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Waikato regional peat subsidence lidar monitoring

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REGIONAL COUNCIL
Te Kaunihera ā Rohe o Waikato

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Waikato regional peat subsidence LiDAR monitoring

Prepared for: Waikato Regional Council

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Contract Report: LC5000

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Summary

Project and Client

- Waikato Region has about 70,000 ha[1] of drained agricultural peatlands that are subsiding due to ongoing shrinkage, consolidation, and oxidation. Continued subsidence results in higher relative water tables, poor trafficability, and increased risk of flooding. Consequently, there is a need for ongoing drainage upgrades and maintenance of other infrastructure. Ongoing subsidence also threatens adjacent wetlands and peat oxidation results in carbon emissions.
- Waikato Regional Council (WRC) require robust spatial information on regional peatland subsidence rates and spatial variation in subsidence rates for state of the environment monitoring, to support implementation of the Waikato Regional Policy Statement (WRPS) and to inform long-term planning.
- WRC have contracted Manaaki Whenua – Landcare Research (MWLR) in collaboration with the University of Waikato and the University of Canterbury to develop a new Waikato regional peat subsidence monitoring network for peatlands under agriculture.
- Previous technical reports summarised subsidence monitoring measurement options (Pronger et al. 2019), testing, accuracy, and uncertainties associated with airborne LiDAR as the chosen survey method (Pronger et al. 2020), and the regional monitoring network design (Pronger et al. 2021). Here we document the first round of regional monitoring and installation of the regional peat surface oscillation monitoring network.

Objectives

- Implement the first round of regional helicopter-based LiDAR flights covering about 10% of peat soils in the Waikato Region. The monitoring network was to cover the range of peat types, peat depths, land use, and drainage management and should be repeated every 5-years.
- Set up long-term continuous monitoring sites within the LiDAR monitoring network to provide continuous measurements of water table levels, peat surface oscillation (PSO) and surface subsidence. Improved understanding of the magnitude and spatial variation of PSO is important for timing of future LiDAR flights to ensure apparent surface change is due to permanent subsidence as opposed to reversable surface oscillation.

LiDAR flights and processing

- LiDAR was acquired across the 12 polygons selected during the monitoring network design phase (Pronger et al. 2021) with a Riegl VUX-240 LiDAR system using an EC120 helicopter under optimal weather conditions on 28 April 2021.

[1] This area estimate is calculated from the area of drained land uses identified in LCDB v5, which includes high and low producing exotic grassland, cropland, orchards, forestry and urban land, on Organic Soils. This area was correct at the time of writing. However, since this report was written area estimates for Organic Soils have changed based more recent soil mapping and landcover may have changed. Frequent soil map updates occurred throughout the project.

- LiDAR data were processed, calibrated, and classified using standard routines into ground and off ground. The average density of classified ground returns was 80 points/m^2 across about 11,000 ha.
- Analysis of the differences between airborne LiDAR (classified ground returns) and ground-based check point data (RTK GNSS) for hard surfaces found a mean 'error' of 0.002 m and a root mean squared error of 0.013 m.
- The reliability of ground identification is affected by vegetation cover. Analysis of densely surveyed plots and LiDAR residuals by Pronger et al. (2020), found that for LiDAR flown at a point density of 45–50 points/m^2, the expected level of vertical change detection will be on average 0.05–0.06 m. This is suitable for measuring expected changes of 0.1 m over 5-year monitoring intervals. Advances in LiDAR technology, including the use of the VUX-240 sensor with greater point density (80 points/m^2) will improve the vertical resolution of change detection. However, detecting differences between land uses, if they exist, may not be possible if differences are small.
- LiDAR flights should be repeated in 5-years at the lowest point in the PSO cycle, likely late autumn 2026. After the second round of flights DEM differencing will be required to quantify subsidence rates.
- Spatial uncertainty in the DEM that reflects average positional errors and incorporates the effects of the apparent ground roughness, principally a function of the vegetation height/structure, will need to be determined from both time points. We recommend spatial uncertainty estimates are derived simultaneously from both DEMs using a suitable Geomorphic Change Detection software suite.

Peat surface oscillation (PSO) monitoring

- The surface of natural peatlands has been shown to oscillate seasonally because of changes in the water-table (Fritz et al. 2008); the magnitude in drained peatlands was unknown before this programme of work.
- Preliminary investigation into the magnitude of PSO on drained agricultural peatlands indicated intra-annual PSO could be of a similar order of magnitude to the expected surface level change over a 5-year monitoring interval (Glover-Clark 2020).
- PSO may therefore confound estimates of subsidence over 5-yearly monitoring intervals, and we recommended establishment of regionally distributed long-term monitoring sites to provide more certainty around the spatial and temporal variation and magnitude of PSO.
- Five paired pressure transducer sites have now been installed on drained peatlands in the Waikato Region: two at Moanatuatua, and one at Rukuhia, Torehape, Komakorau, and the Lower Waikato.
- These continuous monitoring sites will both improve our understanding of the magnitude and spatial variation in PSO and enable us to ensure consistency in PSO position between 5-yearly LiDAR flights or allow us to adjust for PSO. They are therefore critically important for the success of the regional monitoring network.

Summary

- Airborne LiDAR was flown over the Waikato region on 28 April 2021, aiming to capture the lowest water tables and hence lowest point in the PSO cycle. Data were acquired using the University of Canterbury's Riegl VUX-240 LiDAR system mounted on an Eurocopter EC120. LiDAR data was processed, and raw and processed data and digital elevation and digital surface models (DEMs) were provided to Waikato Regional Council.
- Six paired pressure transducer sites have been installed on drained peatlands in the Waikato Region. These continuous monitoring sites will both improve our understanding of the magnitude and spatial variation in PSO, which is likely critically important for the success of the regional monitoring network, and provide detailed information on spatial variation in subsidence and on the response of subsidence to land use and management.

Recommendations

- LiDAR flights should be repeated in 5-years at the lowest point in the PSO cycle, likely late autumn 2026. After this second round of flights, DEM differencing will be required to quantify subsidence rates. Based on current costs a budget of $100,000 should be sufficient to complete future surveys, but this will need to be adjusted for inflation through time.
- Spatial uncertainty in the DEM, from both time points, will need to be determined that reflects average positional errors and incorporates the effects of the apparent ground roughness, which is a function (principally) of the vegetation height/structure. We recommend spatial uncertainty estimates are derived simultaneously from both DEMs using a suitable Geomorphic Change Detection software suite. This will ensure equivalent approaches are used for both DEMs and future advances in uncertainty estimation are incorporated.
- For each of the long-term peat surface oscillation sites, we recommend land management information is collected to inform interpretation of the data. Proposed land use questionnaires are included in Appendix 1. We recommend this information is collected once a longer term (1 year+) data set has been collected.
- PSO sites should be visited bi-monthly for the next 5-years to check all equipment is operational, undertake maintenance, collect manual check measurements, and download sensor data. Global Navigation Satellite System (GNSS) surveying should be repeated annually.
- Rain gauges should be installed (or suitable existing gauges identified) that are closer to the Torehape, Komakorau, and Lower Waikato sites.
- Soil physical properties (e.g. bulk density) at each of the PSO monitoring sites should be characterised to help explain differences in PSO behaviour between sites.

1 Background

The Waikato Region has about 90,000 ha[2] of peatlands, of which about 70,000 ha has been drained, mostly for agriculture, resulting in shrinkage, consolidation, and oxidation of the Organic Soil. These three processes are collectively called peat subsidence, which results in a gradual lowering of the land surface. Continued subsidence results in higher relative water tables that reduce trafficability for farm machinery and stock and increased flooding risk. Consequently, there is a need for ongoing drainage upgrades and maintenance of other infrastructure. This ongoing drainage–subsidence cycle threatens adjacent wetlands and ongoing peat oxidation results in carbon emissions. Subsidence rates are spatially and temporally variable, dependent on factors including time since drainage, land use, land and drainage management, and peat type. In the Waikato region, recent work has reported an average peat subsidence rate of about 20 mm/y (Pronger et al. 2014), although initial subsidence rates can be much higher (van der Elst 1980).

Waikato Regional Council (WRC) require robust spatial information on regional peatland subsidence rates and spatial variation for state of the environment monitoring, to support implementation of the WRPS and to inform long-term planning. WRC have contracted Manaaki Whenua – Landcare Research (in collaboration with the University of Waikato and the University of Canterbury) to develop a new Waikato regional peat subsidence monitoring network for peatlands under agriculture.

Here we document the first round of regional helicopter-based LiDAR flights and installation of continuous ground-based water table and surface elevation monitoring sites. Previous technical reports reviewed the measurement options and rationale for selection of helicopter based airborne LiDAR as the preferred measurement method (Pronger et al. 2019), testing, accuracy, and uncertainties associated with the airborne LiDAR survey methods (Pronger et al. 2020) and development of the regional monitoring network (Pronger et al. 2021). In brief:

- Airborne LiDAR was selected because it is proven technology with comparatively straight forward validation procedures. Using helicopter as the platform for a LiDAR sensor provides flexibility in flight height and speed where trade-offs between data quality and coverage can easily be adjusted to suit the monitoring network purpose (Pronger et al. 2019).
- Testing showed that for LiDAR flown at a point density of 45–50 points/m^2 it is likely the change detection threshold will be on average about 0.05–0.06 m (dependent largely on vegetation cover) and therefore suitable for measuring expected change of 0.1 m over 5-year monitoring intervals (Pronger et al. 2020).
- A quantitative sampling focus map was developed and used, together with local knowledge, historic imagery, and expert judgement, to design a regional scale peat subsidence monitoring network (Fig. 1). The monitoring network to be surveyed with

[2] This area estimate is based on the extent of Organic Soils within the Waikato Regional Council boundaries estimated from the combination of S-map where complete and the Fundamental Soils Layer where S-map data was not available and was correct at the time of writing. However, since this report was written area estimates for Organic Soils have changed based more recent soil mapping. Frequent soil map updates occurred throughout the project.

airborne LiDAR consisted of 12 polygons ranging in size from 300 to 2400 ha that covered the range of factors of interest, including peat type and depth, land use, and drainage management (Pronger et al. 2021).

- Repeat LiDAR survey over these polygons should provide robust regional subsidence data and supply WRC with the information needed to meet the requirements of the WRPS. However, assuming difference in management effect subsidence rates, detecting differences between land uses and management practices may not be possible over a 5-year monitoring period if differences are small.

