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Manatū Ahu Matua

Use of modern technology including LiDAR to update the New Zealand Land Resource Inventory

Final Report

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Prepared for Craig Trotter

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Landcare Research Contract Report: LC 3091

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Executive Summary

Manaaki Whenua – Landcare Research were contracted by the Ministry for Primary Industries, under the Sustainable Land Management and Climate Change programme, to develop and test an automated workflow for digitally preparing farm-scale (1:10,000) Land Use Capability (LUC) maps from single-factor land inventory maps (rock, soil, slope, erosion and vegetation) for a 100 km^2 study area between Kaikohe and Paihia.

Methods

- A slope inventory was mapped using a digital elevation model (DEM) built from light detection and radar (LiDAR) point-cloud data flown specifically for the project.
- A soil inventory was mapped, using digital soil mapping techniques, to contemporary New Zealand Soil Classification standards (Hewitt 2010; Webb & Lilburne 2011).
- An erosion inventory was carried out on-screen using both 10 cm digital orthophotography and LiDAR DEM (hill shade and slope classification) flown for the project.
- Rock type and vegetation inventories were carried out using best available regional data from QMAP, and the Land Cover Database (LCDB 4.1), respectively, in both cases also supported by data from the New Zealand Land Resource Inventory.
- A 'segmentation workflow' was developed to combine the five single-factor raster inventory layers into one multifactor vector (polygon) layer of land inventory units, emulating the manual mapping process of traditional LUC mapping.
- An LUC legend based on the Northland regional LUC legend (Harmsworth 1996) was prepared to facilitate classification of the multifactor land inventory polygons at farm scale. This involved splitting some regional units and creating new LUC units to describe areas that were not recognised at 1:50,000 scale in the Northland legend.

LandVision Limited were contracted to carry out business-as-usual traditional LUC mapping on seven properties or part-properties, amounting to 10 km^2, 10% of the Kaikohe study area, to provide a comparison between traditional and digital farm-scale LUC mapping.

Results

- The project delivered digital farm-scale LUC maps that were generally equivalent in accuracy to traditional maps and therefore equally fit for purpose.
- Digital mapping processes were found to be more quantitative and repeatable, with potential for reduced cost for remapping.
- Digital farm-scale LUC mapping was less cost effective per hectare for individual farms, but has potential for economies of scale over much larger areas.

- Comparing maps quantitatively proved difficult. It is easy to get statistics of agreement/disagreement, but determining correctness is difficult, and interpreting the significance of differences between digital and traditional maps was best carried out by visual interpretation.

Conclusions

- The traditional and digital mapping approaches both produced what appear to be acceptable farm-scale maps, but neither mapping approach produced clearly superior maps.
- The methodology developed for transforming the single-factor raster inventory layers into a combined vector LUC polygon product was successful, thus increasing objectivity in the delineation and assignment of digitally derived LUC map units. However, the digitally derived LUC map units are constrained by the quality of the inputs: the inventory data, particularly the soil and parent material, which, along with slope, are the key factors assigning LUC to map units.
- Combined with well-documented field data, covariate layers, and models that have been subjected to stringent quality assurance protocols, the ability to improve individual inventory layers and generate a revised LUC map at much lower cost than complete remapping offers a clear advance in the repeatability and efficiency of LUC mapping.
- The general approach of combining single-factor maps of best available environmental data, using more objective and repeatable methods, to map concepts such as land vulnerability or land suitability (i.e. interpretations that relate to areas rather than point locations) may be of interest well beyond the scope of the current project.

Recommendations

- Digital farm-scale mapping of LUC – and potentially other similar interpretations such as land suitability – shows promise. Research to improve and refine the methods developed in this project should be supported.
- A workshop should be organised with LUC practitioners and technical experts from central government, local government, Crown Research Institutes, Science Challenges, universities, and sector organisations, along with land resource management consultants, to share the results of this research and discuss ‘Where to from here?’
- Given that Northland was a ‘most-difficult’ case study, additional trials of this approach to LUC mapping should be organised in different land systems around New Zealand, where the availability of LiDAR or other suitable DEM, less complex geology/parent material, and existing S-map coverage or suitable soil sample data will allow a wider evaluation of this mapping technique (e.g. the Greater Wellington region, Bay of Plenty region, Hurunui catchment in Canterbury).
- Options should be discussed with GNS Science for a proposal to develop a more detailed parent material map to support both digital soil mapping and digital LUC mapping.

- The development of an erosion susceptibility map at a suitable scale to support digital LUC mapping and other key legislation (e.g. National Environmental Standard – Production Forestry NES-PF) should be investigated.

1 Introduction

This project was developed from a Ministry for Primary Industries (MPI) Sustainable Land Management and Climate Change Request for Proposals (RFP) release in October 2014. That RFP requested submissions on ‘Capturing LiDAR data for Northland region and using this to remap the Land Resource Inventory and Land Use Capability for the region’. Indicative funding available for the RFP was approximately $300,000.

MPI’s overall aim, stated in the RFP documentation, was to ‘provide knowledge that will assist in the identification of environmentally sustainable primary sector land use development opportunities’ in the region. Accordingly, the scale of mapping required was ‘farm-scale’.

Based on the indicative available budget and MPI’s priority for Northland to be the subject of this RFP, Manaaki Whenua – Landcare Research (MWLR) proposed an alternative approach involving a pilot study to test automated digital methods for Land Use Capability (LUC) mapping over a sufficiently large area of Northland to be a useful test of regional mapping at farm-scale, utilising light detection and radar (LiDAR) and other digital technologies.

2 Aims and Objectives

2.1 Aim

The aim of this project was to carry out a pilot study of part of Northland, over an area of approximately 100 km^2, to update the New Zealand Land Resource Inventory (NZLRI) and the LUC classification. It was proposed that the update would be undertaken at farm-scale (1:10,000), using digital mapping techniques to build a series of single-factor layers for rock type, soils, slope, erosion and vegetation, from which LUCs might be derived.

2.2 Objectives

The objectives of the project were to determine whether, compared to traditional LUC mapping, more automated digital mapping LUC procedures can:

- deliver accurate inventory layers at farm-scale
- deliver LUC maps that are fit for purpose
- reduce the overall cost per hectare of LUC mapping
- make LUC mapping procedures more quantitative / less subjective
- make LUC mapping procedures more repeatable
- make remapping of LUC less costly
- establish a method for comparing traditional and digital map products.

2.3 Background to the project and issues with legacy data

The RFP for this project had a clear focus on using elevation data derived from LiDAR technology to support automated digital LUC mapping procedures. This project has been designed around the premise that there is government interest in updating the NZLRI and LUC in some regions where new techniques make it sufficiently rapid and economically feasible to justify the investment. The costs and benefits of the traditional and proposed more automated approach are therefore considered.

This project is also a test of the capability of current digital mapping techniques to deliver farm-scale LUC maps of a reasonable standard of accuracy, reliability, repeatability and fitness for purpose over a significant area.

Constraints considered while undertaking this project included the following.

- There was no operational procedure for automated digital LRI/LUC mapping from LiDAR and other digital data sources.
- Northland has very complex geology and landscapes, including some of the oldest landscapes in New Zealand. With the exception of Holocene tephra, alluvium and colluvium, the parent materials are deeply weathered and therefore the influence of rock type on soil distribution is different, perhaps muted, compared with the majority of New Zealand landscapes. Had there not been other reasons for selecting Northland, this would have made it an unlikely candidate for a project such as this.
- Legacy soils data available in Northland are at a scale of 1:100,000. Published maps date from the late 1970s to the early 1980s (Sutherland et al. 1980), but the bulk of the field work was undertaken between 1937 and 1951, according to unpublished DSIR Soil

Bureau records. The soil series mapped in that survey are not compatible with current S-map soil taxa (family and sibling) (Webb & Lilburne 2011) and have only had likely New Zealand Soil Classification (NZSC; Hewitt 2010) assigned post survey.
- Digital soil mapping (DSM) procedures currently being developed for mapping S-map at 1:50,000 scale could be used at farm-scale (c. 1:10,000) but would require significant field work and data collection, and a more detailed parent material map.
- The LUC extended legend for Northland may need to be revised to cope with mapping at a different scale, which may result in units needing to be split or new units defined to describe LUC units that can only be mapped independently at a finer scale (1:10,000).
- The LUC mapping criteria follow the protocols outlined in Lynn et al. 2009.

The digital mapping techniques used in this project are underpinned by a high-resolution LiDAR-based digital elevation model (DEM), and targeted field work for mapping landforms, geology, soil distribution, and erosion. Best available inventory data sets of medium to high resolution (e.g. Land Cover Database, radiometrics, at 15 m and 50 m resolution, respectively), legacy data sets at various scales (e.g. NZLRI and farm plans), and LUC knowledge (e.g. regional and national LUC extended legends) were utilised wherever possible.

Individual inventory layers were prepared and digitally combined into an LRI and LUC data set, as opposed to the traditional multifactor mapping approach of manually preparing a single set of vector polygons and populating them with LRI and LUC attributes. Resource mapping and assessment techniques developed in this pilot are expected to be applicable throughout the Northland region and elsewhere New Zealand. The data outputs from this mapping process, including enhanced LRI, LUC, landforms, geology, soils, and erosion information, have the potential to be applied to a wide range of resource management issues that rely on accurate land resource information at approximately 1:10,000 scale.

A key part of the project was to carry out a quantitative comparison of the thematic and spatial information derived from the modern single-factor approach developed in this project, with information collected independently using traditional multifactor mapping techniques at c. 1:10,000 scale for 10% of the Kaikohe study area. We report on the results, and on the level of agreement between the two approaches.

The most recent LUC regional mapping work (Harmsworth 1996) was second edition NZLRI mapping carried out in the 1990s. It involved traditional LUC mapping of the region at 1:50,000 scale, with an LUC regional legend optimised for describing LUC units at that mapping scale. Northland is one of four regions that were mapped to edition 2 standard, representing the highest-quality data in the NZLRI.

The Northland Regional Council (NRC) has used a variety of mapping tools for policy, compliance, and farm extension applications. It considers the NZLRI the most up-to-date and complete data set for this purpose (D. Kervell, pers. comm.). However, for soils information there has been a legacy preference for the Northland Soil Survey (Cox et al. 1983) for farm planning, specifically in the Kaikohe study area the map of Sutherland et al. (1980) published as part of the Department of Lands and Survey – New Zealand Land Inventory (New Zealand Map Series 290). This soil survey has a nominal scale of 1:100,000, and a map window is shown in Figure 1 beside an NZLRI 1:50,000 scale compilation of soils data to illustrate map resolutions.

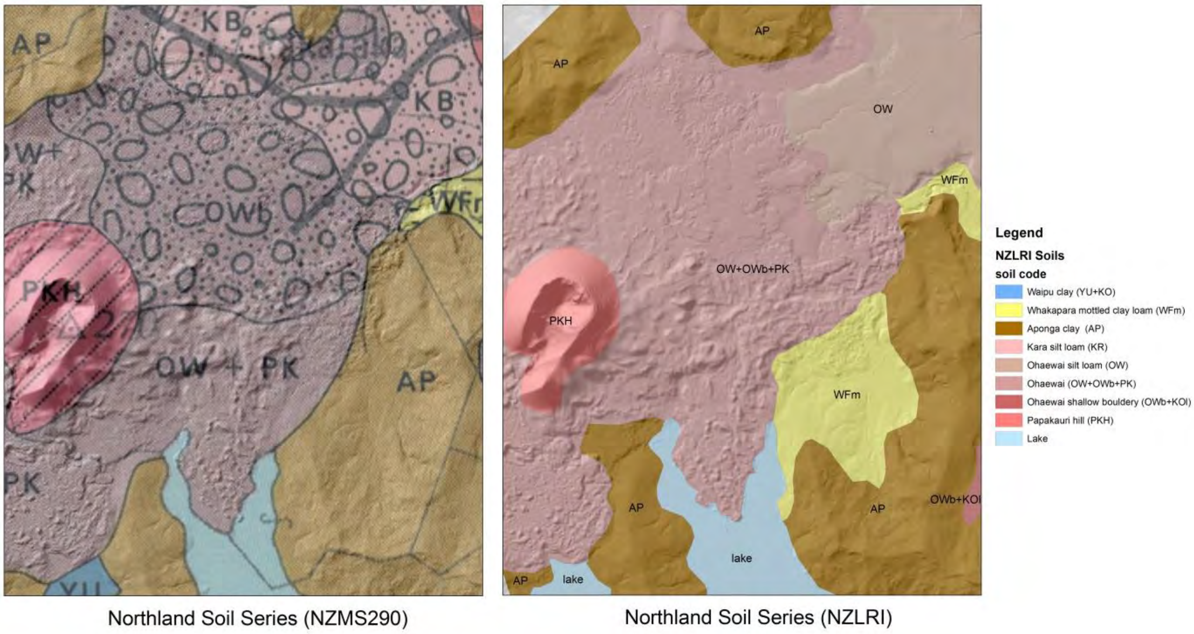

Figure 1 Comparison of the NZMS290 and NZLRI legacy soils data for part of the Kaikohe study area. Note the boundary discrepancies between distinctive topographic features, such as the volcanic cone (centre left) and the complex topography; and also the distribution of low-elevation, broken rocky terrain and that mapped as bouldery (OWb), which is all clearly visible in the LiDAR hill shade underlying both map.

There are no publicly available soil profile descriptions to accompany the published soil series map of Sutherland et al. (1980). However, there are unpublished soil profile descriptions from 1950 to 1970 relevant to some of the soil series and availalable for 77 of the soil series (i.e. 20 soil series have no documentation).

A soil series is a grouping of soil types with similar modal profiles, similar temperature and moisture regimes, and the same or very similar parent materials (Taylor & Pohlen 1979). Consequently, soil series used as soil mapping units, especially at scales of 1:100,000, can contain considerable variability with respect to features such as texture, slope, stoniness, topographic position, drainage, parent materials, and depth to bedrock, where these characteristics do not greatly modify the kind and arrangement of soil horizons.

Modern soil survey and land evaluation require more precise definitions of classes and keys for their recognition, as documented in the NZSC (Hewitt 2010). Hence in this study the soils have been mapped in terms of the NZSC because it:

- is hierarchical, providing ascending levels of generalisation
- groups soils into classes based on similarity of measured soil properties rather than genesis
- allows the greatest number of precise accessory statements to be made about them, consistent with their level in the hierarchy
- differentia are based on soil properties that can be reproducibly and precisely measured or observed
- differentia where possible, allow field assignment of soil to classes, either directly or by tested inferences.

Also, the nomenclature of the higher categories in the NZSC is more readily acceptable to non-specialists (i.e. soil order, group and sub-group).

The soil mapping units used are primarily based on the first three categories of the NZSC: order, group and subgroup (Hewitt 2010), and where needed to identify the physical attributes of soil profiles more precisely, the fourth (family) and fifth (sibling) level categories (Webb & Lilburne 2011). Soils, where described in terms of Milne et al. (1995), are compatible with the S-map definitions and descriptions (Lilburne et al. 2004) https://soils.landcareresearch.co.nz/describing-soils).

3 Study Area

3.1 Selection of study area

The main aim of the project was to carry out a realistic trial for digital LUC mapping at farm scale (1:10,000) over a large enough area to be a useful test of digital mapping techniques, and one that contained enough complexity to be considered representative of the wider Northland region. We assessed potential study areas to ensure they included, within the constraint of a 100 km^2 size, as many of the diverse terrains (slopes and landforms), rock types, erosion susceptibilities, and vegetation types that occur throughout Northland.

The overall size of the proposed study area was determined by the indicative budget for the project, and agreed to at the project proposal phase. This figure was arrived at by evaluating the cost of acquiring raw LiDAR data somewhere in Northland, south of the Hokianga Harbour and Kaitāia (within 100 km of Whangārei Airport), and the anticipated costs of inventory preparation, particularly field work for soil mapping using DSM techniques in terms of proximity to road and 4WD track access. We considered accessibility in terms of land use and ownership, and potential issues of permission to carry out essential field work.

The overall shape of the study area was also given consideration. Both regular shapes, which simplify LiDAR survey logistics and flight planning, and irregular shapes (catchment areas) were considered, as the latter offered some advantages in terms of environmental data sets for digital soil mapping. For hydrologically based layers such as the Combined Topographic Index (Gessler et al. 1995), which incorporate slope and catchment area calculations, using a study area that is not a complete catchment can compromise analyses.

Environmental issues were not a primary driver of site selection, but NRC was consulted to determine if any such issues could be used to ensure the final site selection was as relevant as possible to current policy or management issues in the region. The final study area selection was discussed and agreed with NRC.

