, where minimum SE had been reached at Site SD hump and mid-slope positions while shrinkage continued at Site BD hump; following slightly delayed patterns of RWL recovery.

5. Conclusions and Recommendations

Here, we reported on an extended PSO dataset for two drained peatland sites under similar management but different drainage design and drainage histories in the Waikato Region. By extending the study period of Glover-Clark (2020) by seven months, we have provided further insights into PSO dynamics on Moanatuatua drained peatland. At both sites over 17 months, reversible oscillations were evident, and on an annual basis exceeded most other published values in the international literature, highlighting the importance of separately considering reversible and irreversible subsidence processes.

Experience collecting and processing the 17 months of PSO data has led to a number of recommendations for future use of the paired transducer methodology, which will act to improve the accuracy of data, minimise the time spent processing data, and allow for long term deployment of sites as part of the Waikato Regional Council's subsidence monitoring programme. We recommend:

- Laboratory calibration of each pressure transducer prior to field deployment, so that each probe records the same depth change for any given change in water level;
- Use of a semi-permanent or permanent method to attach RWL probes to the peat surface, to ensure that the probe is returned to exactly the same position in the dipwell after data downloads;
- Instead of having a fully below-ground system, use a small fenced enclosure. This will remove the need to annually readjust the AWL benchmark rod, and allow the RWL probe to be suspended off a larger surface area;
- Dipwell length should be extended from 2 m to 2.5 m, and the distance between RWL and AWL probes should be extended in order to lengthen the time period before readjustment of probe depths is required. Ideally, the RWL would be suspended at least 250 mm above the bottom of the dipwell, and the AWL probe approximately 200 mm above the RWL probe;
- Long term subsidence measurements (i.e. airborne lidar measurements) be surveyed when SE is more stable (i.e. at driest or wettest times), for which the seasonal pattern of RWL will give a good indication of;
- Estimations of irreversible subsidence from the paired pressure transducers be calculated from the points of both maximum surface elevation following the wet winter period, and minimum surface elevation following the dry summer period, averaged over a number of years where possible.

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Appendix 1: Abbreviations

Abbreviation	Term	Explanation
PSO	Peat surface oscillation	Reversible oscillations of the peat surface in response to hydro-climatic conditions.
RWL	Relative water level	Water table depth relative to the peat surface.
AWL	Absolute water level	Water table height above a datum i.e., mean sea level.
VMC	Volumetric moisture content	Moisture content of the peat, represented as the ratio of the volume of water to the volume of peat.
SE	Surface elevation	Elevation of the peat surface level.