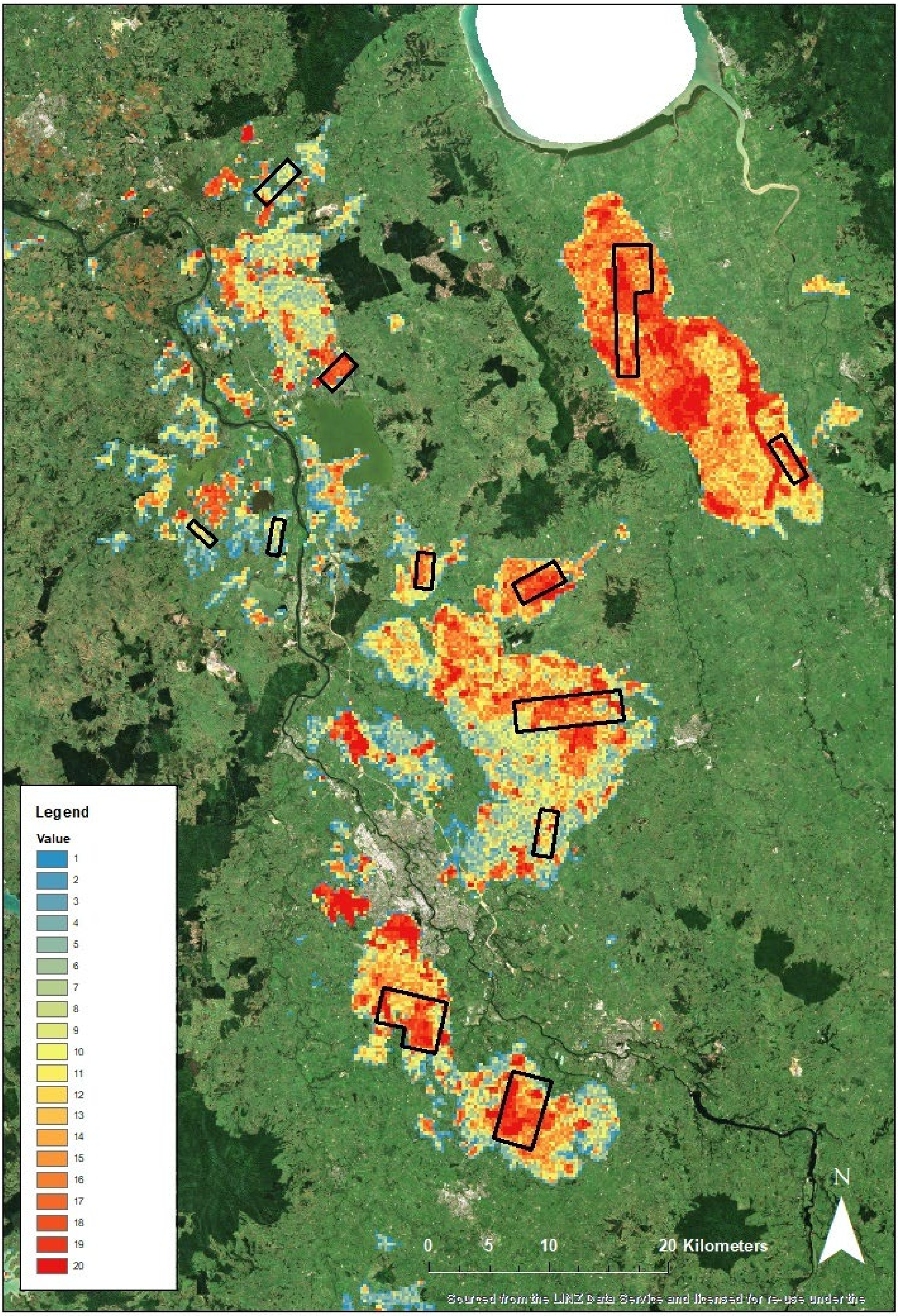

Figure 1. Sampling focus map for the Waikato Region. Blue colours show areas where the combination of factors of interest are common, while red colours show where the combination of factors of interest are less common.

2 Objectives

The objective of the final phase of Waikato Regional peat subsidence monitoring project was to implement the first round of regional helicopter based LiDAR flights covering about 10% of peat soils in the Waikato Region (including the Lower Waikato River catchment, the Hauraki Plains and Hamilton Basins). The monitoring network covered the range of peat types, peat depths, land use, and drainage management and should be repeated every 5-years. An additional objective was to set up long-term continuous monitoring sites within the LiDAR monitoring network to provide continuous measurements of water table levels, peat surface oscillation (PSO) and surface subsidence. Improved understanding of the magnitude and spatial variation of PSO is important for timing of future LiDAR flights to ensure apparent surface change is due to permanent subsidence as opposed to reversable surface oscillation.

3 LiDAR data collection

3.1 Flight planning

3.1.1 Landowner contact

Letters were sent to all landowners in the polygons or within 500 m of the boundary to explain what was being done, its purpose, and approximate timing of flights. Contact information was provided so that landowners could discuss concerns with us. A small proportion of landowners were concerned about the helicopter scaring stock, especially horses. Concerned landowners were contacted the day prior to flights to let them know exactly when the helicopter was flying. We are not aware that any adverse effects on stock occurred during the flights, we deliberately used a quiet helicopter (Eurocopter EC120) and flew at 245 m elevation to minimise potential disturbance.

3.1.2 Helicopter operator

Christchurch Helicopters were the preferred operator because they had suitable experience and were working with the University of Canterbury (UoC) to develop a system that integrates UoCs Riegl VUX-240 LiDAR, an inertial measurement unit (IMU) and a high resolution camera system. This integration reduced the potential for data errors or reliability issues and given the time and cost required to set up an integrated system, justified the significant ferry cost from Christchurch (4–5 hours flight time each way). The UoC and Christchurch Helicopters were able to complete other work while in the North Island, therefore spreading the impact of the ferry flight from Christchurch.

3.1.3 Flight plan

A flight plan was developed (Fig. 2) based on the chosen polygons using Hamilton airport (Helicorp Ltd) as base. The above ground survey height (245 m) and flight speed (90 knots) were defined to acquire LiDAR data at a nominal pulse density (NPD) of 80 points/m^2 and across a swath width of 280 m (based on a 60-degree field of view). For each survey area, flight lines were oriented parallel to the longest axis of the area of interest to minimise the number of turns. An additional flight line was flown at 90 degrees to this long-axis, to provide a consistent reference to support adjustment of all swaths to a common dataset (Fig. 3). An Airbus EC120 was used to deploy the LiDAR, supported by a single LiDAR operator, and flight management system (TopoFlight) to guide the pilot.

The survey was flown approximately South-to-North, in the order: Hamilton Basin; Lower Waikato; then Hauraki. Two stops for refuelling were required, first at Hamilton Airport and then at Thames Airport.

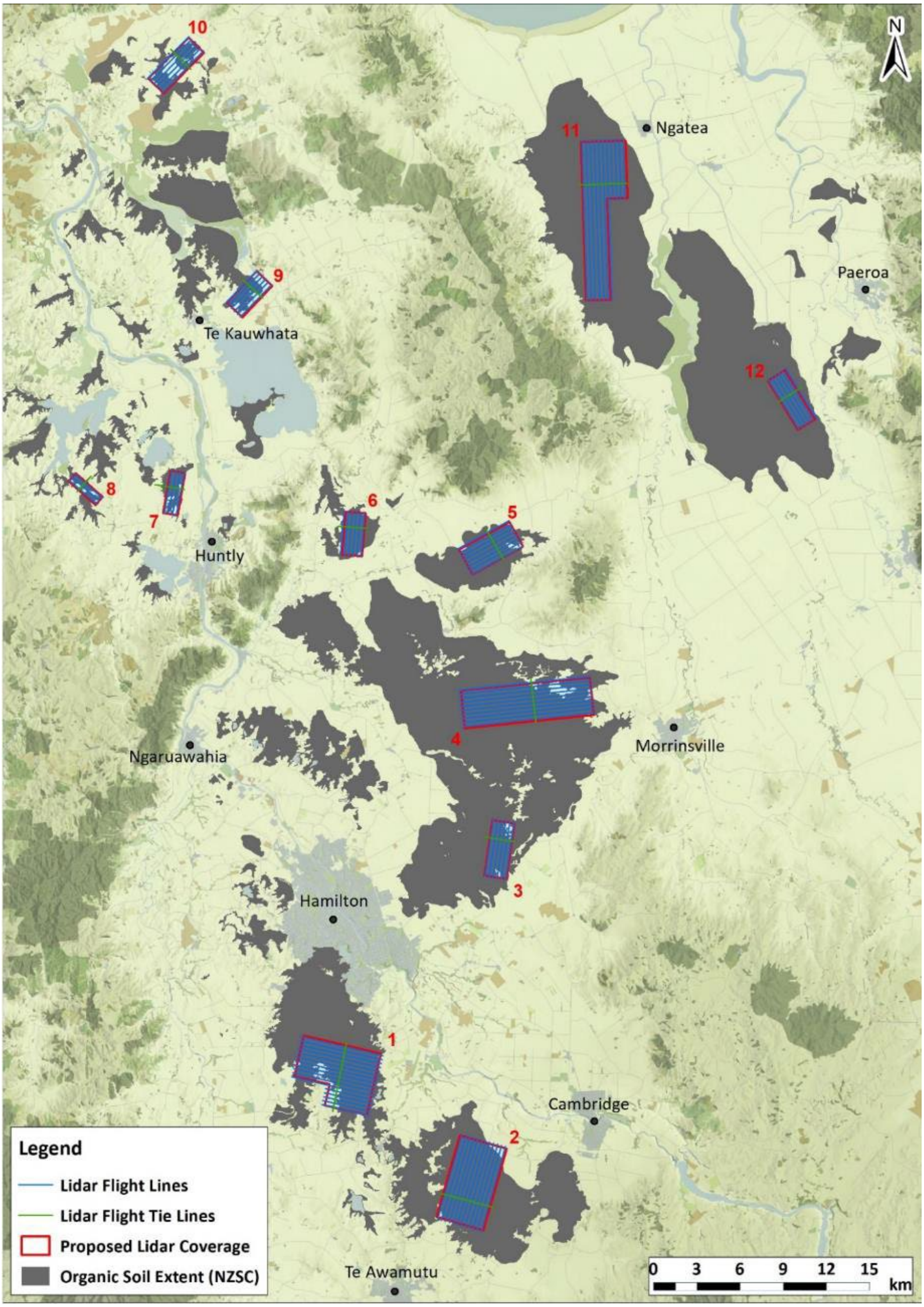

Figure 2. Waikato Regional flight plan. The blue lines show the actual flight lines over each proposed LiDAR coverage area, these are shown as red polygons. The numbers show the order of flight, with 1 being flown first and 12 the last. Dark grey = extent of Organic Soils, and therefore the area of interest.

Figure 3. Example of flight lines and actual LiDAR coverage area from Moanatuatua, which was flown second (see Fig. 2). LiDAR flight lines, in blue, were flown along the longest axis to minimise turning time, and then a perpendicular flight line, in green, was carried out at completion to tie all flight lines together. LiDAR captured from each flight line overlapped the next, and actual LiDAR coverage, indicated by the black lines, was slightly larger than the proposed area, shown as by the red polygon.