The degree to which the landscape and environment of the potential study area are representative was assessed using the following national or regional data sets:

- New Zealand Land Resource Inventory (NZLRI) edition 2 Northland data set (https://lris.scinfo.org.nz/layer/134-nzlri-north-island-edition-2-all-attributes/), to include a range of LUC units from Northland, parent materials and soils
- QMAP, the most current geology map with national coverage, from GNS (https://www.gns.cri.nz/Home/Our-Science/Earth-Science/Regional-Geology/Geological-Maps/1-250-000-Geological-Map-of-New-Zealand-QMAP/Digital-Data-and-Downloads); the ‘Main Rock’ and ‘Stratigraphic Unit’ fields in the QMAP database were used to identify volcanic parent materials (e.g. andesite, basalt, and other volcanic rocks), Tertiary sediments (e.g. limestone, mudstone, sandstone, siltstone), greywacke, and crushed rocks (e.g. argillite and melange)
- MWLR’s national 25 m DEM data set (https://lris.scinfo.org.nz/layer/131-nzdem-north-island-25-metre/): prior to LiDAR acquisition, these were the best-available elevation data to ensure the study area covers the full range of slopes and landforms typical of Northland

- the Ministry for the Environment's LCDB v4.1 (https://lris.scinfo.org.nz/layer/423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/), which was utilised to ensure the study area includes areas of grassland, exotic forest, native forest, scrub and possibly cropland, to test if taller and thicker vegetation make slope and terrain analysis from LiDAR more difficult
- the erosion terrains, which are derived from the NZLRI (https://lris.scinfo.org.nz/layer/418-new-zealand-erosion/), to ensure the study area includes, as far as possible, a range of erosion types, especially mass movement processes, which was assessed using the erosion terrains to identify landform groupings that incorporate floodplains, terraces, downlands, hill country, and steeplands
- the Erosion Susceptibility Classification (ESC) developed in support of the National Environmental Standard for Plantation Forestry (Basher & Barringer 2017), which is the best currently available integrator of erosion susceptibility (all four ESC classes are represented).

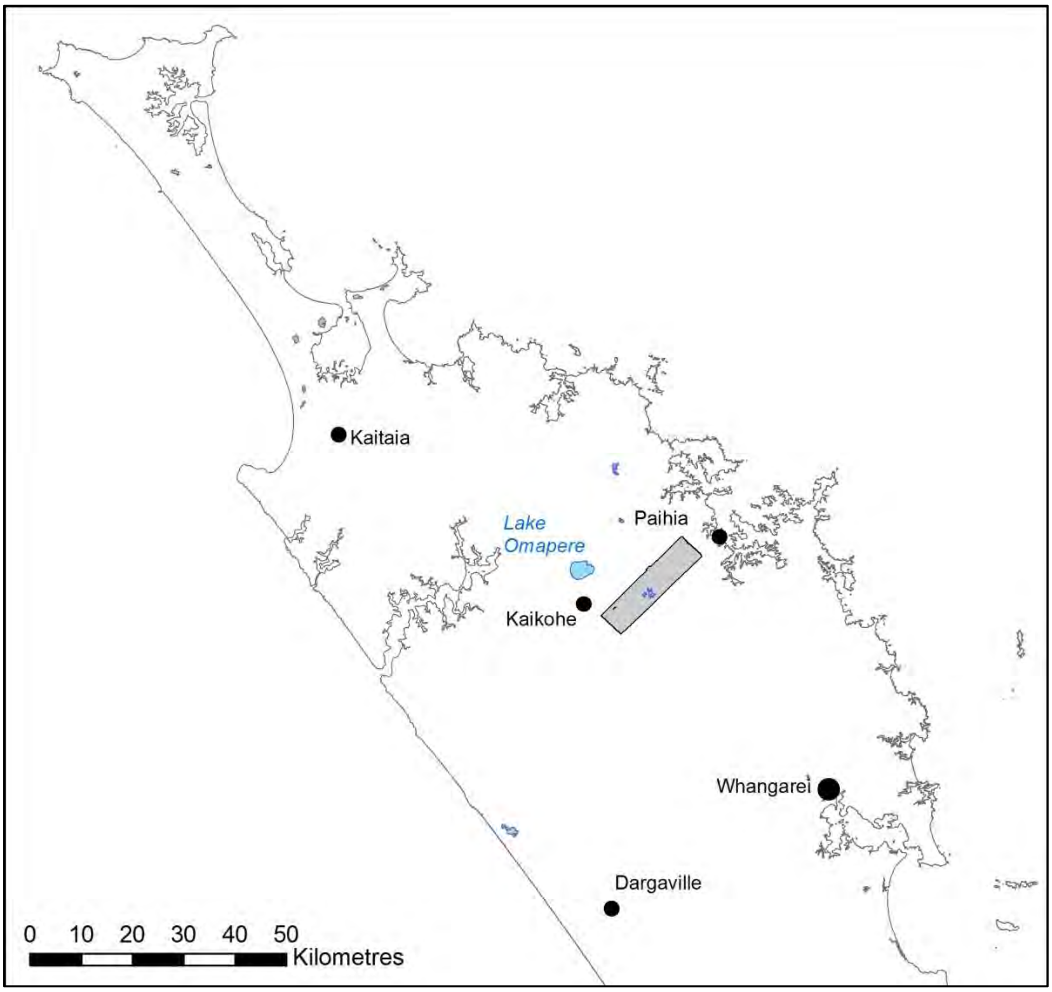

Figure 2 Location map showing the general location of the Kaikohe study area relative to Whangārei and the Northland region.

3.2 Description of study area

The result of this analysis was to select a rectangular study area 21 km long and 4.5 km wide (95.5 km^2) lying east of Lake Ōmāpere (Figures 2, 3 and 4) and running from near Paihia in the north-east to near Kaikohe in the south-west.

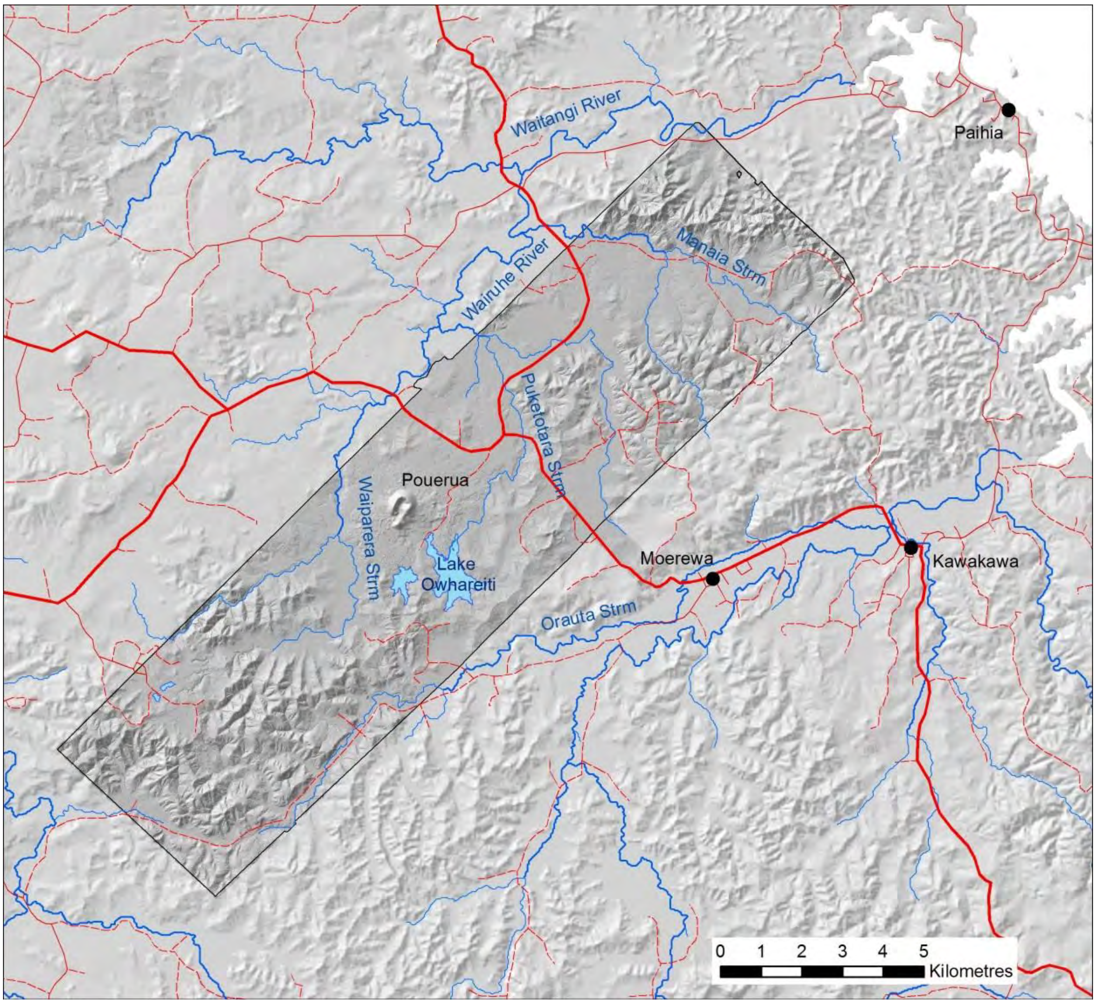

Figure 3 A closer view of the Kaikohe study area, giving a general indication of the variable terrain from shaded relief and accessibility via major roads.

The Northland region covers 13,789 km^2, so the Kaikohe study area is less than 1% of the total land area of Northland. However, the study area includes 26 out of the 93 (27%) LUC units in the NZLRI 2nd edition Northland Extended Legend (Harmsworth 1996), as shown in Table 1 and Figure 4. The Kaikohe study area was mapped using 89 map units in the NZLRI (2nd edition) at 1:50,000 scale.

Table 1 Number of regional NZLRI LUC classes mapped in the Kaikohe study area

LUC class	Number of units	% study area
3	7	9.0
4	9	31.0
5	1	<1.0
6	8	52.0
7	1	6.0
Table totals	26	99

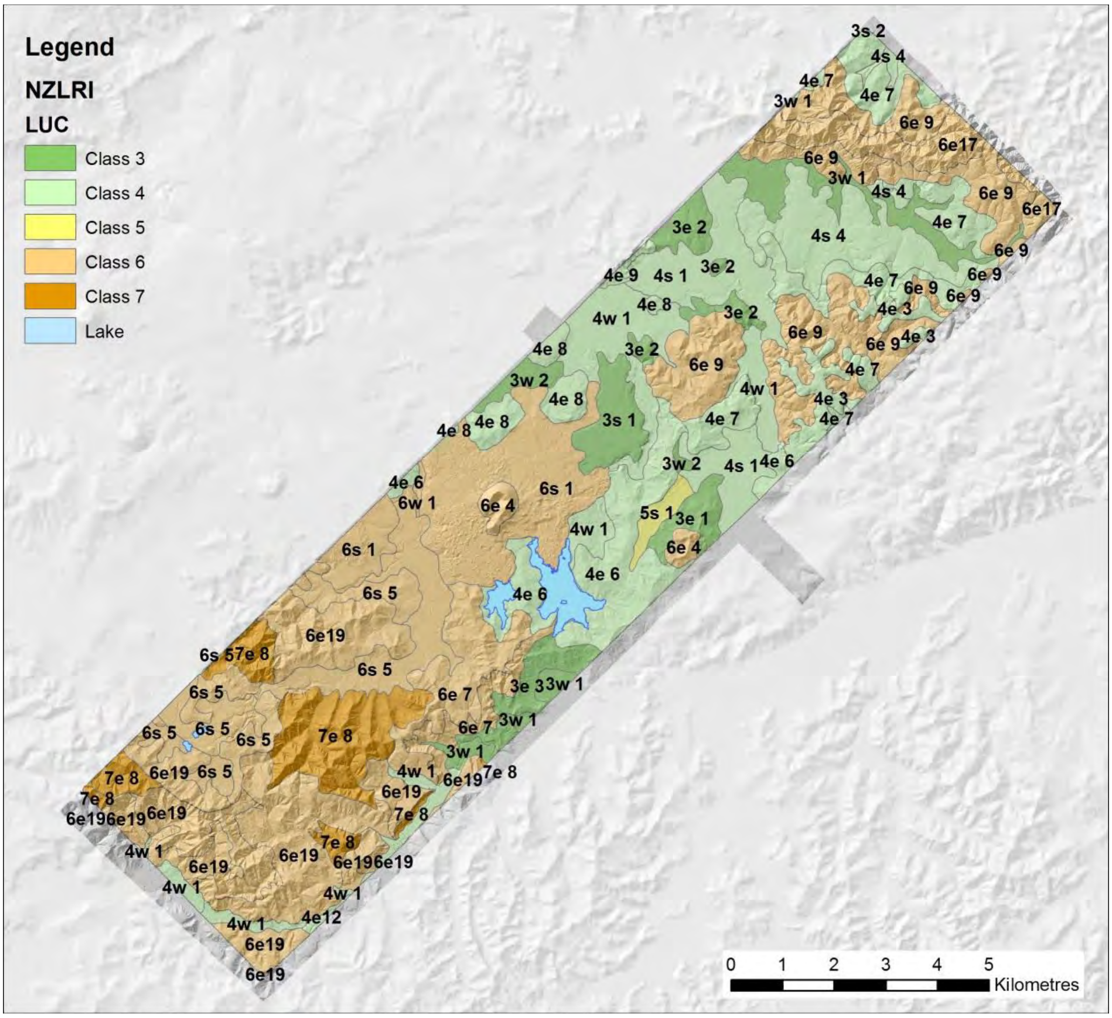

Figure 4 NZLRI 1:50,000 scale LUC units for the Kaikohe study area, showing the range of LUC classes, ranging from LUC Class 3 in the more stable valleys, to Class 7 in the steeper, infertile crushed argillite terrain in the south-west of the study area.

The Kaikohe study area is characterised by major variations in parent material and terrain (see Figure 8). In the north-east, weathered greywacke (Late Permian to Jurassic) underlies steep (26–35°) to rolling hill country (18–22°) and downlands (8–20°) enclosing the valley of the Manaia Stream. On the gently to strongly rolling (8–20°) ridge-crests, spurs, and footslopes, an intermittent mantle of basaltic tephra of variable depth is present. On more stable slopes, Mottled Orthic Brown and Mottled Yellow Ultic Soils were mapped, with Mottled Orthic Allophanic Soils mapped where the tephra mantle is greater than 30 cm thick.

This terrain was previously mapped with a combination of regional LUC Class 4e7, 4s4, 6e9 and 6e17 units. These LUC units do not acknowledge the tephra component, although it was identified in the description in the NZLRI. A complex soil pattern is present in the alluvium in the Manaia Stream valley, containing Gley and Fluvial Recent Soils previously mapped as regional LUC Class 3w1 units.

The central third of the Kaikohe study area is dominated by undulating to strongly rolling (4–20°) Pliocene- to Pleistocene-aged basaltic lava flows and steep to very steep (26–35°) scoria cones of the Kerikeri Volcanics, overlain by or extruded from gently rolling to strongly rolling (8–20°) country, and underlain by Cenozoic-aged siliceous and non-siliceous sandstone and mudstones of the Northland melange. In the study area the melange is covered by intermittent tephra of variable depth.

The area immediately surrounding the Pouerua volcanic cone exhibits some well-preserved flow features, which are characterised by strongly textured, rolling (8–15°) terrain with many boulders, rock outcrops, and fertile soils. Allophanic Soils with highly variable depths, fine earth textures, and stone and boulder contents are present on this landscape. This volcanic terrain was previously mapped with a combination of regional LUC Class 3e1, 3s1, 4e3, 4s1, 5s1, 6e4, and 6s1 units.

Mottled Yellow Ultic Soils dominate the siliceous terrain, which was previously mapped with a combination of regional LUC Class 3e3, 4e6 and 4e8 units. The drainage channels through this central terrain are very complex, often infilled or dammed by lava flows, covering and/or being covered by a thin and sometimes patchy veneer of recent alluvial deposits, as is evident in the Waiaruhe River and Puketōtara Stream drainage basins. Regional LUC Class 3e2 and 3w2 units were delineated in these areas in the 2nd edition NZLRI LUC maps.

The southern third of the Kaikohe study area is predominantly composed of moderately steep (20–25°) to steep (26–35°) land underlain by crushed argillite. Crushed argillite in this area is defined by Rattenbury and Isaac (2012) as weakly to moderately indurated, thinly bedded, repeating bands of siliceous mudstones and sandstones of the Whangai Formation, of Cretaceous age. This hill country is less fertile and has in places been planted in production forestry. Natural vegetation is characteristically scrubby and underlain by Mottled Densipan Ultic Soils and Perch-gley Densipan Ultic Soils, with limited rooting depths and a higher risk of erosion of greater severity than landscapes on other rock types in the Kaikohe study area.

This terrain was previously mapped with a combination of regional LUC Class 4e12, 6e7, 6e19, and 7e8 units. The alluvial valley floor deposits of the Waiparera and Orauta Streams draining this terrain are highly variable and exhibit a wide range of drainage characteristics. They have been mapped with a combination of regional LUC Class 3e3, 3w1, 4e12, 4w1, 6w1 and 6s5 units.

4 Methods and Results: Single-factor Inventory

The development of the data layers for each individual factor in the LRI and the subsequent automated process for combining those inventory data sets into a farm-scale (1:10,000) LUC map is a complex, multi-stepped process. The single-factor inventory data layers have been generated from field or remotely sensed data using statistical and spatial modelling techniques relating field-observed point data to remotely sensed data, and referred to as covariates (e.g. elevation, slope, and climate surfaces).

This approach aims to create objectively derived spatial data layers that are reproducible and can be improved at lower marginal cost by acquiring additional field data, or additional or improved covariate data, and/or by using improved analytical methods. As far as possible the use of manual drafting techniques to draw lines on maps was avoided, although this was not always possible (i.e. for parent material and erosion). The following subsections explain the specifications and methodologies for carrying out the analysis for different inventory components.

The preparation of each data layer is a project in its right, requiring data collection, analysis, and results. For simplicity of explanation, section 4 therefore combines the methodology and results for the preparation of the single-factor inventory layers. The methodology for combining the single-factor inventory layers into a modern version of the multifactor LUC layer, and the results of that process, will be described in section 5.