3.2 LiDAR flights

We flew the first round of monitoring in autumn (28 April 2021) aiming to capture the lowest water tables and hence lowest point in the PSO cycle (see section 4). The LiDAR flights over the Waikato region (Hamilton Basin, Lower Waikato, and Hauraki Basin) were completed in a single day, the EC120 helicopter (Fig. 4a) lifted off from Hamilton airport around 9 am and flights were completed by 5.30 pm. Weather conditions were clear with little wind, a light morning fog and dew were allowed to burn off before lift-off. Unsettled weather earlier in April postponed flights several times.

Figure 4. (a) Airbus EC120 being prepared for LiDAR flights on 28 April 2021 at Hamilton Airport, (b) LiDAR sensor array mounted in an enclosed pod and carried on a forward mounted boom.

3.3 Data acquisition

3.3.1 Airborne data acquisition

Data were acquired using the University of Canterbury's Riegl VUX-240 laser scanner. This sensor was deployed as part of a turnkey LiDAR system that integrates the VUX-240 with an Applanix AP50air inertial navigation system and a PhaseOne iXM50 RGB camera. The sensor array is mounted in an enclosed pod and carried on a forward mounted boom as shown in Figure 4b.

This system represents a significant enhancement on the VUX-1LR scanner used during the trials undertaken in 2019 (see Pronger et al. 2020), with a higher pulse frequency and longer-range capability. This enabled an increase in the nominal pulse density from 40 to 80 pulses per square metre (ppsqm) while also facilitating a higher operating altitude (above ground height from 150 to 245 m) and faster flight speeds (40 to 90 knots). The key differences in the sensor and flight parameters are shown in Table 1.

Table 1. Key differences in the sensor and flight parameters of the VUX1-LR used during testing and the higher specification VUX-240 used for the first round of monitoring

	VUX-1LR	VUX-240
System and Survey Parameters		
Pulse repetition rate (kHz)	820	1800
Scan frequency (lines/sec)	128	400
Field of view (degrees)	60	60
Beam divergence (mrad)	0.5	0.35
Above ground height (m)	150	245
Flight speed (Knots)	40	90
Acquisition Design		
Nominal pulse density (pulse/m^2)	40	90
Swath width (m)	173	283
Footprint diameter (m)	0.05	0.06

Aerial photographs (4-cm ground resolution) were acquired with the LiDAR survey, and used subsequently to colour code each laser point with an associated RGB (red, green, blue) colour index. This supports visual data quality assessment and point cloud classification (into ground and off-ground returns).

3.3.2 Ground support data

Correction of roving position

The sensor trajectory (position and attitude) was captured using an AP50air inertial navigation system, coupled to the LiDAR. This system uses a Trimble AV39 antenna, mounted on the tail of the helicopter to reduce rotor shadow and minimize cycle slips and multipathing, therefore reducing the likelihood of GPS positional errors. Differential correction of the survey trajectory was undertaken using Applanix PosPac MMS software, using SmartBase kinematic processing. This approach is ideally optimized for large area surveys (there is 85 km separating the Moanatuatua and Motukaraka sites) and uses tightly coupled processing with a network of reference GNSS stations to integrate satellite observables and inertial measurements to solve position and orientation.

The Applanix SmartBase processing enables high accuracy, differential kinematic correction by using a network of reference stations to estimate the effects of atmospheric and other errors that affect GNSS observables over a regional 'window'. The approach enables homogeneous correction results over a large survey area, minimizing the effects of distance to individual reference stations, and generating solutions equivalent to short-baseline processing.

The survey used GNSS observations recorded at seven reference stations distributed across the Waikato as shown in Figure 5. These comprise a mix of zero-order LINZ continuously operating reference stations (CORS) and stations on the Trimble VRSnow network. Details of the seven reference stations used to construct the SmartBase network are given in Table 2 below.

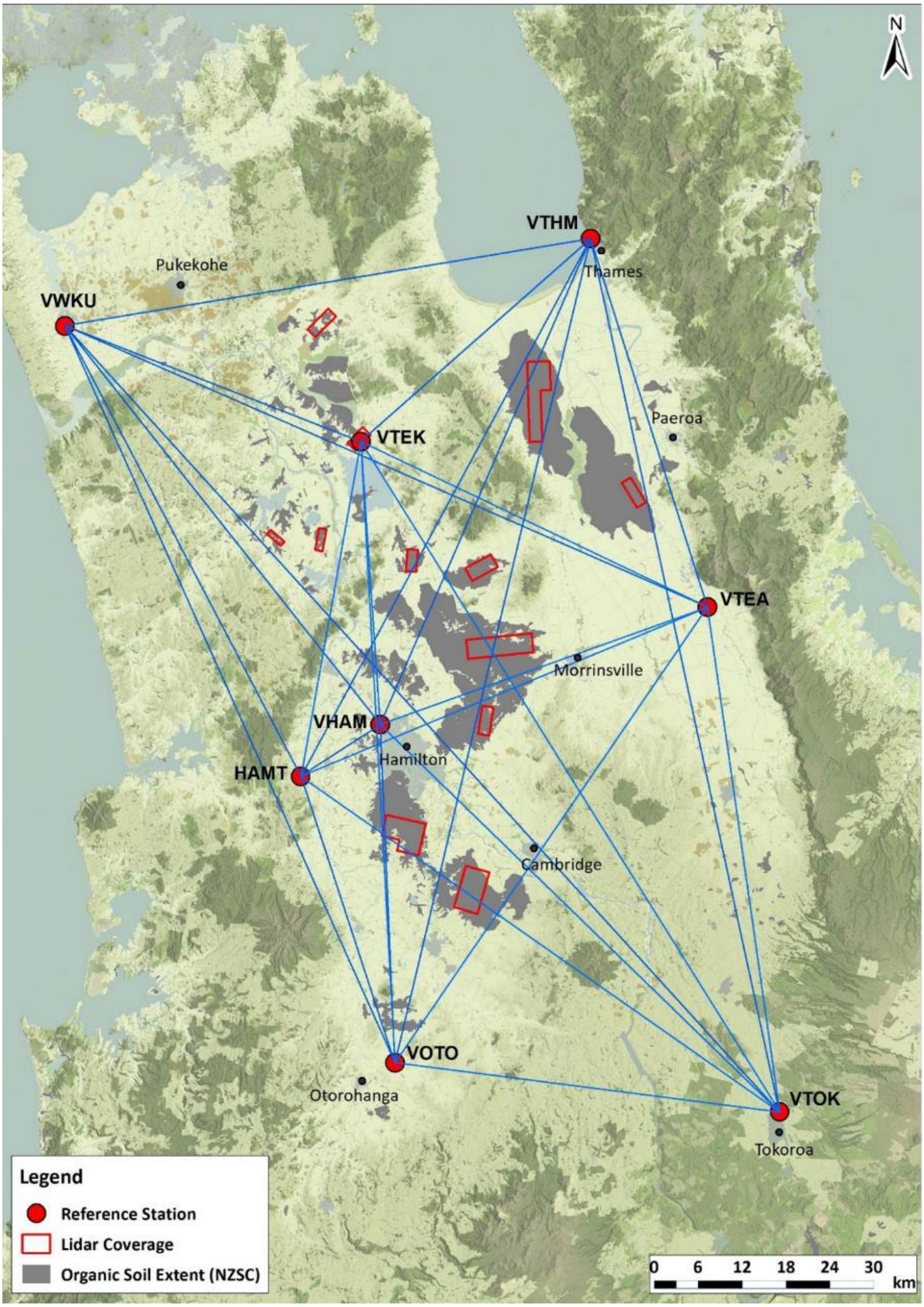

Figure 5. Network of continuously recording GNSS reference stations used to construct the SmartBase network for correction of the sensor trajectory. The blue lines represent the triangulation between sites. Detailed information about each station location and elevation is provided in Table 2.

Table 2. Details of the continuously operating reference stations (CORS) used for trajectory correction

Location	Station Code	Latitude	Longitude	Height (Elevation, m)
LINZ Waiuku	VWKU	S 37° 15' 23.69462"	E 174° 43' 46.08860"	55.921
LINZ Thames	VTHM	S 37° 08' 05.03121"	E 175° 32' 12.37559"	44.448
Te Kauwhata	VTEK	S 37° 23' 32.06063"	E 175° 11' 24.56335"	46.781
Te Aroha	VTEA	S 37° 35' 05.98529"	E 175° 43' 59.43364"	57.612
Hamilton	VHAM	S 37° 44' 25.53255"	E 175° 13' 50.46952"	81.920
Hamilton_LINZ	HAMT	S 37° 48' 24.29269"	E 175° 06' 33.11584"	69.407
Otorohanga	VOTO	S 38° 09' 26.90399"	E 175° 15' 58.48067"	73.646
Tokoroa	VTOK	S 38° 12' 18.90988"	E 175° 52' 09.60787"	373.656

3.4 Data processing

3.4.1 Trajectory processing

LiDAR positioning and orientation was solved using Applanix PosPac MMS, employing the network of seven reference stations described above. Solutions were obtained forward and backwards in time and combined to generate a Smoothed Best Estimated Trajectory (SBET), providing a constant position and orientation of the helicopter to process with the laser range data to calculate the co-ordinates of all measured returns. The resulting timeseries of estimated errors in position and attitude are shown in Figure 6 and were provided in raw 200 Hz format as part of the data deliverables.

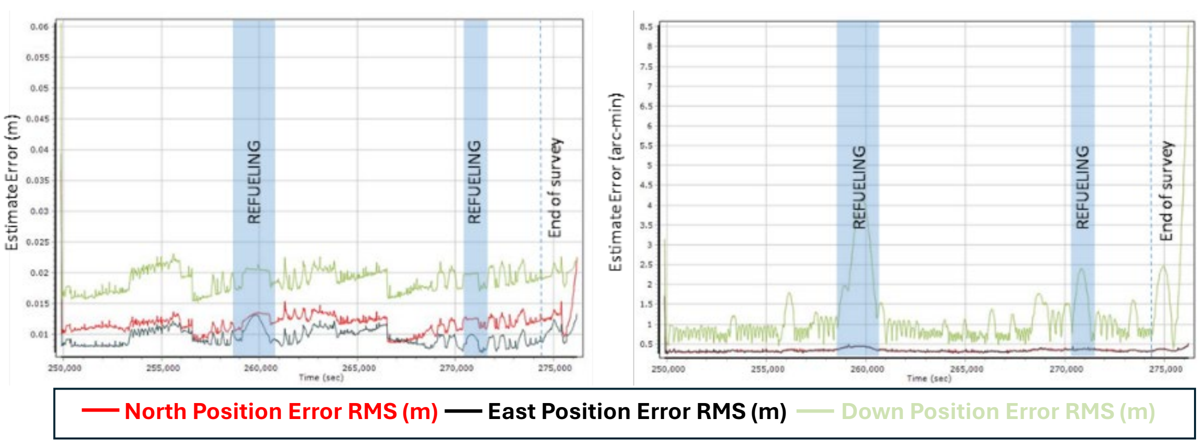

Figure 6. Timeseries of estimated errors in position and attitude.