4.1 LiDAR acquisition and processing

New Zealand Aerial Surveys (NZAS) was contracted to deliver 104.18 km^2 of LiDAR and concurrent orthophotography (digital natural colour imagery capture at 10.4 cm resolution). NZAS operates an Optech Orion H300 LiDAR sensor, which delivers at least 2 pulses per square metre with a vertical accuracy of ±6 cm and a horizontal accuracy of ±20 cm. NZAS processed the LiDAR data into a 'raw 3-D point cloud' (unclassified point cloud) and supplied this directly to MWLR for post-processing. [1]

Ground classification of the raw point-cloud and the subsequent DEM and canopy height model (CHM) workflow were performed on the New Zealand eScience Infrastructure (NESI) high-performance computer system at Auckland University. The processing methods were based on open-source LiDAR software package SPDlib (Bunting et al. 2013a, 2013b).

The ground classification involved a two-stage automated algorithm applied as overlapping tiles, each tile being processed on a unique core of the NESI supercomputer. The ground points that satisfied both algorithm stages were interpolated to generate a 1 m resolution DEM. A CHM was also interpolated from the points that remained unclassified by either of

[1] Ground classification of the raw point cloud and DEM/CHM generation is usually carried out by the LiDAR operator/vendor, but MWLR has this capability and preferred to manage this task in-house.

the two ground classification stages. The interpolation method used for DEM and CHM generation was the natural neighbour process. The CHM had additional 5 × 5 median filtering, and a minimum height threshold of 0.5 m was applied to remove noise.

The classified point cloud was supplied back to NZAS for ortho-rectification of the RGB imagery[2]. NZAS then generated individual very high resolution (10 cm) RGB orthophoto tiles (TIFF/TFW format with associated DXF layout file) and a single seamless ECW file (compressed image format) covering the entire Kaikohe study area.

4.2 DEM slope mapping

4.2.1 Slope mapping methodology

The DEM generated from the raw LiDAR cloud was processed using the standard slope algorithm in ArcGIS. The original LiDAR DEM has more spatial resolution at 1 m than is required for farm-scale (1:10,000) mapping of slope angle. Despite filtering of non-ground classified points from the LiDAR raw point cloud, the level of surface detail far exceeds that typical of manual slope mapping for manual LUC mapping and can be affected by surface texture features like rocks, tight clumps of grass or hummocky wetlands.

At 1 m resolution, slope is assessed at 1 million locations per square kilometre. Resampling the DEM to 5 m spatial resolution before generating the slope map filters out some of this high-frequency textural noise and provides a smoother raster mapping of slope. But this data set still contains a far richer representation of slope than is normally mapped manually for farm-scale LUC (i.e. slope assessed at 40,000 locations per square kilometre).

To produce a vector slope map fit for LUC mapping at farm-scale we subjected the resampled raster slope map to a segmentation process (e.g. Minár & Evans 2008; Le Bas et al. 2015) to generate a set of slope polygons of generally homogeneous slope. The segmentation process used has been under development at MWLR but is not published. It uses standard ArcGIS raster and vector functions in a multi-step process (Figure 5), as follows.

1. RECLASS the filtered DEM into the standard LUC slope classes, as defined for the NZLRI (Lynn et al. 2009).
2. Convert the classified filtered raster DEM to polygon format.
3. SMOOTH and SIMPLIFY the automatically generated polygon line work, which initially retains edges that reflect the original raster cells. The SMOOTH command has the effect of densifying the vertices that define the polygon boundaries, but also begins to round off sharp corners. The SIMPLIFY command removes vertices to reduce the number of points defining boundaries, completing the task of removing sharp corners related to the original raster cells. Carrying out SIMPLIFY without first using SMOOTH results in excessive simplification of boundaries and loss of critical boundary definition.

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[2] Provision of RGB othophotos is a standard option for LiDAR surveys by NZ Aerial Mapping because the aircraft is set up to record LiDAR and optical imagery simultaneously from the same sensor platform.

4. ELIMINATE 'sliver' polygons. To derive slope polygons for farm-scale LUC mapping units we based a segmentation process on soil mapping criteria for minimum-sized mapping units. At 1:10,000 scale the minimum size for soil map units is recommended to be 0.4 ha (Soil Science Division Staff 2017). ELIMINATE merges small polygons with the neighbour with which they share the longest boundary.
5. Assign dominant slope class according to ZONAL STATISTICS calculated for each polygon from the original raster slope map.

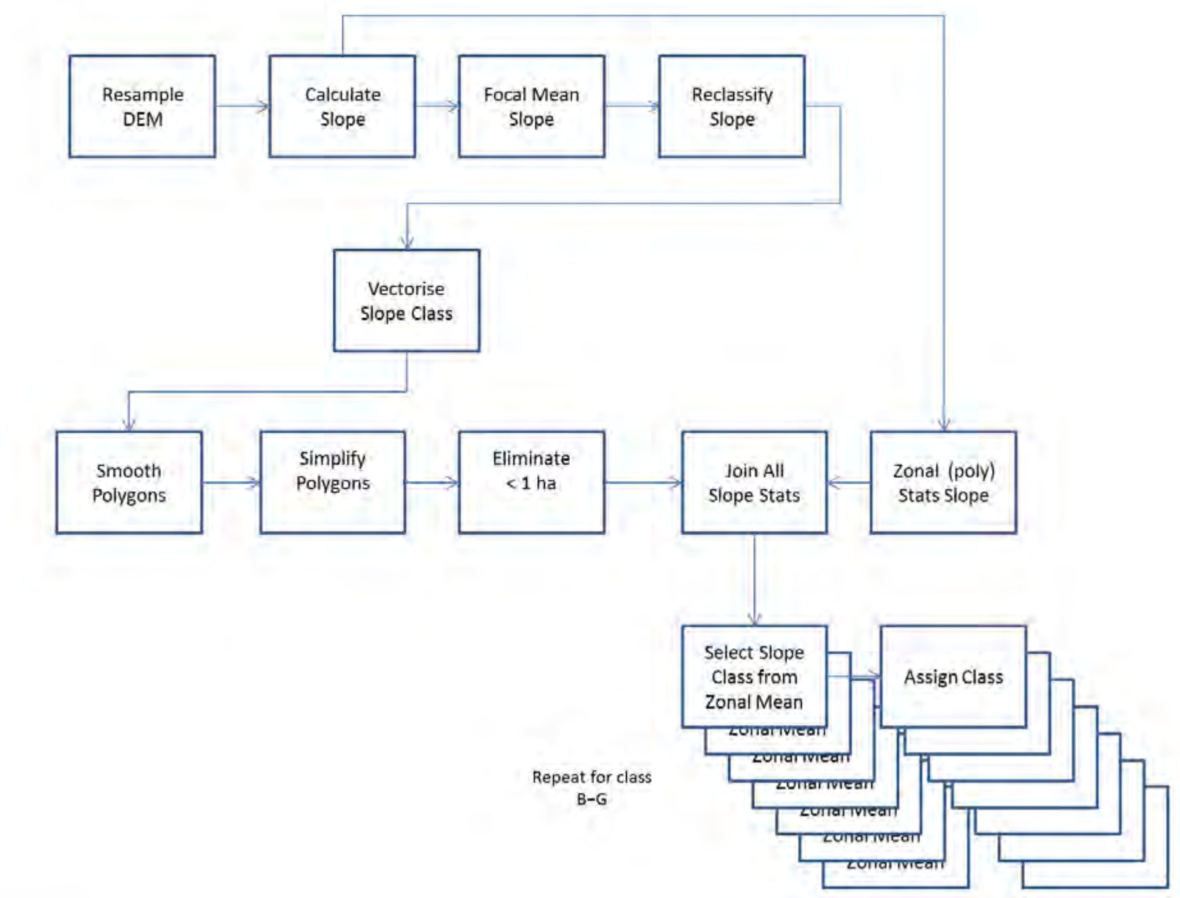

Figure 5 Schematic representation of the segmentation process for converting the continuous raster slope map derived from LiDAR-based DEM.

4.2.2 Digital slope and terrain maps

The LiDAR DEM has more spatial resolution at 1 m than is required for farm-scale mapping. However, the slope polygons created by the automated segmentation process provide a quantitative, objective method of delineating areas dominated by a slope class, and for mapping with precision the boundary between areas of differing slope class (Figure 6). So even though the cost of LiDAR acquisition is high, this is offset by the speed and low cost of computer processing. If regional LiDAR were already available to LINZ specification (i.e. https://www.linz.govt.nz/system/.../loci_nz-lidar-base-specification-20161220.pdf), slope mapping could be implemented at minimal additional cost over the whole region.

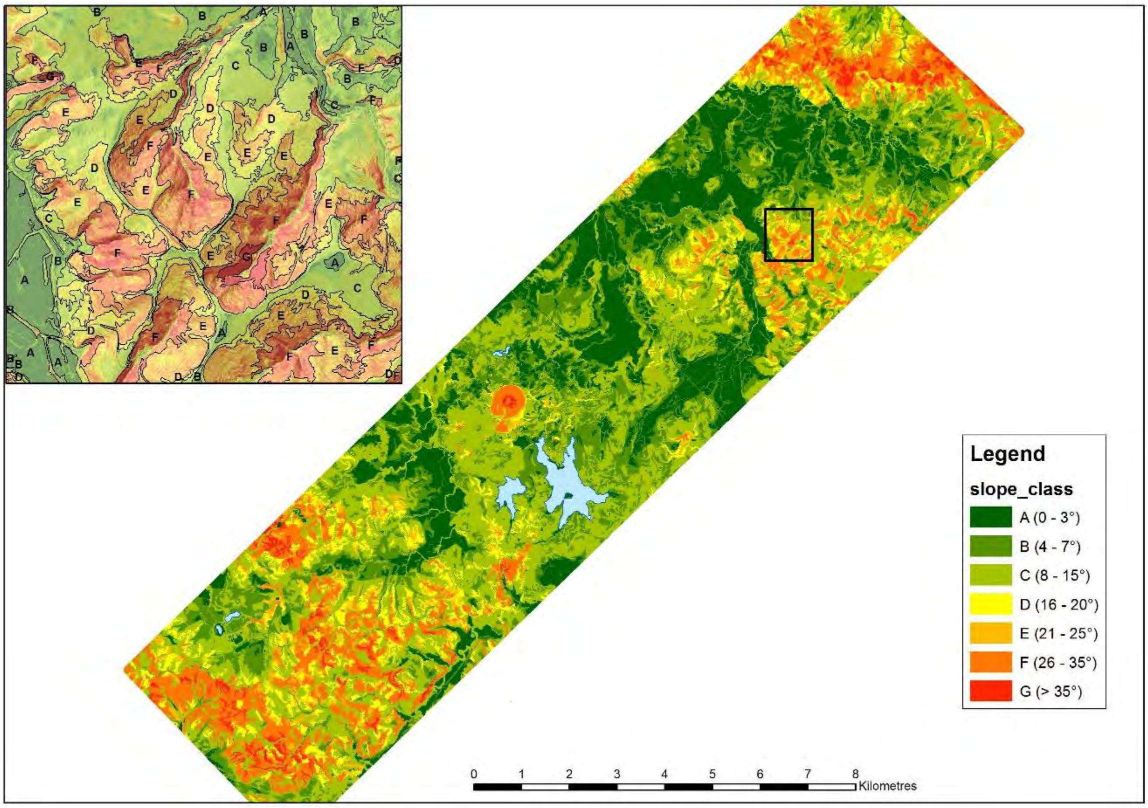

Figure 6 Raster slope map derived from LiDAR-based 1 m resolution DEM, with inset showing segmented slope polygon boundaries for an area of approximately 1 km^2, with labels showing dominant slope class and overlaying the original raster slope map to give an indication of the heterogeneity of slope within the polygons created by the automated process.

4.3 Rock type methodology and results

Rock type is one of the primary inventory layers for LUC mapping. At the time of national NZLRI mapping, existing geological information, which was mostly derived from coarse-scaled (1:100,000–1:250,000 scale) geological maps, was recompiled to 1:50,000 scale to assist with the identification of terrain and landscape characteristics, erosion type associations, and soil parent material distribution, all of which are critical inputs for assessing LUC.

Refining the detail of geological mapping to develop an adequate representation of rock type at 1:10,000 scale presents a significant challenge for farm-scale mapping. The available parent material information for New Zealand is still largely confined to QMAP (https://www.gns.cri.nz/Home/Our-Science/Earth-Science/Regional-Geology/Geological-Maps/1-250-000-Geological-Map-of-New-Zealand-QMAP). The map units in QMAP are composed of groups of different-aged rocks that can vary in terms of facies (i.e. the source of materials and depositional environment in which the rocks were first formed). For example, one QMAP geological map unit could consist of conglomerate, sandstone, siltstone, claystone and limestone (i.e. many lithologies). Although field-compiled at 1:50,000 scale, QMAP is nominally a 1:250,000 scale data set. In contrast, the NZLRI (https://lris.scinfo.org.nz/layer/65-nzlri-rock/), while similarly at 1:50,000 scale, maps rock type (i.e. lithology) rather than same-aged groupings of rock.

The problem with both of these sources of parent material information is that the data sets contain many boundaries that are generalised at 1:10,000 scale. An obvious example of this is the boundary between the greywacke hills north of Manaia Stream and the adjacent alluvial deposits of the stream valley. The 1:250,000 scale QMAP or 1:50,000 scale NZLRI boundary for this transition is a relatively smooth line, but at 1:10,000 scale this boundary should be much more complex (Figure 7). If this coarse-scaled rock type information is used for LUC mapping without enhancement, rock types may occur in confounding combinations with other inventory factors like soil or slope.

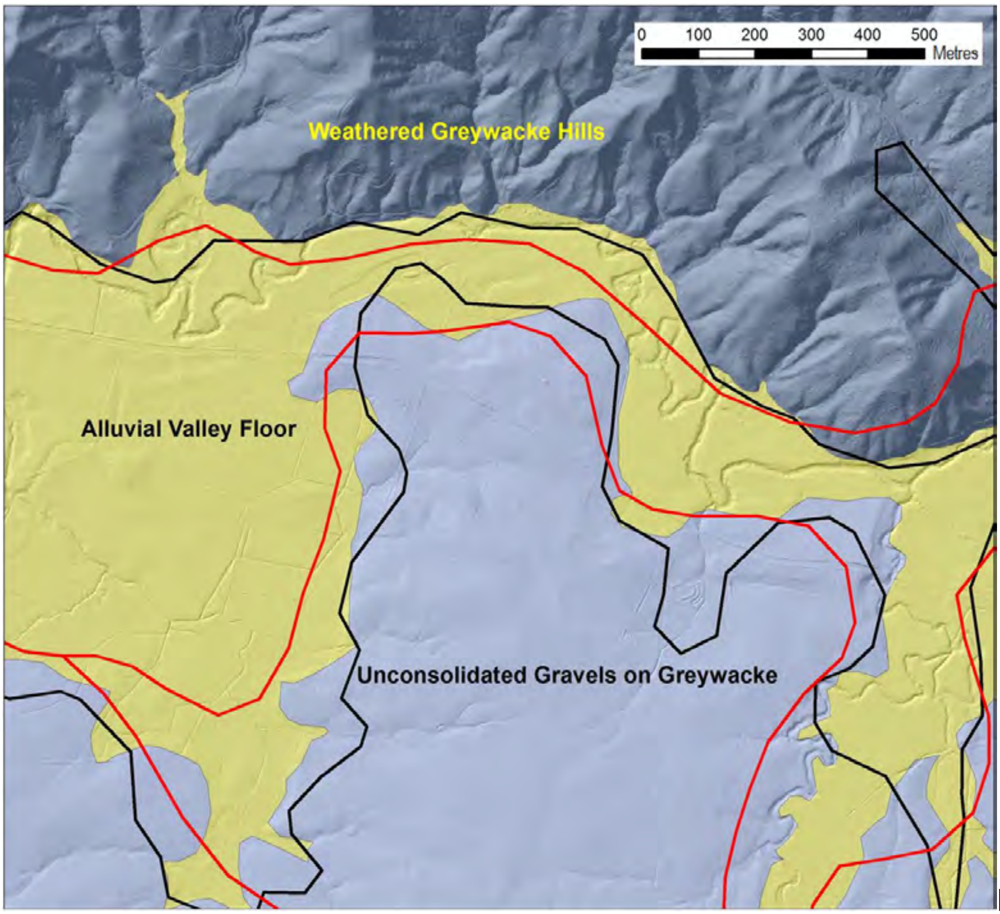

Figure 7
Illustration of scale-related boundary issues between QMAP (red), NZLRI rock type (black) and LiDAR terrain (shade map) at Manaia Stream.

There is some literature on the subject of digital geological mapping (e.g. Cracknel & Reading 2014), but it is relatively recent and limited, and our attempts to digitally generate a high-resolution parent material map using disaggregation methods previously applied in soil science (Holmes et al. 2014), using LiDAR terrain data, QMAP and the NZLRI, were unsuccessful.

However, in our search of DSM literature and resources we found that in the United Kingdom the British Geological Survey have developed a parent material model at 1:50,000 scale, detailing the distribution of physiochemical properties of the weathered and unweathered parent materials of the UK. This model:

- facilitates spatial mapping of UK soil properties
- identifies soils and landscapes sensitive to erosion
- provides a national overview of the soil resource
- develops a better understanding of weathering properties and processes.[3]

While the method used for generating this parent material model layer is not published, and the scale is similar to that of the NZLRI, we determined that the only viable option for this project would be to develop our own equivalent layer and establish whether this approach would be viable over larger areas.