These reveal instantaneous horizontal errors typically in the range 0.008–0.015 m, slightly higher vertical errors (as expected) between 0.015 and 0.02 m, and attitude errors all below 1 arc-min during survey periods.

3.4.2 Analysis of LiDAR echoes and georeferencing

Initial post-processing of the LiDAR data involved: (1) analysis of the LiDAR waveforms to detect targets; (2) georeferencing the LiDAR 'echos' (laser returns) to using information on the position and attitude of the sensor encoded in the corrected trajectory (3); calibration of the data to minimize differences between overlapping areas (so-called swath adjustment); and (4) absolute adjustment to known (observed) targets measured in a local or global coordinate system.

This post-processing workflow was undertaken using the Riegl RiUnite 1.9 software suite, which also provided tools to map RGB (red, green, blue) colour intensities in the simultaneously acquired camera imagery on to each LiDAR return.

3.4.3 Ground and above ground classification

Data were classified using standard routines into ground, above ground and noise using the LAStools suite for LiDAR data processing (Fig. 7). The resulting median ground return density over the entire survey area averaged 80–85 points/m^2.

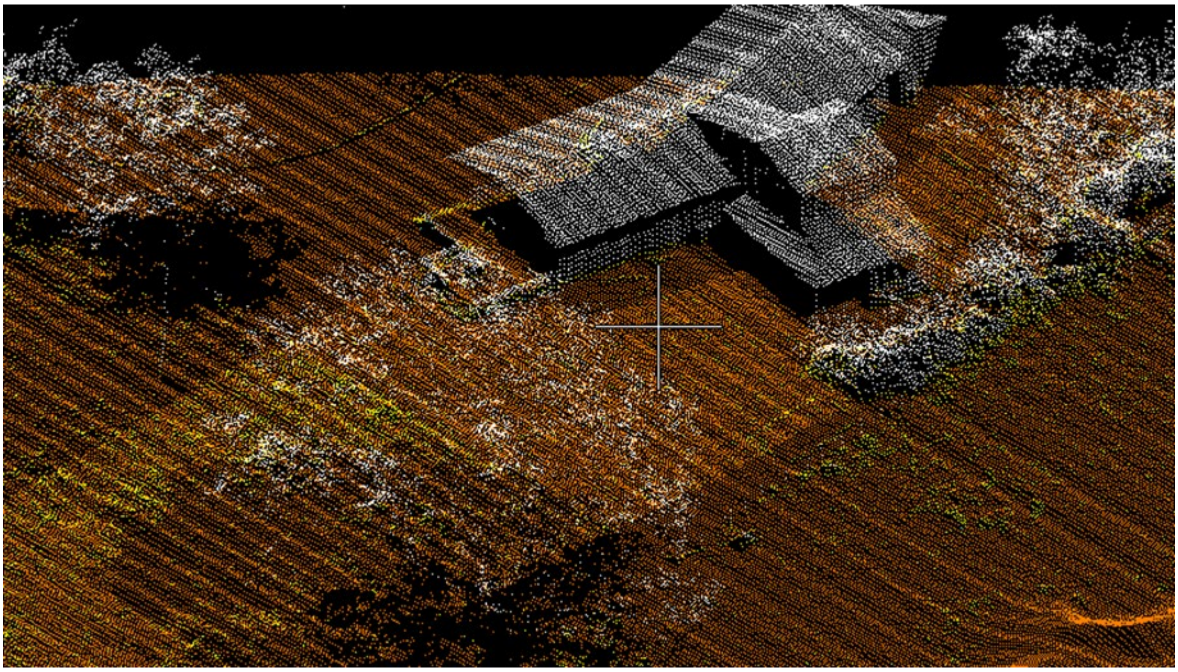

Figure 7. 3D perspective view of a section of classified point cloud from the Motukaraka survey. Data are classified as ground = orange; above ground = white.

The breakdown of classified LiDAR returns, distinguished into ground and above-ground classes (ignoring noise), is provided in statistical summary files for each plot, supplied in the data package (See section 3.6 for further details). These incorporate information on the time of collection, the number of returns (classified into first, last, intermediate, and single) and the number of classified ground and off-ground returns. An example of the classified results for the Rukuhia survey area (comprising over 2.3 billion survey points) is presented in Table 3.

Table 3. Breakdown of classified returns at Rukuhia

Variable	Classification Code	Class	Number Observations
Classified Ground	2	Ground	2,113,004,059
Classified Off-Ground	1	Above Ground	126,028,835

3.5 Check point analysis

3.5.1 Ground-based check point data

A ground survey of check point data was collected for hard surfaces only across the Waikato Region on 28 and 29 April 2021 co-incident with the airborne survey. Check point data were acquired using Leica GS16 GNSS system operating using network RTK GNSS based on the Global Survey SmartFix network. Where possible, we targeted road intersections where painted road marking could be used to ensure airborne LiDAR and ground-based checkpoint data were directly comparable.

The analysis of elevation deviations between the LiDAR and ground survey observations involved comparison of single GNSS elevation checkpoints against a plane fitted to the nearest 20 ground returns, as specified by the American Society of Photogrammetry and Remote Sensing (ASPRS 2015). Based on these point-to-plane comparisons, 95% of the LiDAR observations fall within 0.026 m of the observations. It should be noted that this is a conservative estimate, which implicitly incorporates uncertainty in the GNSS check-data, so that the comparison with a 'true' reference dataset is likely to reveal a higher level of performance.

Hard surfaces (*n*=): 177.

SD of elevations = 0.013 m; RMSE = 0.013 m; mean difference = 0.002 m.

3.6 Summary of workflow

1. LiDAR data was acquired on 28 April 2021 covering 12 polygons over a total of about 11,000 ha of drained peat soils in the Waikato region.
2. Trajectories were processed in PosPac MMS 8.6, using SMARTBASE processing from network of CORS (Fig. 5).
3. LiDAR was processed in RiProcess. This included target identification, georeferencing, swath alignment, calibration, and isolated point filtering.
4. All data projected into NZTM-NZVD16.
5. LAS data colourised using boresight calibrated PhaseOne iXM50 imagery acquired simultaneously with LiDAR.
6. Point cloud was classified using LASTools (Table 3).

7 Quality assurance including comparison to ground-based check point data and data tiling using Terrascan.

8 DEM, DSM, and intensity rasters were generated at 1 m using LASTools BLAST.

9 Data package was compiled and supplied to WRC as detailed below.

3.7 LiDAR data package

A data package was supplied to WRC that included:

- Reports
  - Trajectory processing reports for the correction and smoothing of the flight trajectories.
  - Calibration and check point data including a swath alignment report and spreadsheet containing ground control points.
  - LAS information by area of interest including information summaries per point cloud, generated from LASTools.
- Spatial data and models
  - Tiled classified (codes 1 and 2) LAS files using LINZ tile index.
  - Gridded data with 1 m rasters including DEM, DSM, and intensity.
  - Area of interest shapefiles.
  - Trajectory at 200 hertz position data in GPS time of day (NZTM/NZVD16).
- GNSS reference data
  - Continuously operating reference station data as GNSS Rinex files for all reference stations used in the trajectory modelling.
- Calibration and check point data
  - Spreadsheet containing 3D calibration and checkpoint residuals.

Examples of the digital surface model (DSM, Fig. 8) and digital elevation model (DEM, Fig. 9) produced from the regional LiDAR survey are shown below. The DSM includes the elevations of trees, buildings and other natural and built features above bare earth; a DEM, however, represents only bare earth referenced to the NZVD 2016 vertical datum.

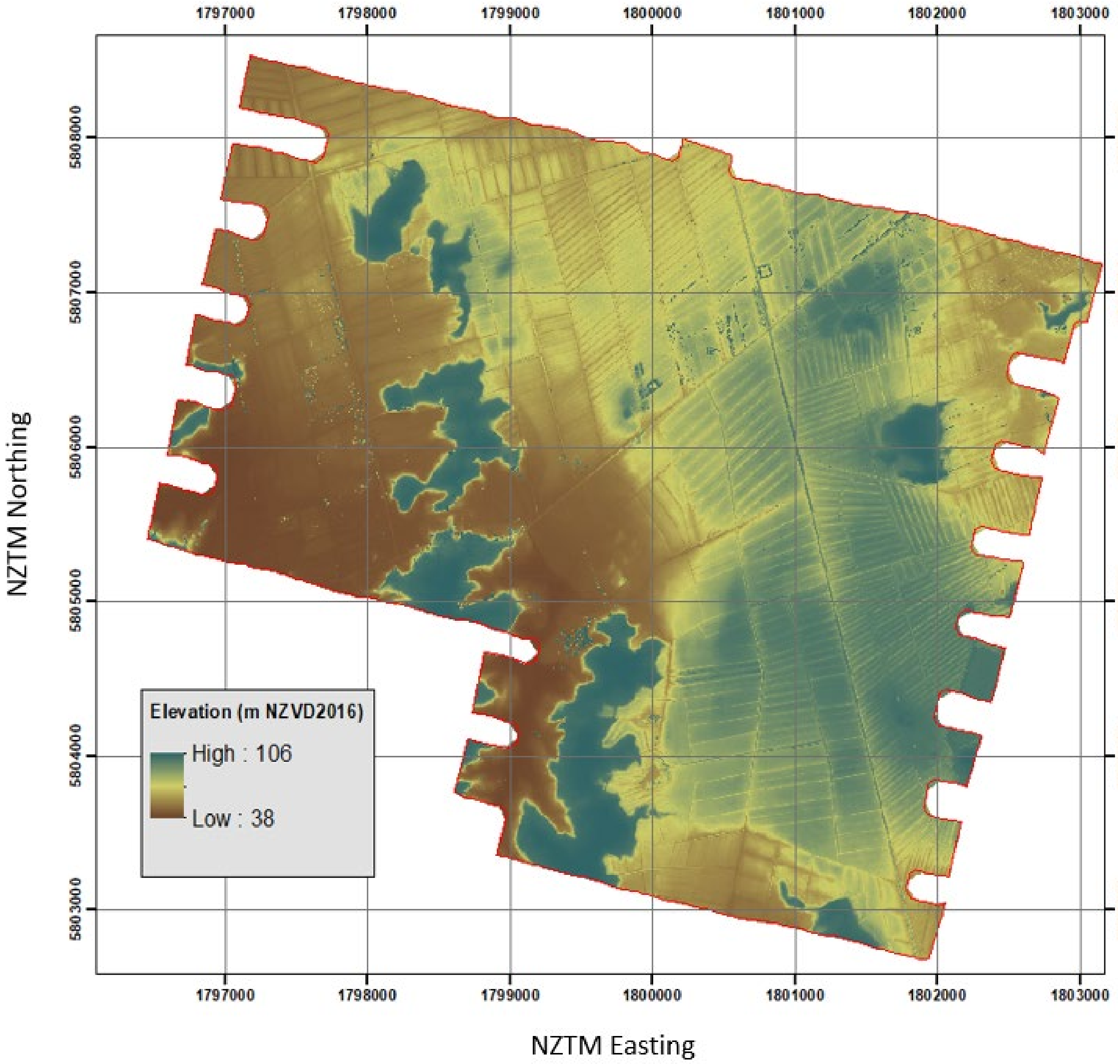

Figure 8. Example digital surface model (DSM) for the Rukuhia LiDAR transect.

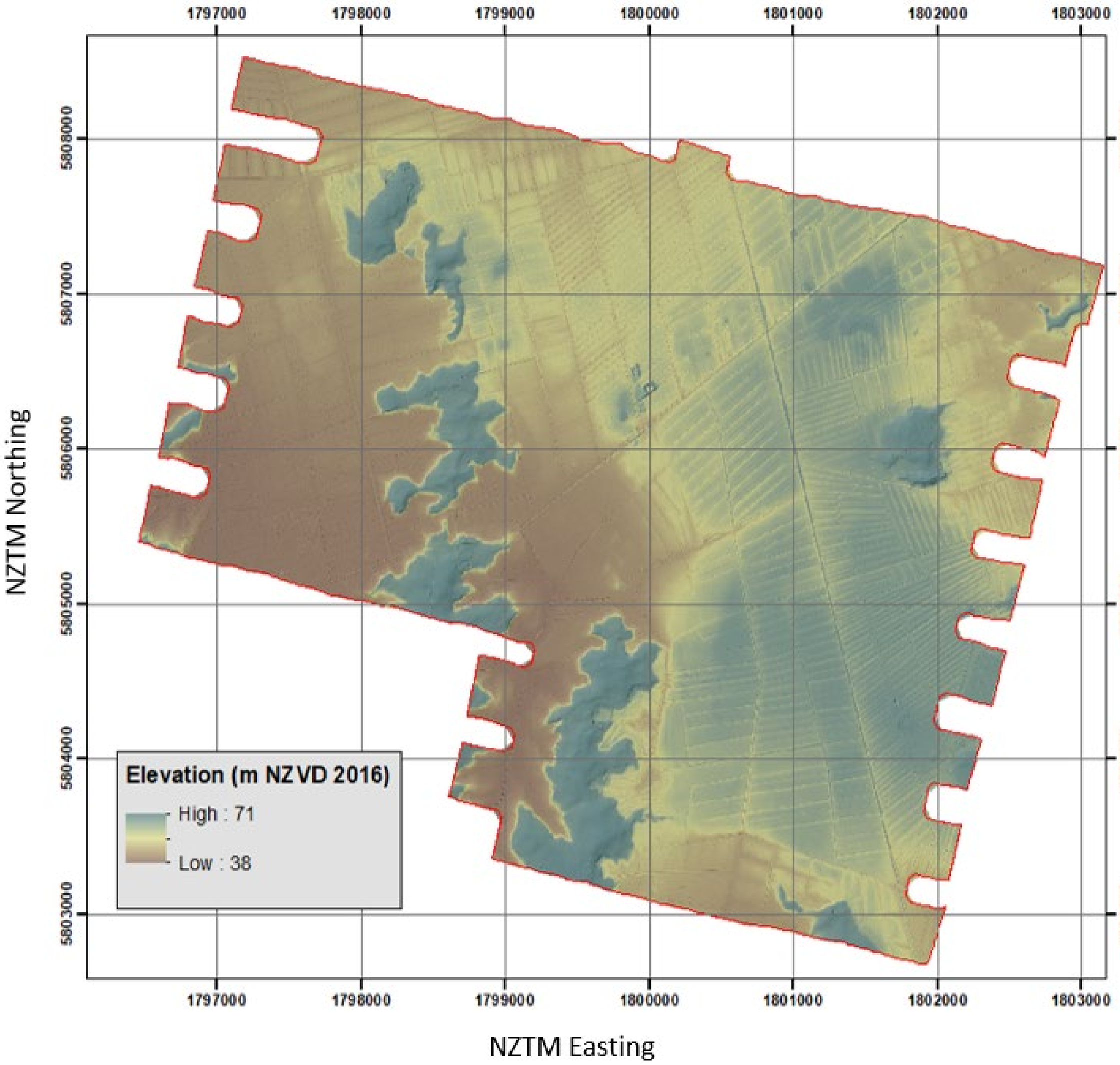

Figure 9. Example digital elevation model (DEM) for the Rukuhia LiDAR transect.

3.8 Future DEM differencing and uncertainty estimation

Future regional subsidence estimates will be based on differencing of LiDAR derived DEMs. We recommend spatial uncertainty estimates are derived that reflect average positional uncertainty and the effects of the apparent ground roughness, which is a function (principally) of the vegetation height/structure. This approach to characterizing DEM uncertainty is readily incorporated into approaches to quantify elevation change by DEM differencing (see Brasington et al. 2003; Wheaton et al. 2010) and implemented using the Geomorphic Change Detection software suite (Vericat et al. 2017). This would involve the calculation of a 'total propagated error' metric for each DEM that combines a global measure of georectification accuracy with a spatial distributed measure of surface uncertainty (roughness).

An example of the proposed approach to quantify surface roughness is detailed in an earlier report (Pronger et al. 2020, section 5.5). The example used LiDAR data collected over Moanatuatua peatland in June 2019 and was based on the approach pioneered by

Brasington et al. (2012) to quantify gravel particle-grain size on exposed river-bed sediments from laser scan data. In brief, a regular grid is used to sample the classified ground returns and determine the local moments (mean, SD, kurtosis, and skewness) of the elevation distribution corresponding to each grid cell. The sampling grid is then detrended to disambiguate the effects of topography (low frequency elevation variability) from the observed surface roughness (higher frequency variability). Classified ground returns, and the resulting mapped pattern of detrended standard deviation of elevation shown in Figure 10. This map clearly captures the effects of pasture grazing at the paddock scale, with recently grazed surfaces characterized by a low SD of elevation (0.01–0.02 m), while paddocks with longer pasture have detrended SD in the range of 0.04–0.05 m. This metric could be combined to generate a composite measure of DEM uncertainty, combining the average positional (as an areal average) and the spatially variable roughness metric.

Assessment of uncertainty associated with vegetated surfaces was quantified during the testing phase of this project (see Pronger et al. 2020). Briefly, for LiDAR collected at about 50 points/m^2 using the Riegel VUX-1LR LiDAR we calculated an average change detection threshold over vegetated surfaces of about 6 cm but expected this to vary with pasture length (see further detail in Pronger et al. 2020). Budget constraints meant the labour-intensive process used to determine vertical accuracy over a range of vegetated surfaces could not be repeated for the current survey using the VUX-240. However, the regional LiDAR survey detailed in this report was collected at a higher return density (about 80 points/m^2) using a more advanced LiDAR (Riegel VUX-240) and this will improve the vertical resolution of change detection.

Figure 10. Detrended SD of elevation of the ground returns calculated at a 0.5-m grid sampling for the Moanatuatua LiDAR testing flown in June 2019. Shorter pasture is characterised by low SD of elevation (darker colours), while longer pasture (rougher surfaces) have higher SD of elevations (lighter colours).

3.9 Budget for future monitoring

WRC requested that future round of 5 yearly monitoring cost no more than $100,000, at present day costs (mid-2021). Based on the first round of monitoring we think this is achievable and that the tasks should be split as follows; 15% of the budget for project management (job safety assessment, flight planning, liaising with landowners), 25% for helicopter time, 10% for ground truthing, 30% for data processing and DEM differencing, and 20% for reporting and communication of results.

4 Peat surface oscillation (PSO) monitoring

Preliminary investigation into the magnitude of PSO on drained agricultural peatlands indicated intra-annual PSO could be of a similar order of magnitude to the expected surface level change over a 5-year monitoring interval (Glover-Clark 2020). PSO may therefore confound estimates of subsidence over 5-yearly monitoring intervals, and we recommended establishment of regionally distributed long-term monitoring sites to provide more certainty around the spatial and temporal variation and magnitude of PSO. These monitoring sites would ensure consistency in PSO position between 5-yearly LiDAR flights or allow us to adjust for peat surface oscillation if necessary.

While the focus for this contract was to install sites on pastoral land use, an aligned contract with the University of Waikato (funded by WRC) installed additional sites, paired to the pasture sites, to determine if there is a difference in subsidence rates between different land uses on drained peat soils in the Waikato Region (Glover-Clark 2021).

It is also important to note that during contracting and scoping of this project, it was suggested to sample 100 ground-based point measurements across the Waikato region coincident with the regional airborne LiDAR survey. At each of these points it was proposed to measure peat depth, water table depth, ground surface height and collect land management information. However, given the standard deviation (SD) of sample differences between LiDAR acquired during testing at ~50 points/m^2 (Moanatuatua) and ground-based checkpoint data for grass (the dominant landcover) were between 0.01 and 0.02 m (Pronger et al. 2020), there was limited value in one-off ground-based RTK GNSS spread across the region (beyond expected ground truthing of LiDAR survey). In consultation with WRC it was decided greater long-term value would be gained by using allocated budget to establish several long-term continuous monitoring sites spread across the region. Continuous monitoring sites will both improve our understanding of the magnitude and spatial variation in peat surface oscillation, which is likely critically important for the success of the regional monitoring network and provide detailed information on spatial variation in subsidence and on the response of subsidence to climate, land use and management.

4.1 Site selection

The objectives of this monitoring network were to provide regionally distributed information of the magnitude and temporal variation in PSO and to examine differences in subsidence between different land uses. The preferred design was to install replicate clusters of three contrasting land uses (blueberries, drystock, and dairy) (Fig. 11). However, because of the difficulty in finding the three land uses in close proximity, on similar depth peat, and then gaining permission from the three adjacent landowners we ended up compromising and selecting paired blueberry and dairy pasture sites. If land use effects exist, this comparison should maximise our chance of detecting significant differences because of the very different management practices between dairy farming and blueberry production. Drystock sites on peat soils were difficult to find because most pastoral land use on peat is used for dairy farming. Only two large representative drystock farms were identified on peat soils (at Rukuhia and Komakarau) and sites were established on these farms separately from the paired sites to provide data from this land use.