Our methodology was to carry out on-screen digitising where the existing coarse-scale parent material maps are overlaid over the LiDAR hill shade and contours, and boundaries hand-digitised to align with the terrain. The result is illustrated in Figure 8 and represents a combination of QMAP and NZLRI lithological information, with revised boundaries. Where visual terrain analysis cannot identify a more detailed boundary, the existing boundary is retained or in some cases re-aligned to fit a landscape feature. For example, the boundary between greywacke and sandstone had no visible surface expression and cut across landscape features. The boundary here was 'realigned' by removing polygon slivers and following features such as ridgelines. This approach assumes that the QMAP and NZLRI regional data sets are broadly accurate.

During soil field work this draft soil parent material layer was checked for polygon boundary accuracy when relating observed soil types to geological units. Boundaries (e.g. between lava flows and sedimentary rocks) were generally very accurate − within a few metres − and related to abrupt soil type boundaries. However, sedimentary rock types could only be confirmed on steep slopes or road cuttings, where the underlying geological material was exposed, otherwise boundaries could only be assumed.

On land in the Kaikohe study area with low relief or stable slopes, the sedimentary rocks were highly weathered and the relationship between geology and soil type was weak. Because the rock was deeply and uniformly weathered across the landscape, soils on map units thought to contain different rock types were not discernible using classical field-based pedological techniques. The relationship between soil type and sedimentary geological units was stronger on steeper slopes, where repeated erosion has exposed unweathered rock at the surface. The same thing occurs where mass movement erosion of the underlying geology has influenced the surface soil processes (e.g. between sandstone and crushed argillite hills). It was difficult to reconcile some units between QMAP and NZLRI, particularly in the central region mapped by QMAP as melange in Figure 8. Here the DEM and observed soil pattern were used to interpret the landscape. Melange is associated with complex soil−landscape patterns.

A clear relationship was observed between soil type and tephra cover-bed deposits where they occurred over sedimentary rocks, but QMAP does not record cover beds and the NZLRI has poor boundary delineation, so tephra cover beds were not included as a rock type unit in this project. Unlike the boundaries between different sedimentary rock units, the extent of tephra cover beds could be observed using the 100 cm-deep soil auger observations.

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[3] http://www.bgs.ac.uk/research/climatechange/sustainableSoils/parentmaterialmap.html

Modifications were made to the soil parent material layer based on the field observations outlined above, but further work would be required to accurately delineate these boundaries. In recent DSM work in the Waipā catchment a similar problem was solved by creating a covariate that defined the distance to the probable sources of tephra. In the current case there were numerous possible local sources of tephra, and without more field work it wasn't possible to define sources of local tephra.

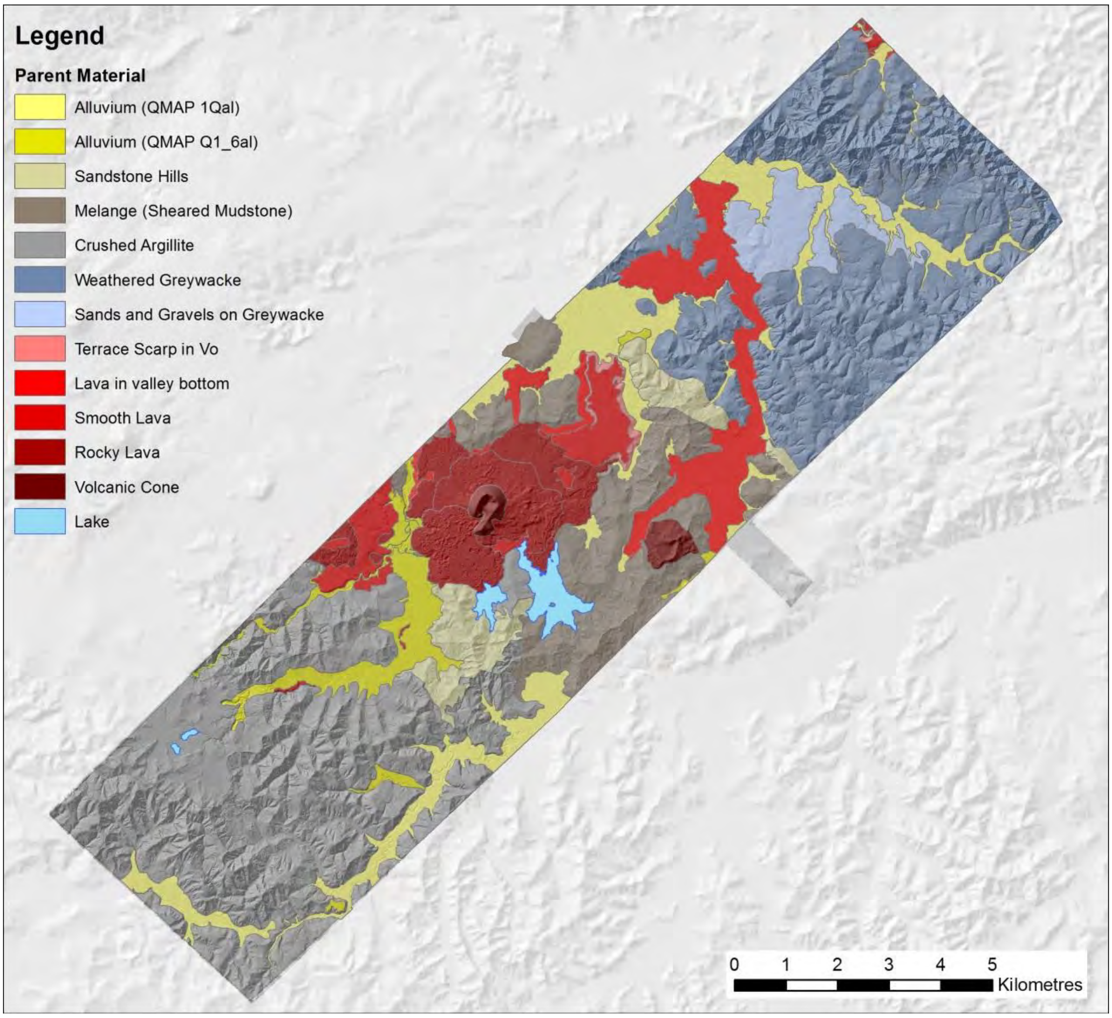

Figure 8 Basal rock type contributing to the soil parent materials.

4.4 Digital soil mapping

4.4.1 Digital soil mapping – method

Soil is a key component of LUC mapping because it is the most influential in determining LUC class. Soils have properties derived from the combined effect of climate and biotic activities (organisms), modified by topographic effects, acting on parent materials over time (Brady & Weil 2007). The parent material of a soil influences the physical and chemical properties of the soil, and hence its soil classification. In stable locations parent material will become less important over time as climate, topography, and vegetation become more important influences on the evolving character of a soil. Therefore, knowing the parent material, age (nature and degree of weathering) and stability of the surfaces on which soils form is critical to being able to accurately map soils across landscapes such as those found in the Kaikohe study area.

The ability to digitally map soils at farm scale is a critical success factor for this project. The overall approach to DSM was to investigate legacy soil data, together with a reconnaissance survey to develop *a posteriori* soil–landscape relationships that explain soil distribution. Once these broad relationships were understood, further sampling was required to gather sufficient data for statistical modelling using a random forests analysis (Breiman 2017).

Soil field survey

The Kaikohe study area (Figure 3) was the subject of a reconnaissance field survey in May 2016, during which the pedologists from MWLR carried out a preliminary *ad hoc* soil auger survey to evaluate the quality of the available legacy soil data and gain sufficient *empirical* knowledge to understand basic soil–landscape relationships.

The main survey campaign included 15 localities used to broadly define clustered sampling areas that encompassed the range of environmental covariate space important to modelling soil while minimising travel time between observations. These are shown in red in Figure 9. Sampling was not strictly confined to these areas. Their primary purpose was to ensure that pedologists' sampling efforts included all the main groupings of covariate space in the Kaikohe study area, and to investigate some of the important thresholds between these groupings, not to dictate a statistically robust randomised sampling pattern.

The 15 localities were sampled and surveyed by MWLR in May 2016. Site observations and soil descriptions were recorded following Milne et al. 1995. The soils were classified to sub-group in terms of the NZSC (Hewitt 2010; Webb & Lilburne 2011), and S-map criteria (Lilburne et al. 2012) from soil pits, auger observations, cuttings and natural exposures. Soils were described to a depth of 100 cm, and the thickness of each soil layer was recorded, along with its horizon nomenclature, colour, soil texture, soil structure, parent material, depth to a slow hydraulic conducting layer, pH and phosphorous retention (if required). Key attributes recorded for LUC unit assignment are shown in Table 2.

A total of 500 field soil observations were made (Figure 9), and these included soils within the Allophanic, Brown, Gley, Organic, Recent and Ultic soil orders. All observation locations were geolocated using a Garmin GPSMap 60CSx set to the New Zealand Transverse Mercator projection.

In addition, some 175 tacit points were identified and recorded. We define a tacit point in this instance as a location where prior knowledge of the relationship between the occurrence of a specific soil and a combination of one or more covariate classes is sufficiently strong for the soil class to be predicted within acceptable limits of uncertainty by those covariates. Tacit points are valuable for ensuring even distribution of soil map units in the sample, and for providing a better geographical sample where access is difficult or impossible, and confidence is high regarding soil distribution. A common use of tacit points in DSM is the prediction of imperfectly and poorly drained soils where rushes are abundant in aerial photography. These tacit points were not visited in the field, and are clearly identified, together with the covariate information that has led to the prediction, so they can be included or excluded from later analyses as required.

Soil classification, soil attributes and land use capability

While soils were described in the field based on S-map data requirements, not all observations were required to characterise soils to the sibling level. Some laboratory data from the National Soils Database, new phosphorus retention (P-ret), soil acidity (pH) and particle size distribution (psd) data, and information from soils characterised on the unpublished Northland soil unit sheets were used to better define soils and taxonomic differences. Map units defined for modelling were an amalgamation of associated soils and complexes that could be logically modelled to give a practical soil map. There were no pure map units of a single soil defined.

Previous DSM work by MWLR (e.g. Palmer et al. 2015) has used post-modelling rule-based analysis to match S-map siblings to map units. This has been undertaken using NZSC soil classification, as opposed to mapping soil series identified in legacy soil maps (e.g. Sutherland et al. 1980). Siblings (or sibling combinations) are assigned to each map unit. In this study, identifying only soil map units to NZSC (group + sub-group level) would be insufficient to generate a map of LUC. In this case, the post-modelling rule-based analysis used map unit and classified soil field data, recording classified soil depth, soil texture, soil drainage and soil profile material (see Table 2 for an explanation of class values) in order to ensure sufficient information was available to assess LUC from the land inventory data collected (see section 5).

Table 2 Classified soil attribute data recorded along with NZSC during survey

Attribute	Class	Description
Soil depth	Deep	>100 cm
	Moderately deep	45–100 cm
	Shallow	20–45 cm
	Very shallow	<20 cm
Soil texture	Clay (c)	
	Loam (l)	
	Silt (z)	
	Sand (s)	
	Peat (o)	
Soil drainage	Well drained (w)	
	Moderately well drained (mw)	
	Imperfectly drained (i)	
	Poorly drained (p)	
	Very poorly drained (vp)	
Profile material	Peat (Sd)	
	Deep – no stones (Md)	
	Tephra (Mt)	
	Moderately deep to rock (Mm)	
	With stones (Ms)	
	Paralithic (Mp)	<45 cm to 'soft rock'
	Lithic (Ml)	<45 cm to 'hard rock'
	Angular – stony (Ma)	
	Fragmental (Mf)	

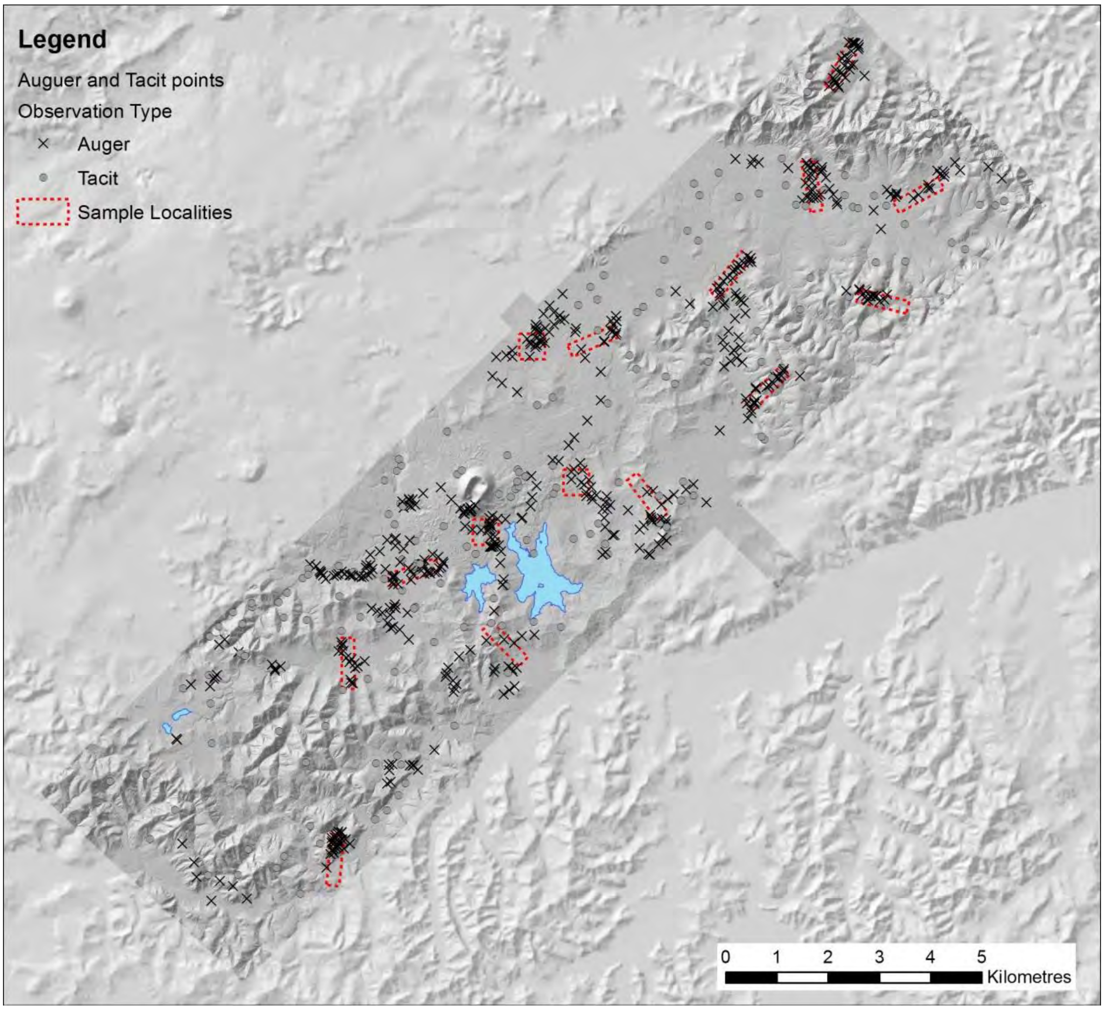

Figure 9 Location of sample localities and field observations (×) and and tacit points (●) for digital soil mapping.

Soil covariate data

For the purposes of DSM analysis, a series of covariate layers was derived from the LiDAR-based DEM. Although the original DEM was generated at 1 m resolution, the DSM processing was undertaken at 5 m resolution, for processing, memory and logistical reasons, and because of the scale issues (see section 4.3). The following covariates were prepared from the DEM, and in the case of rainfall and temperature from resampling climate surfaces from Land Environments New Zealand (LENZ):

- elevation (DEM5m)
- relative relief (ZREL)
- slope length
- aspect – north–south
- curvature (plan and profile)
- landform elements (LandElem) (Schmidt & Hewitt 2004)
- multi-resolution valley bottom flatness (MrVBF)
- textural indices (e.g. ruggedness)
- terrain wetness index (TWI)
- combined topographic index (CTI)
- sediment transport index (STI)

- topographic exposure (TOPEX)
- distance to streams
- direct insolation (DIR_INSOL)
- annual rainfall (RainTotal)
- mean annual temperature (TAVG).

Both ArcGIS and SAGA GIS were used to generate these covariates because neither had all the tools and algorithms required. All covariate raster layers must have exactly the same grid origin and grid dimensions for use in DSM.

We also used radiometric covariates, including potassium, thorium, total count and dose rate. A soil's gamma radiometric signal is related to the mineralogy and geochemistry of the parent material and its degree of weathering and has been used for DSM with some success in Australian landscapes, where fine-resolution aerial radiometric data are available (e.g. Stockmann et al. 2015).

While the aerial radiometric data available in New Zealand (NZP&M 2011) are not considered coarse-scale (i.e. resolution of 50 m), the intended scale of soil mapping for this project, the complex geomorphology in Northland, and a sensor footprint considerably smaller than the apparent pixel size all raise concerns over the utility of the data. The resolution of the radiometric data especially creates data quality issues, because while radiometric values may correlate with point soil data, the relatively coarse pixel size for farm-scale mapping creates obvious data artefacts during model interpolation, and it is questionable whether it is valid to resample this type of data to finer resolution. Nonetheless, we resampled these data to 5 m resolution using bilinear interpolation to test whether they improved predictions.