Regional coverage required sites in the Hamilton Basin (Moanatuatua, Rukuhia and Komakarau), the Hauraki, and the Lower Waikato (Fig. 12). An existing site was already established on a dairy site at Moanatuatua (Moa, UoW research site). This site had been operational for close to 2 years (20 months) and a continuous record here was valuable. We retained this site but reconstructed it to reflect the improved design outlined in 4.3, thus having to place the new site adjacent to the existing site. Taking into consideration the scarcity of blueberry land use across the region, we established another dairy site further north at Moanatuatua and paired both Moanatuatua dairy sites with blueberry sites (established under the aligned contract with UoW). A dairy and a drystock site were also established at Rukuhia (Ruk) and the dairy site was paired with a blueberry site under the aligned UoW contract. A drystock site was established at Komakarau (Kom), here unfortunately we were unable to gain access to the only suitable blueberry site. A dairy site was established at Torehape (Tor) in the Hauraki, and this was paired with a blueberry site under the aligned UoW contract. A dairy site was also established in the lower Waikato (LoW) at Motukaraka and plans are in place to establish another dairy site in the Lower Waikato at Te Ohaki.

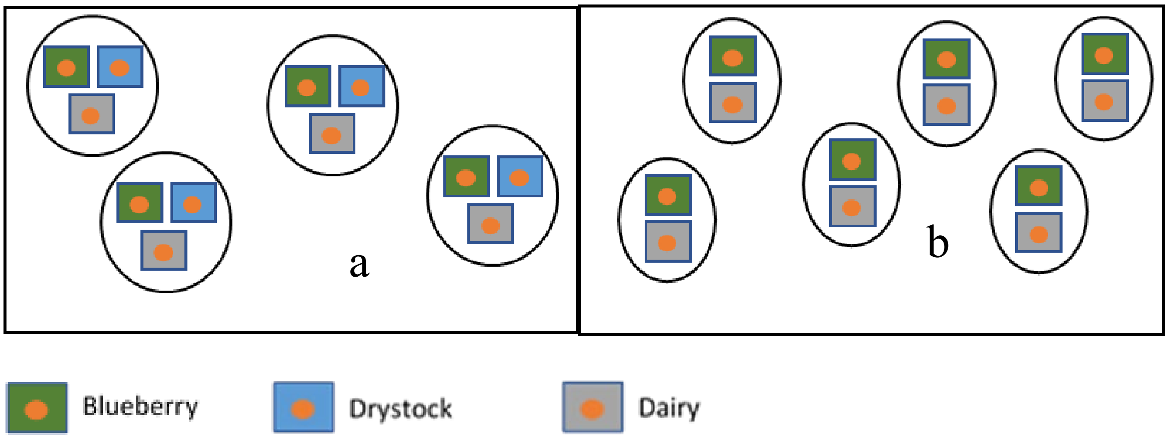

Figure 11. Panel a shows the preferred design for the peat surface oscillation sites (replicated clusters of blueberries, drystock and dairy). Panel b shows the compromise made (compare blueberry to dairy pasture) because of the difficulty in finding the three adjacent land uses in close proximity, on similar depth peat, and then gaining permission from the three landowners.

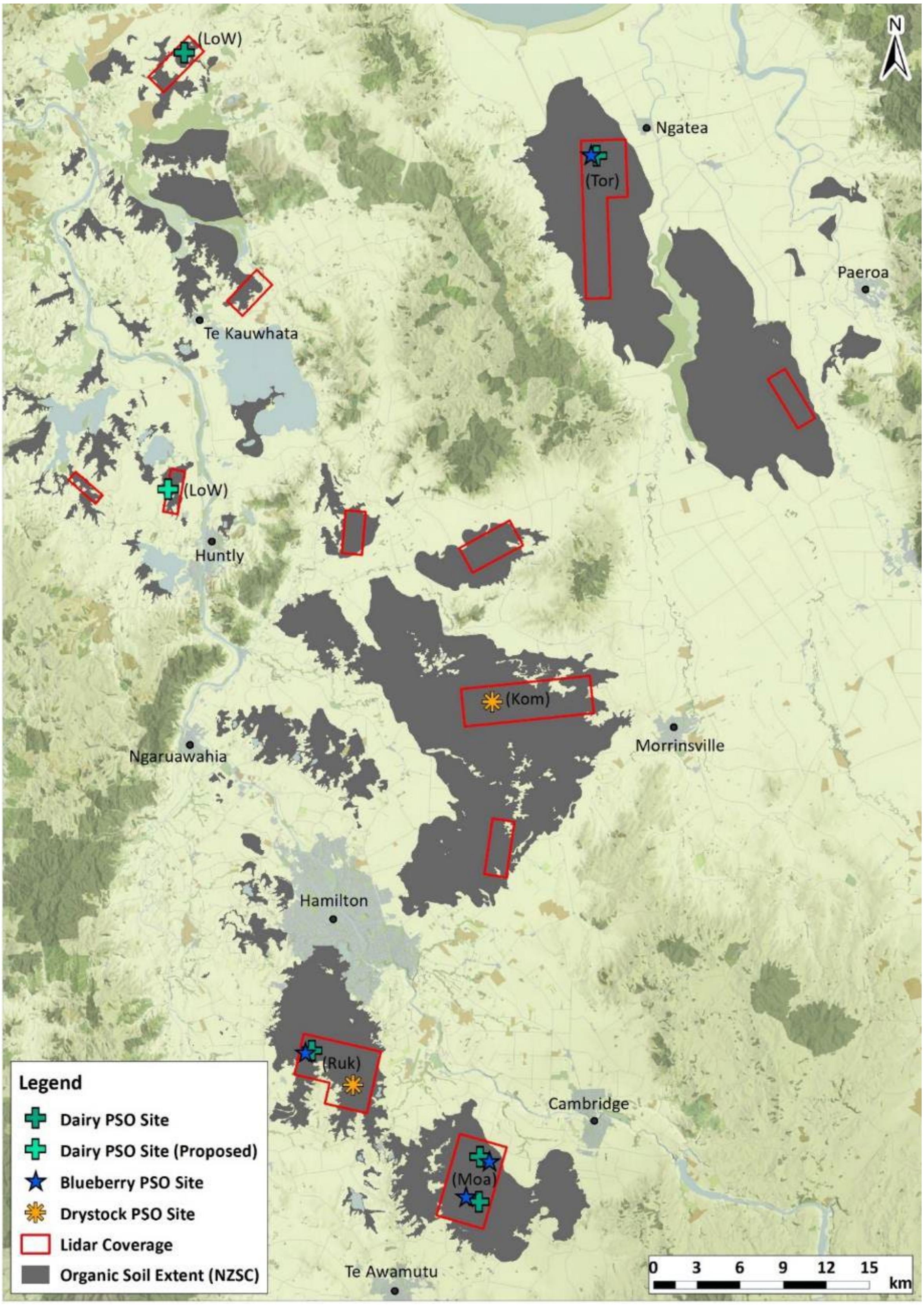

Figure 12. Location of installed and proposed peat surface oscillation (PSO) monitoring sites. The purpose of all sites is to provide a check for repeat LiDAR surveys and to better understand peat surface oscillation. Where dairy and blueberry sites occur adjacent to each other they are also for the purpose of paired land use investigations. The text in parenthesis are abbreviations of site locations referred to in the body of the report.

4.2 Landowner contact and permission

To seek permission to install a continuous monitoring site at the selected locations, landowners were sent a letter (landowner contact details was sourced through Agribase) explaining what we were doing and why, including photos and diagrams of the proposed set up. This was followed up with a phone call, and if agreeable, an in-person meeting to discuss and gain permission to install and revisit sites for bi-monthly downloading of data.

Appendix 1 includes a draft communication and land use questionnaire to collect information that will help us to interpret results from the peat surface oscillation sites. We recommend this is sent to landowners once a longer term (1 year+) data set has been collected.

4.3 System Design

The system design was based on the approach used by Fritz et al. (2008) and Glover-Clark (2020). Half-hourly fluctuations in water table depth and peat surface elevation were measured using paired pressure transducer probes (Levelogger 5, Solinst, Georgetown ON Canada). The two transducers were suspended in a single dipwell using Kevlar line (Fig. 13). One probe was suspended from a steel benchmark rod anchored in the substratum adjacent to the dipwell to measure absolute water level (AWL). The other was suspended from a mesh square (0.5 m × 0.5 m) fixed to the peat surface, free to move with the peat and measure relative water level (RWL). Following the approach of Fritz et al. (2008), the water table acted as a mobile benchmark, and changes in surface elevation were calculated by subtracting RWL from AWL.

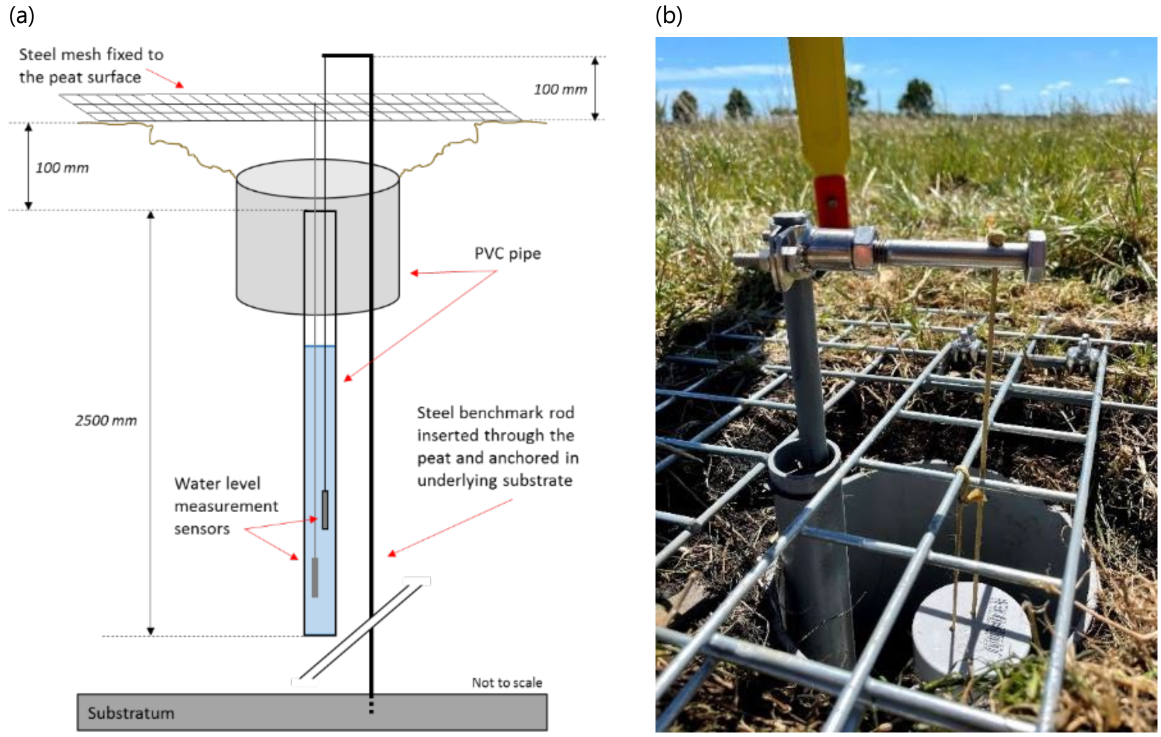

Figure 13. (a) Cross-sectional diagram of the paired pressure transducer method, and (b) photograph of above ground hardware, showing steel benchmark rod, steel mesh, Kevlar attachment methods and top of dipwell.

4.4 Site installation

Sites were established across the region between December 2020 and June 2021 within the polygons where LiDAR was acquired. Monitoring sites were installed on drained peatland areas at Moanatuatua (Moa), Rukuhia (Ruk), Torehape (Tor), Komakorau (Kom) and Lower Waikato (Low) (refer to Section 4.1 and Fig. 12 for more detail on selected sites).

At each site the design described in Section 4.3 was installed within a 1 m x 1 m enclosure (or similar) with an electrified fence to ensure the dipwell installation and sensors were protected and visible. During equipment installation, the elevation of the top of the steel benchmark rod anchored in the substratum was collected using post-processed GNSS survey methods (Viva GS16 Unlimited GNSS Smart Receiver, Leica Geosystems, Heerbrugg, Switzerland). Manual water level measurements, surface level and peat depths were also recorded with respect to the benchmark rod.

Sites are to be visited bi-monthly to check everything is operational, undertake maintenance, collect manual check measurements, and download sensor data. GNSS surveying should be repeated annually. Detailed site design, installation, and maintenance procedures can be found in Glover-Clark (2021).

4.5 Preliminary PSO data

The first data download was done on 20 April 2021 and covered the period from 5 February to 20 April (before installation of lower Waikato site at Motukaraka). Data from this download were summarised in Glover-Clark (2021) and are included below. To compare changes in RWL and surface elevation (SE) associated with rainfall (RF), data from nearby rain gauges situated at Gamma Farm (Moa RF), Kopuatai Peat Bog (Kop RF) and the University of Waikato (UoW RF) were included.

Rainfall totals at representative locations between 5 February and 20 April 2021 totalled 281 mm at Moa RF, 198 mm at Kop RF, and 273 mm at UoW RF. RWL receded at the Moanatuatua (Fig. 14a), Rukuhia (Fig. 14b), and Komakorau (Fig. 14d) sites between 5 February and 27 March 2021, aside from a few smaller fluctuations in water levels. A rainfall event spanning a few days around 28 March caused increases in RWL of between 300 and 800 mm, with the Moanatuatua sites appearing to be most affected by this rainfall. RWL receded at the Torehape sites (Fig. 14c) throughout the whole measurement period, relatively unaffected by rainfall events compared with the other sites (total Kop RF was about 80 mm less over the measurement compared with Moa RF and UoW RF). RWL at the Torehape sites appeared to be less coupled to hydroclimatic conditions at the surface, or, alternatively, to have different soil physical or hydraulic properties (i.e. hydraulic conductivity), thus influencing the movement of soil water through the profile.

During the measurement period, there was a general decrease in SE at most, but not all, sites between 1 March[3] and 20 April 2021 (Fig. 15). The total change in SE ranged between 8 mm and –22 mm during this time at Moa2_BB and Tor_Dairy sites, respectively. Within each drained peatland area there appeared to be no obvious correlation between RWL and the magnitude of SE change. For example, Moa2_BB and Tor_BB had deeper RWL than the paired dairy sites for the whole of the measurement period, yet there was less overall change in SE at both sites. There is potential that soil physical and hydraulic properties (e.g. bulk density, specific yield) differ between sites and thus have influenced these results.

Focusing on the temporal variability, patterns of SE change appeared to be similar within each pair of land uses but differed between each drained peatland area. At the Moanatuatua sites (Fig. 15a) and Rukuhia sites (Fig. 15b), SE followed a similar pattern to RWL: decreasing overall until the rainfall event in late March, and then increasing. During the measurement period, SE of the dairy and blueberry sites for both these drained peatland areas exhibited a few small decreases that occurred in the absence of rainfall events. It is unlikely that such sudden and large shrinkage events would occur. Examination of the data has not revealed any indication of the cause. The same large shrinkage events were not measured at Moa2_BB, and despite having a deep-water table, SE appeared to be closely correlated with RWL.

Similar to RWL at the Torehape sites, SE of these sites (Fig. 15c) had a fairly constant rate of decrease over the whole time period, except for a small increase near mid-March. At Komakorau (Fig. 15d), rainfall soon after the site was established caused SE to increase from

[3] Note that Figure 15 has a different time period start date from Figure 14, to remove SE changes related to site establishment.

the beginning of the measurement period. There was an overall decrease in SE for the remainder of the measurement period, with sizeable oscillations in SE, some of which occurred in the absence of rainfall events. It is important to consider that, due to geographical separation, the rainfall at UoW (Fig. 15d) and Kop (Fig. 15c) may not be entirely representative of what is occurring at the Komakorau and Torehape sites, but were the closest accessible rain gauges.

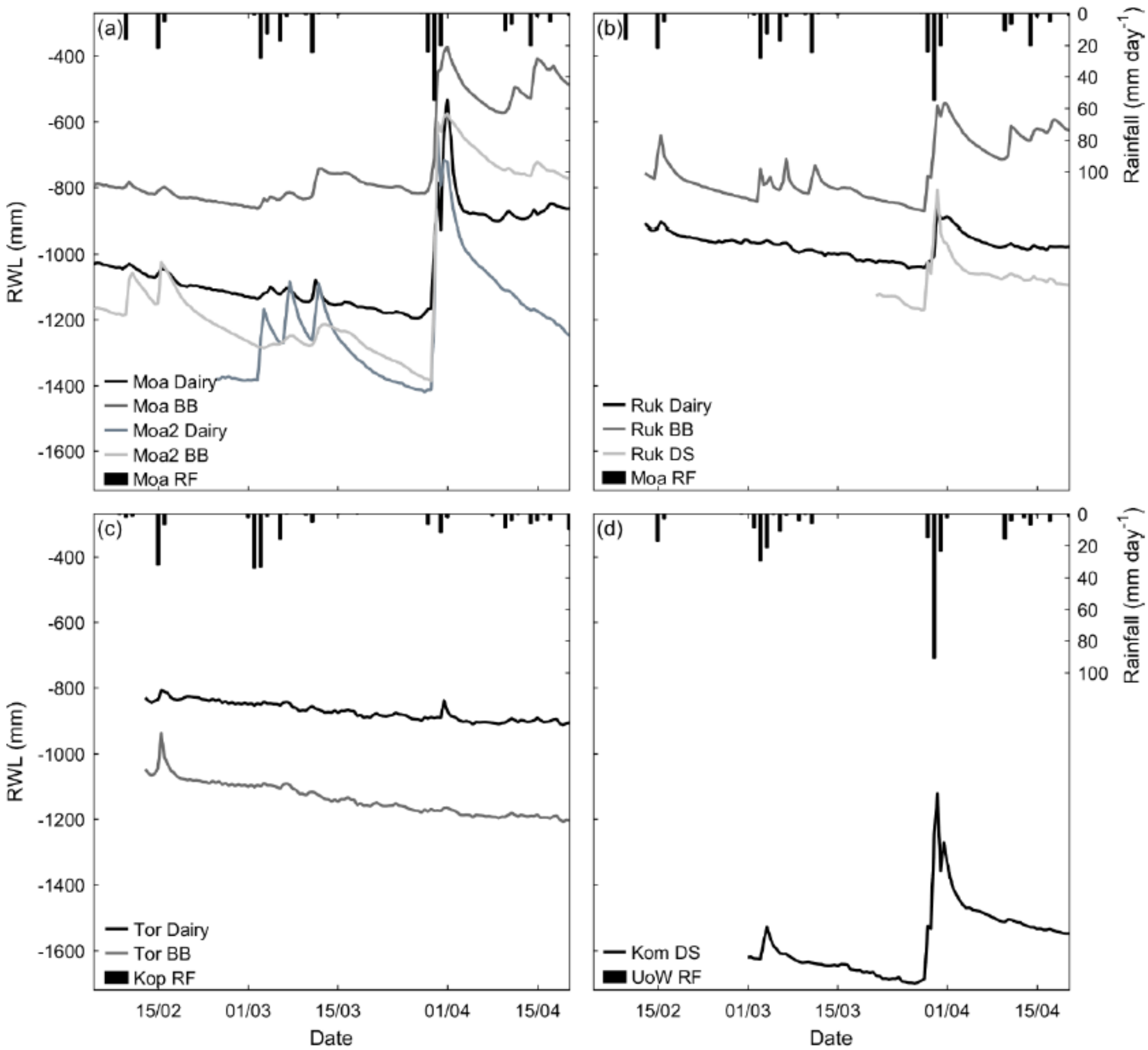

Figure 14. Six-hourly mean changes in relative water level (RWL) and daily rainfall totals at paired pressure transducer sites on the drained peatland areas (a) Moanatuatua, (b) Rukuhia, (c) Torehape, and (d) Komakorau during the time period 5 February to 20 April 2021. Note that the ranges of the X and Y axes are the same for all subplots.