Statistical analysis for digital soil mapping

Once field data collection was completed, several iterations of the random forest modelling were run to discover the combination of covariate layers that provided the best soil classification results. We used the open source statistical package R (https://www.r-project.org/). There is a rich literature and a variety of options for carrying out DSM using R (e.g. Malone et al. 2017). For generating soil polygons for LUC mapping we focused on using the random forest analysis because it works well for modelling classified soil data (https://cran.r-project.org/web/packages/randomForest/randomForest.pdf).

The random forest model divides the available data into a training data set and holds back a subset of the data as a test (validation) data set. The model repeats the analysis multiple times using different subsets of the data as training and testing data. This cross-validation approach allows the model to use the full data set most effectively.

The modelling process consists of the following steps.

1. The required location and soil observation data are imported from a database holding the field observations of soils.

2. A raster stack is created, combining all the covariate layers into a multi-raster data structure.

3. Covariate data are extracted for every soil observation from that sample location in the covariate raster stack.

This constitutes the training data set for the random forest analysis and is stored in a text file for R. At this time, the test data set is also prepared and placed in a similar text file for validation purposes.

4.4.2 Digital soil mapping – results

Soil survey

The field soil survey highlighted six main points.

1. The presence of undescribed soils developed in basaltic tephra of variable depth mantling parts of the landscape was revealed. Historically, these soils were incorrectly mapped as members of a soil suite derived from greywacke and argillite and identified as Marua soils by Sutherland et al. (1980). As a result, farmers within the Kaikohe study area associate the name of the soil type on their farm with a soil with good physical properties, whereas in most other places where the soil type is correctly mapped it has poor physical properties. This creates a source of confusion for land-use options on this soil type.

2. Soil spatial variability is high because of the presence of basalt flows of varying age, composition, and degree of stoniness infilling pre-existing valleys, the distribution and variable depth of basaltic tephra retained on the easier components of the landscape (broad spurs and shoulders, footslopes, and downlands), erosion and mass movement on melange and crushed argillite lithology, and the past effects of the former forest vegetation cover.

3. The use of high-resolution radiometric (gamma ray) data would be expected to effectively differentiate between surfaces of different age. Experience in the Waikato has shown differentiation between tephric and non-tephric soils, as well as different alluvial parent materials. The resampled radiometric data does appear to be important in our model, but there are concerns over the data resolution (50 m) and the validity of resampling these data.

4. Soil processes, presumably under acid vegetation (e.g. kauri), have led to root-restricting pans in some areas, but these have high random spatial variability that could not be mapped at farm-scale.

5. Many soils have poor drainage and/or slow permeability, which restricts land-use options. Identification of the location of the better-drained soils could lead to land-use intensification of small areas.

6. Field work must always be carried out within a context of adequate support for soil mapping to the specified scale, offset against time and budget constraints. In this study, field work was undertaken in two campaigns. Reviewing laboratory data from the soil samples from both field campaigns and DSM results involves an iterative evolution, and validation of understanding about soil properties and their distribution in the study area. At each iteration new knowledge leads to ideas and assumptions that cannot be tested without further field work. Within the time and budgetary constraints of this project a decision was made to forego independent field validation, relying solely on cross-validation to allow for further development of pedological understanding in an area that has soil patterns that are difficult to explain.

Creating soil map units for digital soil modelling

Twenty soil types were classified in the field to the sub-group level of the NZSC, with some minor modifications made later based on laboratory data. Many of these sub-group classes were further split up based on S-map family and sibling criteria (Webb & Lilburne 2011). It was not possible to model all soil types that were described in the field due to an insufficient number of observations of rare soils and the occurrence of some soils in soil map unit complexes that cannot be delineated at 1:10,000 scale using the covariate data available.

Soil map units were identified and modelled based on soil–landscape relationships determined in the field and preliminary modelling. Taxonomically similar soils that occupied similar environmental space were grouped into common map units. Soils that occurred rarely in the landscape were grouped with similar commonly occurring soils. Some soils that are taxonomically distant but occupy a similar covariate space could not be separated. However, it is common practice to group these associated soils within a single map unit while providing information about the map unit composition For example, a map unit might contain 40% Typic Fluvial Recent (RFT), 40% Mottled Fluvial Recent (RFM), and 20% Peaty Orthic Gley (GOO) Soils. Conceptual soil–landscape models were used to illustrate soil patterns that DSM may not be able to resolve at this scale of mapping.

The map units of the Kaikohe study area

The crushed argillite hill country in the south-east is dominated by Ultic Soils with densipans, and these have been grouped in map unit UDM_2, which comprises Mottled Densipan Ultic (UDM) and taxonomically similar Pan Podzol Soils, Perch-gley and Albic sub-groups of Ultic Soils and Acid Gley Soils. A similar pattern is found on older terraces in part of the Q1_6al parent material unit, adjacent to the crushed argillite hills, but with a greater percentage of poorly drained Acid Gley and Perch-gley Ultic Soils. The UYM_1 map unit occurs on less stable hillslopes, where Mottled Yellow Ultic (UYM) Soils predominate. Subdominant soils in the UYM_1 map units include Orthic Brown, Orthic Recent and Orthic Raw Soils, and Rocky Raw Soils associated with erodible steepland.

The central part of the survey area, excluding volcanic areas, has complex geology associated with the Northland Allochthon and is dominated by melange, with Tertiary sandstone and mudstone units around the fringes. Similar soils occur on stable parts of this landscape, but where there is evidence of deep-seated movement as well as surface instability it leads to complex unpredictable soil patterns. Mantling stable positions in this landscape there are local tephra deposits up to 1 m thick, although the tephra sources were not always obvious.

The UYM_1 map unit is dominated by Mottled Yellow Ultic Soils, but also includes Mottled Albic Ultic (UEM) Soils. Map unit LOM_2 recognises stable slopes, where these soils are buried beneath Mottled and Typic Orthic Allophanic (LOM, LOT) Soils. There are often seepage areas associated with these tephric soils, presumably due to permeability differences between the tephra and Ultic paleosols. Typic Orthic Gley (GOT) Soils are mapped in these areas and assigned to the GOT_2 map unit. Some Ultic Soils with pans are also observed, although there is no obvious soil–landscape relationship. On steeper slopes, soil map unit BOM_1_2_5 contains a similar soil pattern to the crushed argillite hill country, but tending more towards Brown Soils than Ultic Soils.

There are two volcanic cones in the survey area and numerous lava flows, some of which originate from volcanic centres outside of the survey area. The soil pattern on these volcanic landscapes is relatively simple and predictable. Volcanic cones have Allophanic (LOT) and

Typic Tephric Recent (RTT) Soils – map unit LOT_4. The LOT_2 and LOT_3 map units occur on younger lava flows, where stony and very stony Allophanic Soils contain many boulder-sized clasts and, near the scoria cones, significant scoria layers. Map unit LOT_1 predominates on older lava flows, which tend to be more distal from their source and are dominated by moderately deep to deep Allophanic and Brown soils. However, some of the most distal valley lava flows do have stony and very stony Allophanic Soils, which are mapped as LOT_2 and LOT_3.

In the north-east, greywacke is the main geological unit and soils are predominantly UYM, with tephric soils on some stable slopes. Because some tephra came from unknown sources outside the survey area, it was difficult to predict the extent of tephra or age of deposition. Tephric soils in the north-east generally appear to have lower phosphate retention (based on field NaF reaction and laboratory data).These soils have been grouped into the LOM_1 map unit, which contains Mottled Orthic Brown (BOM) and to a lesser extent LOM Soils. As with other sedimentary geology in the survey area, the BOM_1_2_5 map unit is dominant on steeper hill country.

Valley bottom alluvium dissects much of the hill country, and on younger surfaces Fluvial Recent (map unit RF_1_2_3) Soils dominate and include Mottled Fluvial Recent Soils (RFM) and Typic (RFT) Fluvial Recent Soils, with a range of textures and stone content. In lower parts of the landscape Gley Soils are dominant – GO_al map units. Mottled Orthic Brown and Typic Orthic Gley (BOM_3_4 map unit) are common on older alluvial surfaces away from regular flooding. Ultic Soils have developed on the oldest alluvial surfaces (UDM_1 map unit).

The sedimentary geology is complex and undoubtedly presents challenges for the DSM analysis. There is weathered greywacke in the east, a crushed argillite lithology (LRI – Ac) in the west, and a complex of sheared sedimentary lithologies in the centre of the Kaikohe study area, described in QMAP as melange, with early- to mid-Tertiary sandstone and mudstone between the greywacke and crushed argillite.

Field observations from the soil survey indicated that tephra over sedimentary rock is more common than the NZLRI indicates. Because this is a strong predictor for LOM Soils on sedimentary parent material, having a covariate layer that precisely outlines the tephra distribution would ensure better mapping of these soils.

Table 3 Final soil map units used for DSM: descriptions and dominant components in terms of NZSC codes (Hewitt 2010)

Map units	Description
BOM_1_2_5	Brown Soils on sedimentary hills without allophanic soil material. Includes Recent and Raw Soils on eroded steepland. Some Ultic (UYM) Soils likely.
BOM_3_4	Brown Soils from alluvium, mostly imperfectly drained (mottled) with some poorly drained Gley Soils and some Fluvial Recent Soils. Old alluvial surfaces may contain Ultic Soils.
BOT_1_2	Brown Soils on volcanic rock including tephra and lava flows, both stony and not stony. Mostly BOT Soils, with some imperfectly drained BOM Soils and soils on the threshold between being classified as BOT Soils and LOT Soils.
GO_al	Orthic Gley Soils from alluvium, predominantly GOT Soils with some GOO and GOA Soils. In addition, there are rare occurrences of GRT, GRA and Organic Soils. There are also some BOM or BOMA Soils present in this unit.
GOA_1	Acid Gley Soils associated with argillite hills and adjacent terraces. This unit also includes GOA, GAY, Perch-gley Ultic, Densipan Ultic and Podzol Soils.
GOT_1	Gley Soils from seepages associated with tephric soil materials on sedimentary hills. This unit includes some LOM, BOM and UYM Soils.
LOM_1	Tephric soil materials with up to 1 m of tephra over an Ultic paleosol. The P-retention is predominantly <85%. BOM (tephra over buried Ultic) and LOM Soils are common. The unit also includes some LOT, BOT, and UYM Soils.
LOM_2	Tephric soil material with up to 1 m of tephra over Ultic paleosols. P-retention is predominantly >85%. LOM and LOT Soils are common in this map unit, along with some BOM, BOT, and UYM Soils. There are also rare occurrences of UEM Soils and Podzol Soils in the sedimentary hill country.
LOT_1	Deep, stoneless, moderately well to well drained Allophanic Soils. Predominantly LOT Soils on old lava flows, with some moderately deep and/or stony LOT and BOT Soils. Some LOT and LOM Soils occur on sedimentary rocks close to tephra sources.
LOT_2	Stony LOT on valley lava flows. Includes stony and very Stony LOT Soils, few without stone or extremely stony. Maybe significant areas locally where lava is buried by local alluvium and contains taxonomically similar BOM and GOT Soils.
LOT_3	Very stony/bouldery lava flows. Difficult to distinguish between LOT_2 and LOT_3 on some valley lava flows. Predominantly very stony/bouldery LOT with many soils proximal to scoria cones containing scoria horizons. Some taxonomically similar deep LOT and BOT Soils and very stony Tephric Recent Soils.
LOT_4	LOT Soils with scoria horizons on or near scoria cones. Predominantly shallow LOT Soils and related Recent (RXT, RTT) Soils that contain >35% angular basalt stones within 45 cm of the soil surface. This unit contains some deep LOT Soils with fewer stones.
RF_1_2_3	Fluvial Recent (RFT, RFM) Soils, mainly deep and stoneless with loam or clay textures. There are some localised shallow stony RFT and RFM Soils (in valleys within the eroding argillite hills). The unit includes some related Gley and Brown Soils.
UDM_1	Densipan Ultic Soils and other related soils on old terraces adjacent to argillite hills. The predominant soils are UDM, UDP, and related Pan Podzol Soils, with some UPT, UEP and GAY Soils.
UDM_2	Densipan Ultic Soils and related Densipan Podzol Soils on argillite hills. The Soils are predominantly UDM, ZDYH, UEM and UYM Soils. Some GAY Soils occur on undulating footslopes.
UYM_1	Ultic Soils without densipans. Predominantly UYM Soils with some related BOM and Recent Soils in steepland, and related Densipan Ultic and Podzol

Soils on more stable argillite hills. It is likely that some soils developed in tephric soil materials will be present in this map unit in the north-east of the study area.

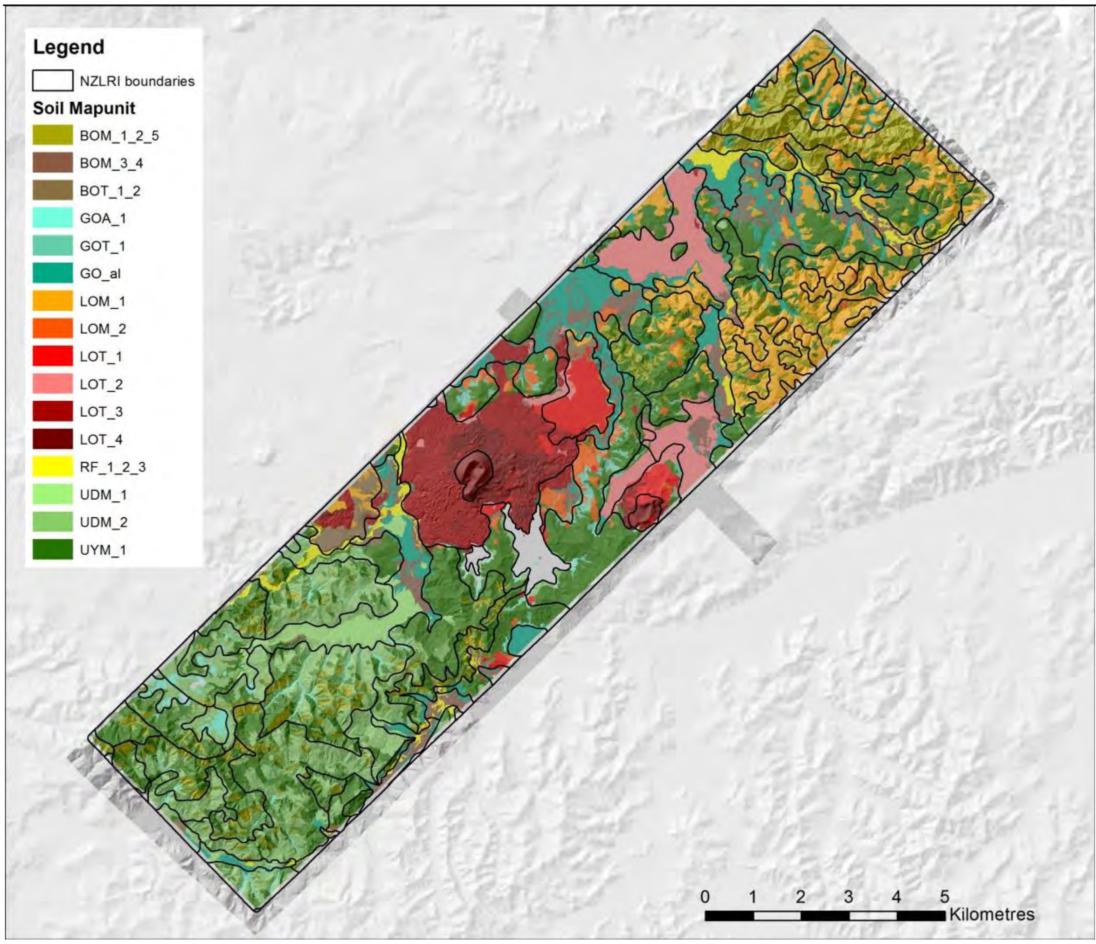

Figure 10 Digital soil map for the Kaikohe study area illustrating the distribution of the16 map units classified by the random forest analysis. The lines show the soil boundaries derived from the NZLRI to give an impression of the increased resolution of soil mapping.

DSM results

The R random forest analysis outputs raster soil maps based on the most probable soil classification (an example is shown in Figure 10), as well as a probability map for each soil map unit. A graphical assessment of the importance of the covariate variables in explaining the soil pattern can be used to revise and simplify the model, removing less relevant covariates that confound the model. Figure 11 shows the variable importance graphic for the final model run. Not surprisingly, parent material had the most influence. Despite reservations regarding resolution, the radiometric covariates, which are also related to parent material and weathering (especially thorium, potassium and uranium), show as important soil predictors.

Important terrain-based covariates were elevation, relative elevation, topographic exposure, sediment transport index, and distance to stream, which generally relate to erosion processes and soil development. Climate factors (direct solar radiation and rainfall) were lesser predictors of soil distribution, also relating to rates of soil development and erosion processes. Interestingly, covariates such as landform element and multi-resolution valley bottom flatness were less useful, and aspect did not seem to be important at all as predictors.

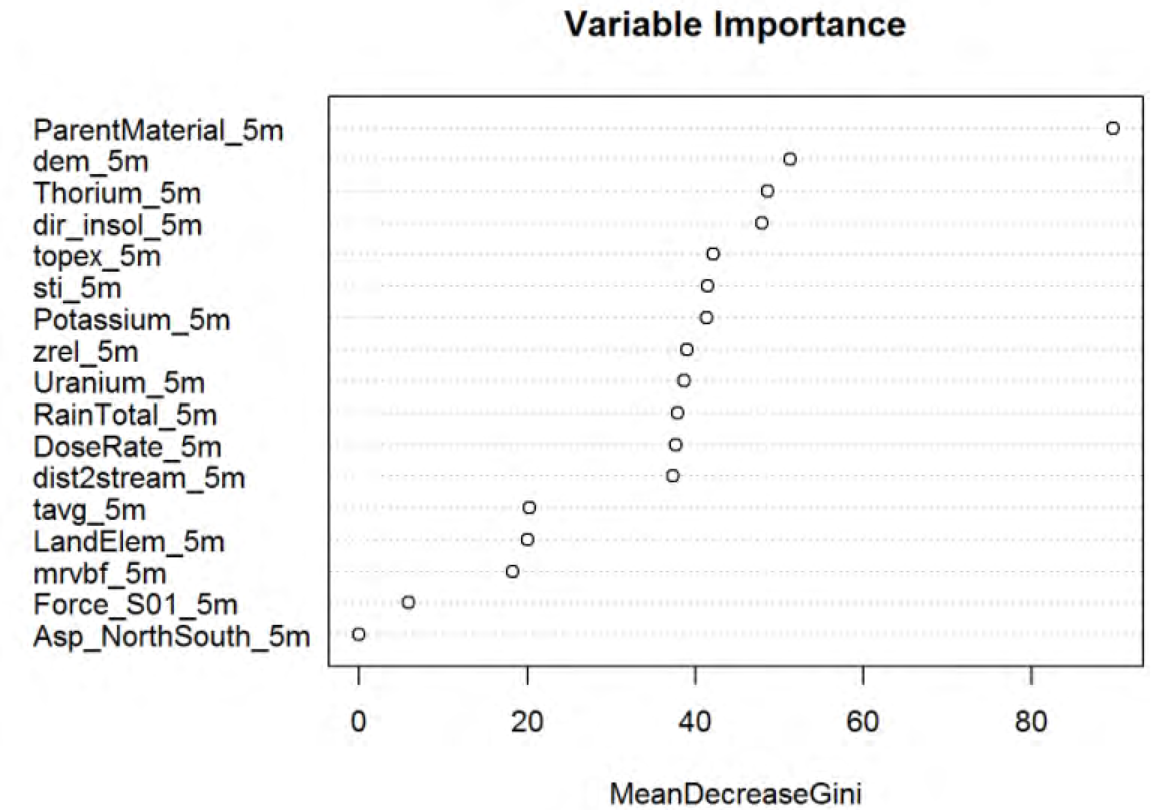

Figure 11 Graphical illustration of the relative importance of the different covariates used by random forests to predict soil class distribution. Gini is defined as a measure of 'node impurity' in tree-based classification. A low Gini (i.e. higher decrease in Gini) means that a particular predictor variable plays a greater role in partitioning the data into the defined classes.

Figure 12 is the confusion matrix for the final model used in our DSM mapping. Correct predictions for soil class at observation locations fall on the diagonal, and incorrect predictions are scattered above and below the diagonal. The observed soil map units are in the left-hand column and predicted soil map units run along the top row.

Thirty percent of the total sample was withheld for cross-validation. The overall accuracy of the model (the total number of correct predictions divided by the total sample number) is 61%. The kappa statistic, which tries to account for the possibility of randomly correct results and is always slightly less than overall accuracy, is 58%. The producer's accuracy represents how well-known soil map units are predicted. This is calculated by dividing the number of correct predictions for each soil map unit by the total number of observation points where that soil map unit was recorded, and taking the mean of these values for all map units. The producer's accuracy tells us that 59% of map unit observations are correctly predicted by this model. The user's accuracy represents the probability that the predicted soil map unit represents the correct map unit on the ground. The mean of user's accuracy across all classes is 65%. These statistics represent a moderate level of agreement (Congalton & Green 1998; Brungard et al. 2015).

Map unit	BOM_1_2_5	BOM_3_4	BOT_1_2	GO_AL	GOA_1	GOT_2	LOM_1	LOM_2	LOT_1	LOT_2	LOT_3	LOT_4	RF_1_2_3	UDM_1	UDM_2	UYM_1	Accuracy
BOM_1_2_5	**28**	1	0	3	0	0	**6**	0	1	0	0	0	0	0	4	**14**	0.49
BOM_3_4	0	**33**	0	**10**	0	0	1	0	0	3	0	0	**8**	1	0	0	0.59
BOT_1_2	0	1	**10**	2	0	0	1	0	1	1	0	0	0	1	0	0	0.59
GO_AL	1	**12**	0	**38**	0	0	1	0	0	1	0	0	2	4	0	4	0.60
GOA_1	0	0	0	0	**8**	1	0	0	0	0	0	0	0	0	**8**	4	0.38
GOT_2	0	0	0	3	0	**5**	0	2	0	0	0	0	0	0	0	4	0.36
LOM_1	3	3	0	1	0	0	**36**	2	0	0	0	0	0	0	0	9	0.67
LOM_2	2	0	0	1	0	1	3	**10**	0	0	0	0	0	0	0	**19**	0.28
LOT_1	0	1	1	0	0	1	0	1	**10**	0	3	2	0	0	0	5	0.42
LOT_2	0	2	1	1	0	0	1	0	1	**20**	4	1	0	0	0	0	0.65
LOT_3	1	1	0	0	0	0	0	0	3	1	**42**	3	0	0	0	1	0.81
LOT_4	0	0	0	0	0	0	0	0	0	0	5	**26**	0	0	0	0	0.84
RF_1_2_3	2	**6**	0	**8**	0	0	0	0	0	0	0	0	**29**	1	0	0	0.63
UDM_1	0	1	0	2	0	0	0	0	0	0	0	0	0	**21**	1	0	0.84
UDM_2	4	0	0	0	2	0	0	0	0	0	0	0	0	0	**33**	**11**	0.66
UYM_1	**5**	1	0	3	3	0	**14**	4	0	0	0	0	0	0	**7**	**60**	0.62
Reliability	0.61	0.53	0.83	0.53	0.62	0.63	0.57	0.53	0.63	0.77	0.78	0.81	0.74	0.75	0.62	0.46	**0.61**

Figure 12 The confusion matrix for the random forest DSM model. The figures in the accuracy column show producer's accuracy, and the reliability row shows user's accuracy for classifications for each class. The overall accuracy of the model is 61%, and the kappa statistic is 58%.

4.5 Erosion mapping

4.5.1 Erosion mapping – method

The aim of the erosion mapping was to provide the basis for deriving a traditional NZLRI-style recording of erosion type and severity, or developing an erosion susceptibility model that could be transferable across large areas of Northland. The latter required recording individual erosion features, as opposed to the traditional approach of polygon-based erosion assessment. A further difference was that both present erosion (defined by the presence of bare ground) and past erosion (recognisable from morphology) were mapped, as opposed to traditional NZLRI-style mapping, where only present erosion is mapped and a post-mapping assessment of potential erosion at LUC unit level is made (see Lynn et al. 2009). Differences between these two approaches and the potential advantages of an erosion susceptibility approach are discussed in Basher et al. 2015. However, after the mapping was completed there was insufficient variation in the types and density of erosion features to attempt the development of an erosion susceptibility model.

Currently there is no reliable automated method for mapping all types of erosion – present and potential. The alternative is a manual office-based compilation. Consequently, erosion mapping was carried out on-screen using the 10 cm digital orthophotography supported by visual terrain analysis using the LiDAR DEM (hill shade and slope classification) (Figure 13). The orthophotos were used to identify the most recent erosion features in the Kaikohe study area; the DEM aided the mapping of features not visible in the orthophotos due to age or vegetation cover. The DEM was especially valuable in areas of plantation forest. Generally, both data sets were used simultaneously (in transparent overlay) to scan the landscape to detect erosion features. A systematic approach using a window size of 1 km^2 ensured comprehensive mapping coverage.

The classification of erosion types followed the categories defined by the *Land Use Capability Survey Handbook* (Lynn et al. 2009), which differentiates between surface erosion, mass movement, fluvial erosion, and deposition. Note that the estimated depth of the landslides (s = shallow, d = deep) was not consistently recorded; instead, the area of the landslides serves as a reasonable proxy.

The LiDAR DEM was used to estimate the approximate age of the erosion features. The age classes were defined as follows:

- 0 – current: very recent (1–5 years) with bare soil still visible
- 1 – recent: still visible, but (partially) revegetated, possibly up to 10–20 years since event
- 2 – historical: date unknown, but likely triggered following initial deforestation.

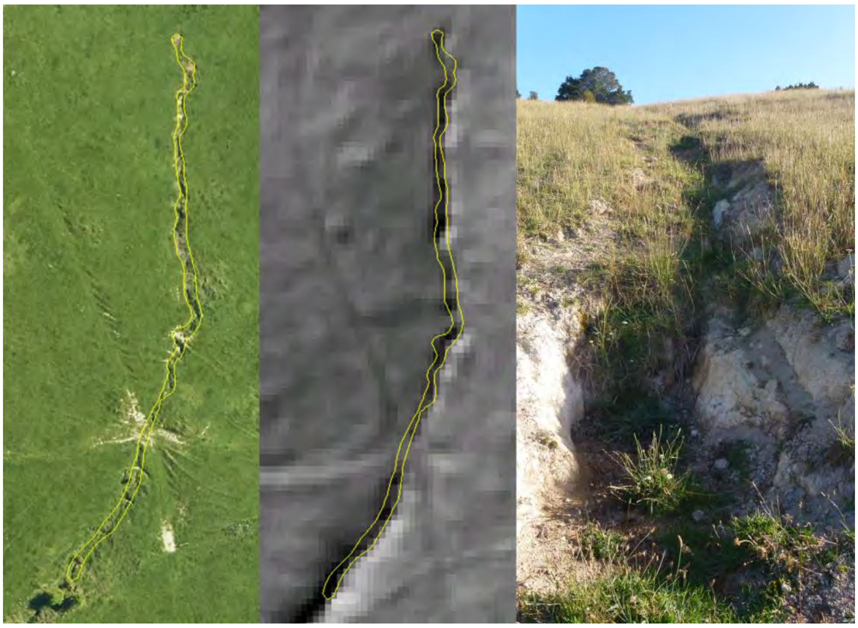

Figure 13 Example of mapping tunnel-gully erosion as seen in (left to right) the orthophoto, the LiDAR DEM, and the field.

Only historical mass movement features and gullies could be detected in the LiDAR DEM. Historical surface and other fluvial erosion features are more difficult to identify and age, because the process is more gradual and these types generally do not cause morphological change at the same scale as mass movement processes.

In addition, the confidence with which features were identified at the time of mapping was recorded: 1 = very confident, 2 = reasonably confident, and 3 = some uncertainty. The level of confidence generally relates to the estimated age of the features, particularly when covered by vegetation. For the purposes of evaluating current erosion the focus is on the current age class.

Three days were spent field validating the mapped erosion features. Eight sites in total were selected within the study area, which covered a range of representative land uses and erosion processes, including three forestry and five pastoral farming sites (Figure 14). Notes on the accuracy of mapping, as well as any other observations, were made directly in the field using QGIS on a tablet. In addition, erosion features observed in the field and not mapped on-screen were identified and mapped on-site. The mapping process would have benefited from a field trip following a preliminary on-screen assessment of erosion processes in the Kaikohe study area. The certainty of mapping is improved where the mapper has greater familiarity with the common erosion features in the field and their representation in the remote-sensing data.

4.5.2 Erosion mapping – results

The mapping method proved capable of generating a comprehensive data set of erosion processes in the Kaikohe study area. The mapping process is time-consuming and needs to be complemented by field work to identify the degree to which older erosion features are currently active.

Table 4 provides an overview of the erosion features mapped in the Kaikohe study area. Soil slips are the dominant erosion process, making up 935 (56%) of 1,667 erosion features mapped. There is a strong relationship between the estimated age of soil slip and the mean area, with historical slips being much larger than recent or current slips. This may indicate that only large (and/or deep) historical soil slips can be detected in the LiDAR DEM.

Of the other erosion types mapped, sheet erosion was the second most common type of erosion mapped, and comprises small areas (63 m^2 mean area) of bare soil. A total of 266 gullies were mapped, with less than half of these showing signs of activity (aged current and recent). Most of the larger gully systems are in the steep hill country in the southern third of the Kaikohe study area. Some 30 tunnel gullies were detected in the orthophotos and confirmed in the field (aided by the DEM, see Figure 13). Their distribution is more widespread than shown in existing NZLRI mapping, while earthflows are less common. Only a small number of earthflow, streambank erosion, and slump features were mapped.

Eight sites were selected within the Kaikohe study area for the field check of results, which provided valuable insights. Each feature within the eight sites was visited on foot to verify the accuracy of mapping. Corrections were made on-site where the feature had been mapped incorrectly. The results of the field check are given in Table 5, listing the count and percent of:

- correctly mapped features
- missed features
- mapped as different type of erosion
- features that extend beyond what was mapped on-screen
- unverifiable erosion features (not observable).

Table 4 Total area covered by each erosion type, and age. Note the total count row contains sum of occurrences for each count column, but the mean area row contains the weighted mean area for average area columns (e.g. $\boldsymbol{Mean\ Area} = \sum(\boldsymbol{Count} \times \boldsymbol{Average\ area})/\boldsymbol{Total\ Count}$

	Current		Recent		Historical			
Erosion type	**Count**	**Average area (m^2)**	**Count**	**Average area (m^2)**	**Count**	**Average area (m^2)**	**Total count**	**Total average area (m^2)**
Soil slip	347	223	185	411	403	1,089	935	633
Sheet	311	63					311	63
Gully	55	2,887	55	6,757	156	5,595	266	5,275
Slump	14	2216	9	4,864	24	6,289	47	4,803
Streambank	43	66	1	38			44	65
Tunnel gully	30	133					30	133
Earthflow	7	1,605	2	2,744	9	3,553	18	2,705
Deposition	11	550	2	503			13	542
Debris flow	1	3,998					1	3,998
Rill	1	1,142					1	1,142
Rock fall	1	31					1	31
Total Count	**821**		**254**		**592**		**1,667**	
Mean Area		**385**		**1,961**		**2,525**		**1,385**

Table 5 Accuracy assessment based on field check of on-screen mapping of erosion processes

	Correct		**Missed**		**Different type**		**Extends**		**Unverifiable**		**Total count**	**Total %**
Erosion process	Count	%	Count	%	Count	%	Count	%	Count	%		
Soil slip	28	29.8	1	1.1	5	5.3		0.0	5	5.3	39	41.5
Earth flow	1	1.1	1	1.1		0.0		0.0		0.0	2	2.1
Slump	5	5.3	2	2.1	1	1.1		0.0		0.0	8	8.5
Gully	17	18.1	6	6.4	1	1.1	1	1.1		0.0	25	26.6
Tunnel gully	16	17.0	1	1.1		0.0		0.0		0.0	17	18.1
Debris flow	1	1.1		0.0		0.0		0.0		0.0	1	1.1
Stream bank	1	1.1	1	1.1		0.0		0.0		0.0	2	2.1
Total	69	73.4	12	12.8	7	7.4	1	1.1	5	5.3	94	100.0

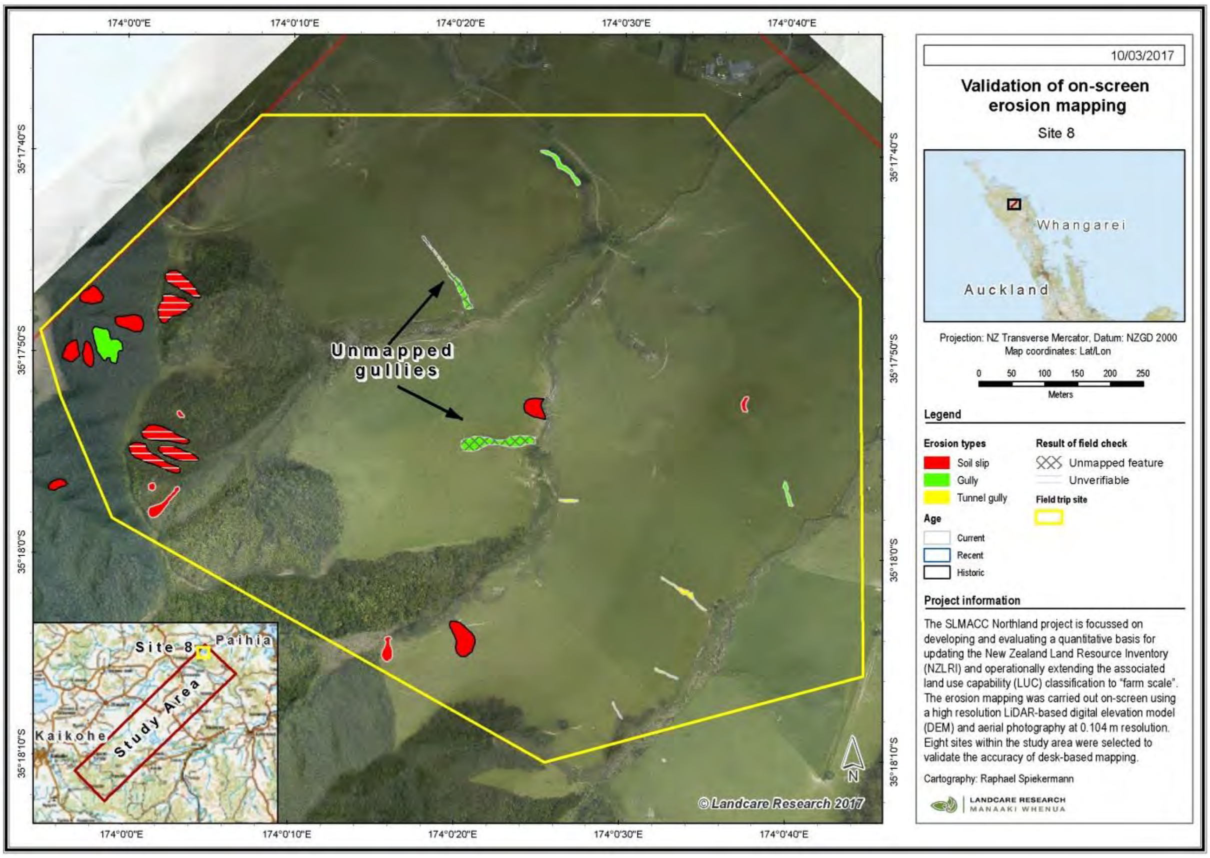

Figure 14 Example of a validation window assessed during the validation field trip, with the erosion features that are not mapped in the on-screen erosion mapping highlighted.