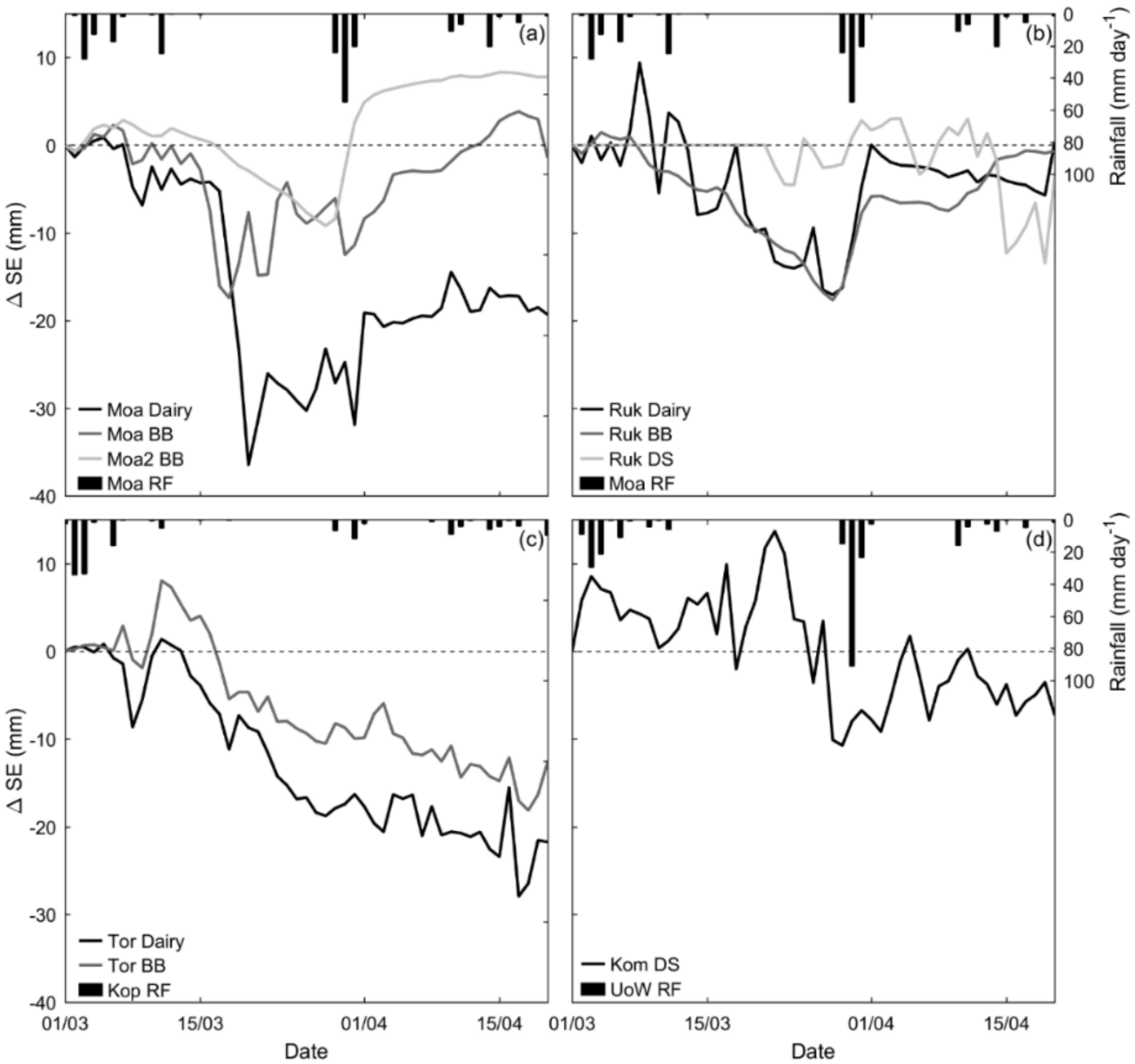

Figure 15. Total changes in peat surface elevation (Δ SE) based on mean daily data from paired pressure transducer sites on the drained peatland areas of (a) Moanatuatua, (b) Rukuhia, (c) Torehape, and (d) Komakorau during the time period 1 March and 20 April 2021. Note that the ranges of the X and Y axes are the same for all subplots. There are no surface elevation data for Moa2 Dairy due to user error in the download of absolute water level data.

5 Summary

- A flight plan was developed based on the desired ground return density (70-80 points/m^2) and flight budget. Airborne LiDAR was flown over the Waikato region (Hamilton Basin, Lower Waikato, and Hauraki Basin) on 28 April 2021 under optimal weather conditions. Data were acquired using the University of Canterbury's Riegl VUX-240 LiDAR system mounted on an Eurocopter EC120. LiDAR data were processed and raw and processed data and DEMs were provided to Waikato Regional Council.
- Five paired pressure transducer sites have been installed on drained peatland areas in the Waikato Region. These continuous monitoring sites will both improve our understanding of the magnitude and spatial variation in PSO, which is likely critically important for the success of the regional monitoring network and provide detailed information on spatial variation in subsidence and on the response of subsidence to climate, land use and management.

6 Recommendations

- LiDAR flights should be repeated in 5-years at the lowest point in the PSO cycle, likely late autumn 2026. After this second round of flights, DEM differencing will be required to quantify subsidence rates. A budget of $100,000 should be sufficient to complete future surveys.
- Spatial uncertainty in the DEM from both time points will need to be determined that reflects average positional errors and incorporates the effects of the apparent ground roughness, which is a function (principally) of the vegetation height/structure. We recommend spatial uncertainty estimates are derived simultaneously from both DEMs using a suitable Geomorphic Change Detection software suite. This will ensure equivalent approaches are used for both DEMs and future advances in uncertainty estimation are incorporated.
- For each of the long-term peat surface oscillation sites, we recommend land use information is collected to inform interpretation of the data. Proposed land use questionnaires are included in Appendix 1. We recommend this information is collected once a longer term (1 year+) data set has been collected.
- PSO sites should be visited bi-monthly for the next 5-years to check everything is operational, undertake maintenance, collect manual check measurements, and download sensor data. GNSS surveying should be repeated annually.
- Rain gauges should be installed (or suitable existing gauges identified) that are closer to the Torehape, Komakorau and Lower Waikato sites
- Soil physical properties at each of the PSO monitoring sites should be characterised to help explain differences between sites

7 Acknowledgements

We would like to thank all landowners who allowed establishment of continuous monitoring sites on their properties. We would like to thank David Campbell (UoW) for ongoing support and advice with respect to installation and ongoing management of the ground-based monitoring network. We also thank Christchurch Helicopters, especially Dougal Monk and the helicopter pilot Scott Snellex. We also thank the onboard LiDAR operator Ross Jeffs (UoC). Finally, we wish to thank Malcolm McLeod and Andrew Neverman for constructive internal review. Thomas Paul and Loretta Garrett are thanked for their constructive review.

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Appendix 1 – Draft communication to landowners of PSO sites to collect land management information

Dear [Xxx xxx]

Waikato Regional Council recently funded the installation of a peat surface oscillation monitoring site on your property in collaboration with Manaaki Whenua – Landcare Research and the University of Waikato. We would like to thank you for working with us and allowing the site to be established on your property. The site is part of a wider regional network of sites being established to continuously monitor the water table and ground surface level under different land uses on peat soils in the Waikato Region.

These sites will help us understand if there are differences in permanent subsidence between contrasting land uses and drainage management, the magnitude and spatial variation in seasonal surface shrink and swell behaviour (peat surface oscillation) that is important for the timing of future regional monitoring (helicopter based LiDAR flights), and to collect data to inform good practice for the management of peat soils in the Waikato Region. This is part of several work programmes being led by Waikato Regional Council to better understand peat subsidence in the Waikato Region.

We would also like to collect a few details on farm/paddock history for each of these sites. A copy of a questionnaire containing the information that would help us is in Appendix 1. You do not have to provide this information, but it will help us better interpret the results of the data collected from your property.

What will happen to the information that we collect?

Information collected will be stored securely by Waikato Regional Council and we will not share this information beyond those who need to know for the purposes of this project.

Key next steps: Within the next [x days/weeks] we will contact you to ask whether you are prepared to provide this information. If you are prepared to provide this information, we will organise a time, either over the phone or in person, to fill in the questionnaire.

Kind regards,

[xxx xxx]

Appendix 1a: Details of farm/paddock history to help interpret the results.

Site Name	
Farmer/contact name(s)	
Total land area (ha)	
Current land use at site: Keep description general as there are some more specific questions below	Dairy Drystock Cropping (please circle) **Duration yrs:** **Description:**
Previous land use(s) at site:	Dairy Drystock Cropping Orchard (please circle) **Duration yrs:** **Description:**
Drainage history	Date drained: Drainage development description:
Any major disturbances to site recently? e.g. recontouring	

Management details. If willing, please circle or ***bold*** *appropriate text or write values (if relevant)*

Drainage management	Type of drainage: Date of last drain maintenance: Maintenance method used (e.g. spraying or mechanical): Typical frequency of drain maintenance:
Liming history	How often: Application rate: Application method: Depth cultivated:

Typical annual mineral N fertiliser <u>type</u> and <u>rate</u> (kg/N/ha/yr).	Urea Ammonium Nitrate	0	<25	26-75	76-125	126-175	176-225	>225

Typical annual P fertiliser <u>type</u> and <u>rate</u> (kg/P/ha/yr).	Type: Rate:	Type: Rate:
Other fertiliser (e.g. manure/effluent)	Type: Rate:	Type: Rate:
Irrigation Yes or No	Method: Rate:	

Animal types (if relevant) % of total stock units	Dairy cattle %	Beef cattle %	Sheep %	Deer %
Stocking rates	Dairy (cows/ha)		Drystock (stock units/ha)	

Crop sequence at sampling site (if relevant)	2020/21	
	2019/20	
	2018/19	
	2017/18	
	2016/17	

Main tillage methods and depth (if relevant):	Conventional	<25%	26-50%	51-75%	>75%
	Non-inversion	<25%	26-50%	51-75%	>75%
	Intermittent	<25%	26-50%	51-75%	>75%
	No-till	<25%	26-50%	51-75%	>75%

Basic production information (e.g. kg MS/ha or maize yield)			
System type	Conventional	Organic	Other:
Other information, especially approaches used to minimise subsidence.			

Appendix 1b: Details of orchard history to help interpret the results.

<table>
<tr><td>Site Name</td><td colspan="8"></td></tr>
<tr><td>Farmer/contact name(s)</td><td colspan="8"></td></tr>
<tr><td>Total land area (ha)</td><td colspan="8"></td></tr>
<tr><td>Current land use at site:
Keep description general as there are some more specific questions below</td><td colspan="8">Duration yrs:
Description:</td></tr>
<tr><td>Previous land use(s) at site:</td><td colspan="8">Dairy Drystock Cropping Orchard (please circle) Duration yrs:
Description:</td></tr>
<tr><td>Drainage history</td><td colspan="8">Date drained:
Drainage development description:</td></tr>
<tr><td>Any major disturbances to site recently?
e.g. recontouring</td><td colspan="8"></td></tr>
<tr><td colspan="9">Management details. If willing, please circle or bold appropriate text or write values (if relevant)</td></tr>
<tr><td>Drainage management</td><td colspan="8">Type of drainage:
Date of last drain maintenance:
Maintenance method used (e.g. spraying or mechanical):

Typical frequency of drain maintenance:</td></tr>
<tr><td>Liming history</td><td colspan="8">How often:
Application rate:
Application method:
Depth cultivated:</td></tr>
<tr><td>Typical annual mineral N fertiliser <u>type</u> and <u>rate</u> (kg/N/ha/yr).</td><td>Urea
Ammonium
Nitrate</td><td>0</td><td><25</td><td>26-75</td><td>76-125</td><td>126-175</td><td>176-225</td><td>>225</td></tr>
<tr><td>Typical annual P fertiliser <u>type</u> and <u>rate</u> (kg/P/ha/yr).</td><td colspan="4">Type:
Rate:</td><td colspan="4">Type:
Rate:</td></tr>
<tr><td>Other fertiliser
(e.g. manure/effluent)</td><td colspan="4">Type:
Rate:</td><td colspan="4">Type:
Rate:</td></tr>
<tr><td>Irrigation Yes or No</td><td colspan="8">Method:
Rate:</td></tr>
<tr><td>Harvest method description (manual or mechanical) and has this changed over time</td><td colspan="8">Description:</td></tr>
<tr><td>Mowing method and frequency and has this changed over time</td><td colspan="8">Description:</td></tr>
<tr><td>Basic production information
(e.g. blueberry yield/ha)</td><td colspan="8"></td></tr>
<tr><td>System type</td><td colspan="2">Conventional</td><td colspan="2">Organic</td><td colspan="4">Other:</td></tr>
<tr><td>Other information, especially approaches used to minimise subsidence.</td><td colspan="8"></td></tr>
</table>