The field check showed that a number of gullies were not identified in the desktop exercise (Figure 15). This is probably due to the fact that the mapper had not visited the Kaikohe study area prior to/during on-screen mapping. An important result of the field check was that the age estimated on-screen is not necessarily an indication of whether the erosion features are still active, but is an approximation of the date of initiation. Observations made in the field indicate that historical erosion features (e.g. gullies) can still be reactivated during significant rainfall events. It is important to keep this in mind when viewing the results in Table 4. Some mapped features could not be verified because access was restricted due to dense vegetation in pine plantations and indigenous forests on steep hill country.

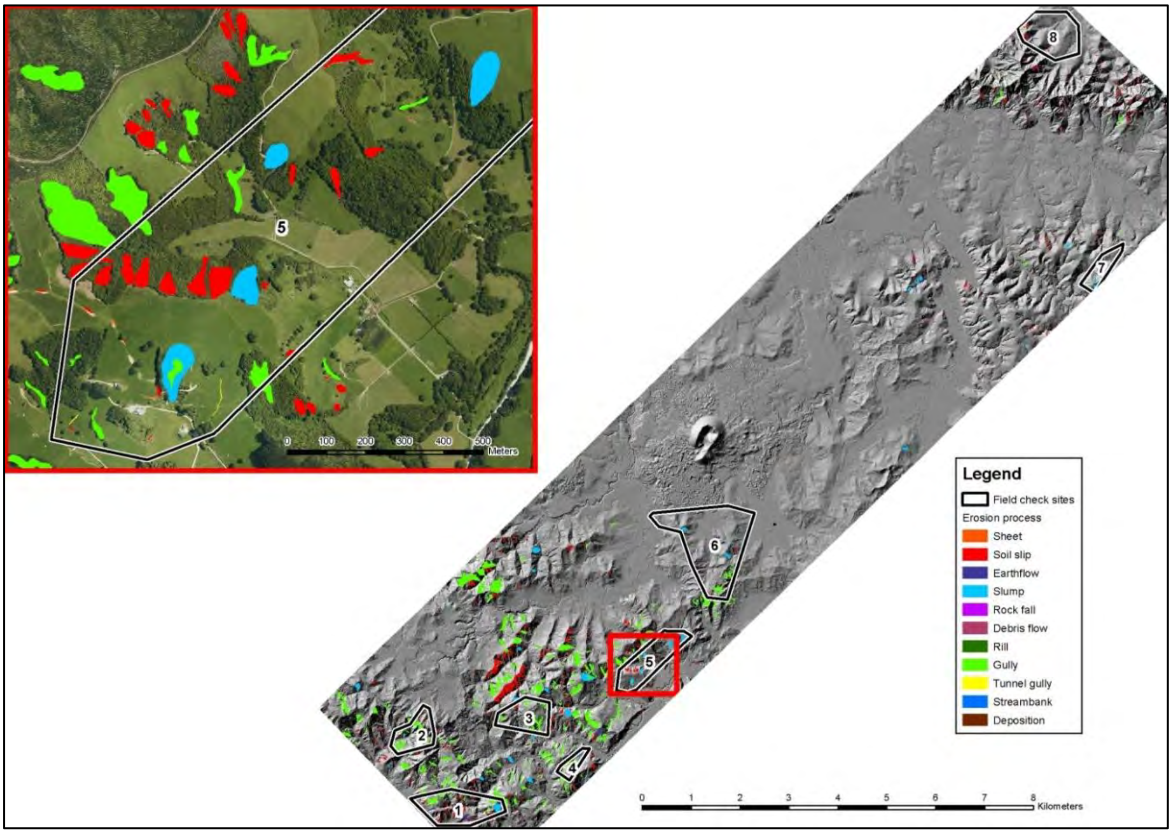

Figure 15 Location of field check sites 1–8. Window shows mapped erosion features in site 5.

4.5.1 Vegetation and forest indices – method

For the purposes of this project we did not attempt to remap vegetation at farm-scale, in part because vegetation has relatively little bearing on LUC classification, and because the Landcover Database (LCDB v4.1) is now regarded as the standard source for digital vegetation cover mapping in New Zealand. Developments in utilising LiDAR CHM or other higher-resolution sources of data to improve these data should be developed through the LCDB project.

The goal in this project was to devise an operational method for assigning an NZLRI vegetation code to each polygon. This is achieved by matching LCDB over classes to the nearest matching NZLRI vegetation class; converting the LCDB to a raster format with the same resolution and dimensions as the soil and other covariate layers for the Kaikohe study area; and using the ZONAL HISTOGRAM function in ArcGIS to assign the percentages of each class occurring within each mapped LUC polygon.

The original NZLRI data set also contained a *Pinus radiata* site index (Jackson & Gifford 1974; Hunter & Gibson 1984), and inclusion of an equivalent forest productivity index was a requirement for this project. The original site index estimates stem volume by age, but research has shown this relationship is affected by stocking rate (planting density), so SCION have replaced the site index with the 300 Index (Kimberley et al. 2005), which assumes a reference stocking rate and age. This is modelled and supplied in raster form at a resolution of 25 m. Although there is a significant resolution difference in data sets, there is no alternative finer resolution data set available, and the method for calculation does not lend itself to generating one for the Kaikohe study area.

Forestry indices supplied by SCION were:

- net profit for a 28-year-old unpruned *Pinus radiata* forest after roading and harvesting costs
- a 300 Index, defined as the mean annual volume increment of *Pinus radiata* at 30 years old, having been thinned to a final crop stocking of 300 stems/ha and pruned to a height of 6 m before a mean crop height of 11 m (Kimberley et al. 2005).

SCION noted that there were some small areas where the roading costs calculation did not work, so the net profit index has some missing values. SCION also noted that for the net profit index, the log volume was modelled assuming best-case growth and the costs were in line with a large company operating at scale: the range of the net profit index is close to double what a small-scale farm forester would be likely to achieve in the region if they were harvesting now. This is considered an optimistic estimate, but the net profit index was considered a better index to use because remote, steep areas far from ports were not capable of producing a valuable crop due to harvest and transport costs.

We again used the ZONAL HISTOGRAM approach to assign mean forestry indices to each polygon. Forest indices were provided at 25 m resolution, so there may be spatial scale issues (uncertainty) in assigning forestry indices to each map unit based on the spatial coincidence across the scales from farm-scale LUC (5 m resolution – 1:10,000 nominal scale) to 25 m resolution forestry (nominally 1:50,000 scale).

4.5.2 Vegetation and forest indices – results

LCDB is mapped at 1:50,000 scale nationally, and at approximately 6-year intervals (i.e. 1996, 2001, 2008, 2012). This means that any attempt to compare contemporary farm-scale vegetation mapping from high-resolution aerial orthophotography will be out of date, in this case by approximately 4 years, and the LCDB will not have been subject to ground checking. In addition, the LCDB is somewhat less rich thematically (in terms of classes and class definitions) compared to the NZLRI vegetation classes (Lynn et al. 2009).

Consideration was given to image classification of the orthophotos to improve on the LCDB representation of vegetation distribution. However, the orthophotos are not true multi-spectral images and have limited value for this type of analysis. Consideration was also given to utilising the CHM from the LiDAR, but using this canopy height information to improve the resolution and accuracy of vegetation or land cover mapping (e.g. mapping smaller woody patches) is still in the research phase and not ready for inclusion in this project.

In the event, the decision was taken not to attempt to expend resources mapping high-resolution vegetation, which is of relatively minor importance in terms of mapping LUC, and to rely on the LCDB and the expectation that future LCDB-type mapping will improve in accuracy and resolution. Using the ZONAL HISTOGRAM methodology developed, incorporating best available vegetation mapping into future digital LUC mapping is expected to be straightforward, and incorporating future improved vegetation mapping into a farm-scale database should not be difficult.

In terms of the forestry indices supplied by SCION, the spatial resolution of the indices is generally coarser than the LUC polygons generated by the automated digital mapping process. In addition, the variability of the indices is relatively low, with a standard deviation of index values for the whole Kaikohe study area in the order of 3−4% of the mean index. Because of these results, the ZONAL HISTOGRAM analysis does not translate well across the scales, resulting in an apparent poor correlation between LUC and forest indices.

In the case of the 300 Index, values in the Kaikohe study area range from 24.4 to 32.9, with a mean value of 28.7, but any relationship between LUC units and the indices is not clear, even at a coarser level (Figures 16 and 17) when the 300 Index is plotted against LUC class and LUC dominant limitation from the farm-scale digital LUC classification. For LUC class (Figure 16) the pattern remains confusing, with LUC Classes 6 and 7 having a higher 300 Index than LUC Class 5 units, which seems counter-intuitive. The LUC dominant limitation (Figure 17 hints at a more conventional relationship, with slightly lower 300 Index values for units with a wetness limitation, but in fact this reduced index value is dominated by 6w4 units, many of which surround the lakes in the Kaikohe study area. In these cases, scale differences in the depiction of the lake shoreline are resulting in incorrect estimation of the indices for these polygons and erroneously reducing 300 Index values.

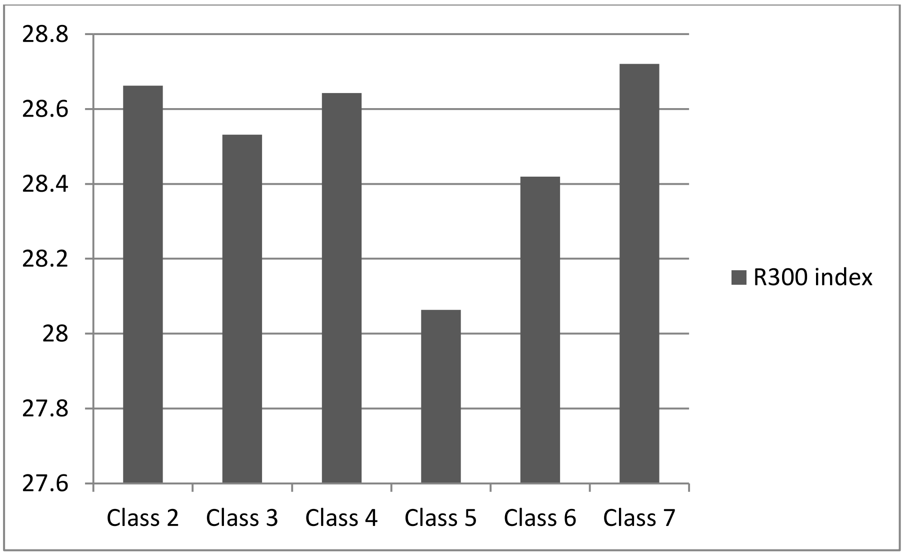

Figure 16 Mean R300 index values plotted against LUC class

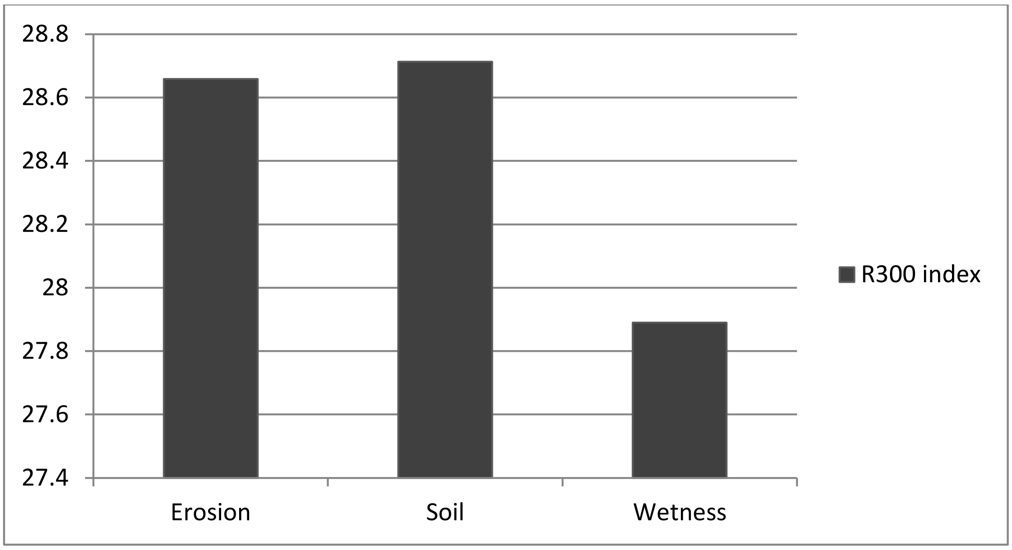

Figure 17 Mean R300 index values plotted against LUC major limitation type.

If forest indices are to be used at this scale, they must be at higher resolution. SCION is part-way through the Growing Confidence in Forestry's Future (GCFF) programme, one of the main aims of which is to refine the micro-site effects for *Pinus radiata* productivity (e.g. nutrients, aspect, altitude, water availability, and temperature). No reliable interim results were available that are applicable to this project.

5 Combining Inventory Layers

5.1 Automatically combining inventory layers

5.1.1 Method

The process of automatically combining the multiple inventory layers into a single set of polygons emulates the traditional process of manual delineation of LRI polygons by land resource mappers through aerial photo interpretation, refined by field validation. The manual mapping process is also deeply entangled with the act of mapping the inventory factors (i.e. rock, soil and erosion), making it difficult to separately evaluate the action of mapping polygons (i.e. delineating boundaries) and the evaluation of the polygon's contents (e.g. what inventory or LUCs are assigned to polygons). Also, LUC classes are assigned to map units (polygons), which represent areas where all inventory factors are broadly homogeneous at the mapping scale. It does not make sense, conceptually, to try to assign LUCs to individual raster cells.

To develop an automated process for digitally creating mapped polygons we have applied the general approach of segmentation, which extracts objects from raster data layers already described for slope inventory in section 4.2.1. These objects are created via a process whereby grid cells in close proximity, and with broadly similar characteristics, are grouped into a segment (the raster equivalent of a polygon). At the same time, grid cells in the same vicinity that are dissimilar but rare get grouped into that segment as well. This simplifies and discretises a highly heterogeneous raster map into a much more homogeneous raster map that can be vectorised (turned from raster into polygon). The resultant polygons represent areas that are dominated by particular properties and are thus very close to the process an LUC surveyor goes through when drawing a boundary around an area with a broadly homogeneous land inventory.

When automatically integrating soils data into LRI maps, it is important to maintain spatial continuity of narrow but continuous landscape features such as valleys and ridge-lines that give map users the sense of natural landscape units. To achieve this, the following steps were undertaken.

1. The raster soil map was masked by a detailed lake shoreline and resampled without interpolation from 5 m to 2.5 m. This resampling was a precursor to expanding selected raster classes by one cell (half of the original cell dimension).

2. Any diagonally oriented narrow units were identified as these often have pinch points where raster cells only meet at a corner (Figure 18). Although these cells touch, the vectorisation process generates a series of raster cell-sized touching polygons that would be eliminated based on their size.

3. These units were resampled and expanded so that the pixels became more connected and the vectorising process retained these properly connected raster cells without unduly compromising the location of the polygon boundary.

Figure 19 gives a schematic of the whole analysis, which again creates a series of soil map unit polygons that are dominantly one soil type, generates smoothed and simplified soil map unit boundaries, and then UNIONs these with the separately prepared slope polygons.

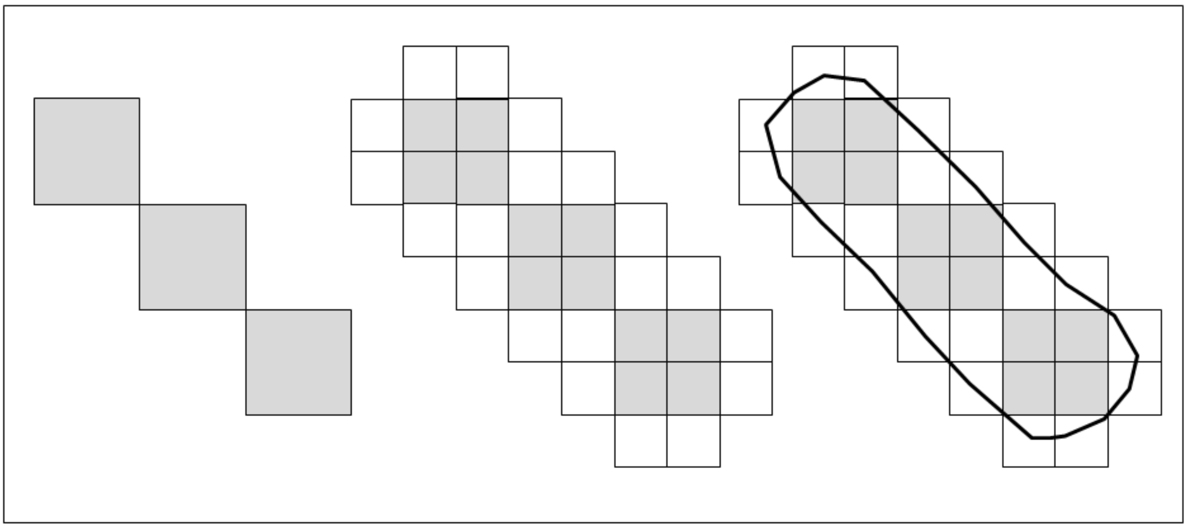

Figure 18 Use of RESAMPLE and EXPAND grid functions to protect linear features during vectorisation.

The final steps after the UNION are also critical. The UNION of the soil and slope polygons will again create many new 'sliver' polygons, where slope and soil boundaries do not quite match. Many of these will be below the minimum size specified for this scale of mapping. Using a simple ELIMINATE to remove all small polygons is too crude and has the effect of eliminating some soil polygons by effectively merging them based on similarity of slope, often undoing the work of the EXPAND function described above. While slope is a factor in modelling soil distribution, some soils occur across multiple slope classes (e.g. A and B). We assume that the soil is the primary attribute on which to carry out the ELIMINATE. In ArcGIS, the function has an optional exclusion parameter that allows the ELIMINATE to work on one soil map unit at a time and effectively protects the soil boundary from being eliminated by minor slope changes.

Apart from setting parameters for minimum polygon size in the ELIMINATE, smoothing algorithm and smoothing tolerance in the SMOOTH, and simplification algorithm and simplification tolerance (allowable line offset) in the SIMPLIFY, these segmentation processes are entirely automated and create a set of polygons from the source raster data without any operator intervention. Tests indicate that the same result is reliably achieved from the same input data and settings.

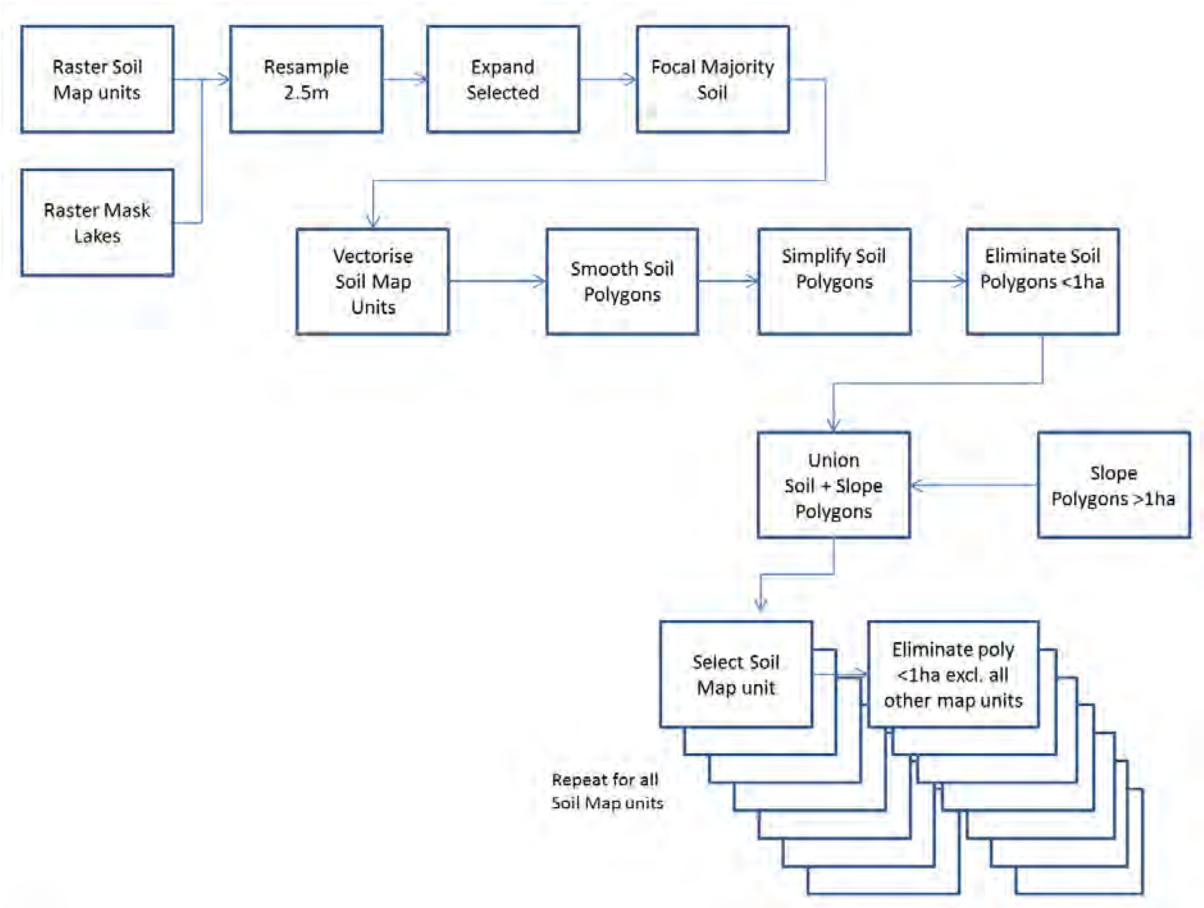

Figure 19 Schematic for generating soil map unit polygons from the soil map unit raster map (the result of the DSM analysis) and the slope polygons (the result of the slope raster segmentation process).

5.1.2 Combining inventory layers – results

The workflow outlined in the previous section could process the entire 100 km^2 Kaikohe study area, starting with the single-factor raster inventory layers and finishing with a single layer of vector polygons ready to have inventory attributes and LUC attached in less than 1 hour of desktop processing time.

There were 3,948 polygons produced by this process, with an average size of 2.63 ha and standard deviation of 7.52 ha. The largest polygon generated was 243.5 ha, but the size distribution is skewed, with 35% of polygons less than 1 ha, and 90% of polygons less than 5 ha in size. There were 153 polygons less than 0.2 ha delineated. These small polygons only occur where a soil polygon has been protected from elimination based on slope.

The polygon boundaries produced by the automated method are characterised by being relatively complex in terms of shape compared with the polygons created by traditional manual digitising techniques. This can be summarised statistically by the area:perimeter ratio of polygons. A circle has the lowest possible ratio, and long, thin and complex shapes have the largest area:perimeter ratios. Generally, smaller polygons will have lower ratios as they tend to be less complex shapes. The mean ratio for the digitally created polygons is 14.74, with a minimum of 0.06 and a maximum of 100.

Visually the polygon boundaries appear to align well with the underlying landscape and inventory layers from which they have been generated (e.g. Figure 20).

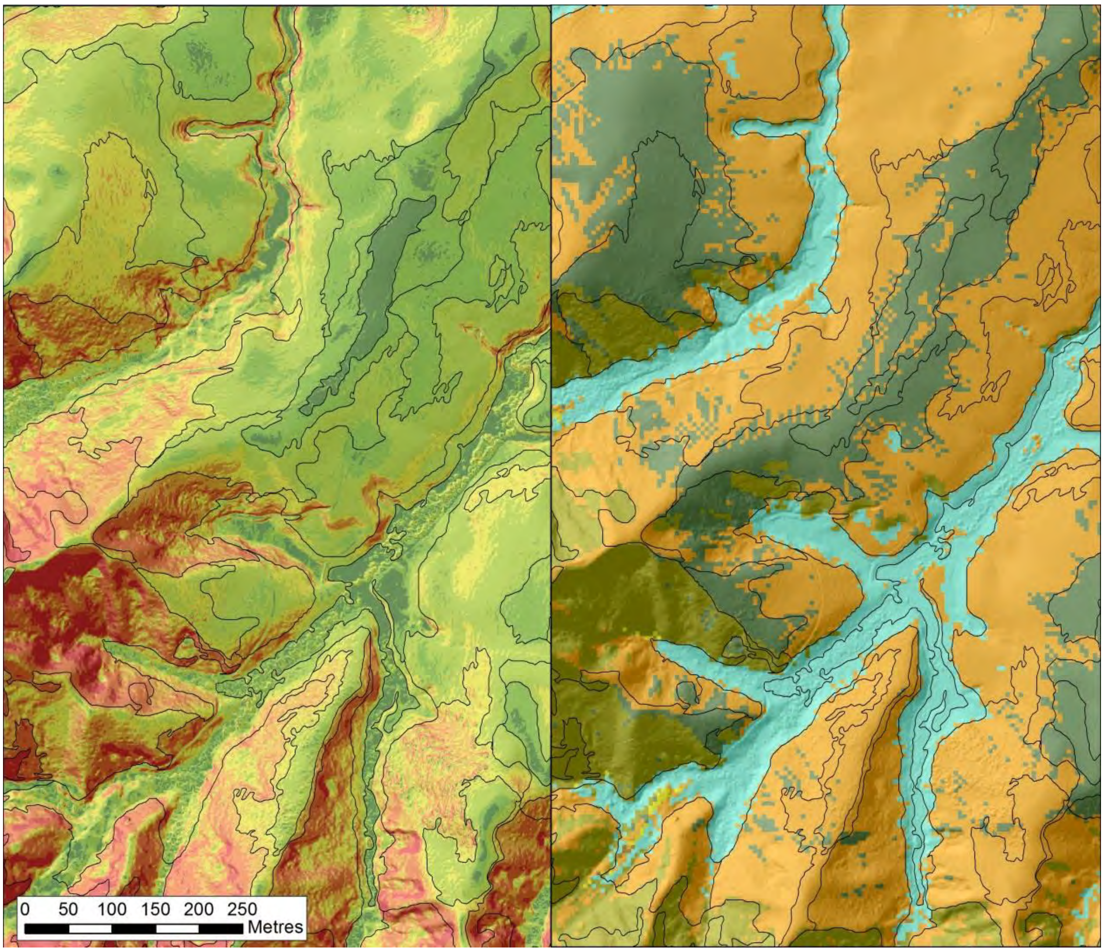

Figure 20 Illustration of definition of automated digital polygon boundaries overlain on the slope raster (left) and soil map unit raster layer (right) to indicate how well the boundaries align with and reflect the underlying inventory information they are derived from. Map scale is 1:5,000, and the same area is shown in both halves of the figure.

5.2 Assigning inventory attributes

5.2.1 Assigning **inventory attributes –** method

The main inventory attributes (e.g. rock, soil, slope, vegetation and erosion) are all assigned to the digitally generated polygons following the same basic procedure, providing an objective means of populating the inventory as well as a measure of variability for inventory factors. Slope is used as an example to describe the method used.

Dominant and sub-dominant slope class for each polygon is assessed using the ZONAL HISTOGRAM function in ArcGIS, with the 'bins' for the histogram defined by the slope class boundaries for LRI mapping (Lynn et al. 2009). This yields a table of frequency of occurrence of cells in each slope class within each unique polygon. The raw table, as exported from ArcGIS, has seven rows (slope classes) and one column per unique polygon ID (i.e. >4,000 columns). Within Microsoft Excel the rows and columns are transposed to get a table with seven slope class columns and >4,000 rows of cell frequency values within each class for each Object-ID (unique polygon identifier).

Columns are added to convert these frequency values into percentage values by calculating total cells in the polygon and calculating the ratio of each class to the total. New column names are added to the table for the three dominant slope classes and their percentage of total area. The Excel INDEX function is used to identify the column headers (i.e. slope classes A to G). The MAX function identifies the cell (and hence column) that contains the highest percentage slope class value for that polygon, and the MATCH function to set the target cell to the appropriate header value for the most common slope class (e.g. A for slope class A).

For the sub-dominant slope class (second and third most common) we use the similar LARGE function to identify the cell (and hence column) that contains the next highest percentage value for that polygon, and the MATCH function to set the target cell to the appropriate header value (e.g. G for slope class G).

In the case of slope, we also experimented with richer descriptions based on the ZONAL HISTOGRAM function output. Although not used in the data set supplied, this was to investigate emulating the traditional mappers' decisions whether to refer to a map unit as having a single slope code (e.g. A), a mixed slope code (e.g. A+B or A/B), or a dissected slope code (e.g. B′). To do this we identified:

- flatter arable areas from steeper areas based on the modal slope for each polygon (i.e. slopes classes A, B, and C are defined as 'Flat' and slope classes D, E, F, and G as 'Steep')
- slope purity, which is based on the percentage of the sub-dominant slope class

Sub-dominant slope class %	Purity class
>35% and <50%	Low
>10% and ≤35%	Medium
≤10%	High

- slope range, which evaluated the number of classes between the dominant and sub-dominant class (e.g. A and C are separated by two classes, A and D by three classes, and so on).

The reasoning here is that inventory polygons with high purity can be designated a single slope class; inventory polygons of medium slope purity or those with a low purity and non-adjacent slope classes can be assigned a combined slope code (e.g. A+B or A+C); and inventory polygons with low purity and adjacent slope classes can be designated transitional slope classes (e.g. A/B).

Inventory polygons that have high or medium purity are dominated by flat slopes, but with steep sub-dominant slopes and more than a slope range of two classes can be designated a dissected class (e.g. A′). Possibly the codes could be modified to show more detail in this case (e.g. A′ + E to designate that a flat surface is dissected by features with slopes of class E.

This transformed table was imported into ArcGIS and joined to the inventory data set using the unique polygon ID to match slope codes to the correct map unit. Note that the table created from ArcGIS ZONAL HISTOGRAM was exported to Excel and manipulated using the transpose and pivot functions to achieve the required table configuration. We retain the lookup table so that the richer histogram data and other slope assessments can be queried should more detailed information regarding slope be needed.

We followed a similar procedure for creating rock type, soil, erosion, and vegetation lookup tables and assigning the primary inventory codes to the main inventory GIS data set.

5.2.2 Assigning inventory attributes – results

The workflow carried out in Excel is quick and effective at reporting the statistical summary of inventory classes occurring within a polygon defined by the segmentation processing, and the process of assigning codes according to this summary is straightforward.

In terms of assigning slope, for example, the process represents an objective measure of the slopes occurring within each polygon, which can be converted into equivalent slope inventory codes following the LUC conventions (Lynn et al. 2009). In addition, the lookup table generated from this workflow contains percentages of all slope classes occurring within each polygon, not just the dominant ones, and represents a far richer data set than that generated through traditional mapping.

Acquiring rock type, soil, erosion, and vegetation codes from the respective inventory layers was an equally straightforward process. This clearly demonstrates that, given suitably accurate and precise inventory layers, this process can be achieved digitally with minimal difficulty. The challenge in terms of data quality lies almost entirely with the quality of the inventory layers available.

5.3 LUC classification and extended legend for digital LUC – method

5.3.1 LUC classification and extended legend for digital LUC – method

The LUC legend for both the traditional and digital mapping has been derived from the existing Northland 2nd edition NZLRI legend (Harmsworth 1996). Both traditional and digital mapping teams acted independently in terms of using units directly, modifying, or (where necessary) creating new units.

For the digital mapping, five new units were established and 26 existing units were subdivided into their major components. This is because mapping for the Northland project is in the order of 1:10,000 scale compared with NZLRI at nominally 1:50,000 scale. The LUC guideline criteria used follow those documented in the 3rd edition of the *Land Use Capability Survey Handbook* (Lynn et al. 2009). We have followed the recommended convention of using ‘a’ and ‘b’ sub-unit notation to ensure the pedigree of the subdivided units is obvious.

In addition, the digital mapping used DSM, which mapped ‘soil map units’ defined by the NZSC taxa (Hewitt 2010), generally to sub-group level, along with additional observations regarding soil texture, depth, drainage, and stoniness. This differs from the legacy Northland Soil Series of Cox et al. (1983) and the Kaikohe study area coverage (Sutherland et al. 1980) used by the traditional mapping team that mapped soil series. Consequently, the LUC unit descriptions of Harmsworth (1996) had to be reworked to align LUC unit definitions with the NZSC soil classification. For the purposes of this project, LUC units were arranged in relation to the soil map units identified through the DSM exercise. Brief LUC unit descriptions and the rules used to assign each mapped polygon to a LUC unit based on its inventory properties are outlined in Appendix 2.

5.3.2 LUC classification and extended legend for digital LUC – results

The LUC legend developed by the digital LUC mapping team can be found in Appendix 2. This legend uses 41 LUC units to capture the diversity of LUC in the whole Kaikohe study area. There are three Class 2 units, eight Class 3, 11 Class 4, one Class 5, 16 Class 6, and two Class 7. Table 6 provides an overview of the LUC units, the frequency of occurrence, and basic statistics for the areas over which they are mapped. This is an increase of 50% in the number of LUC units used to map the whole 100 km^2 Kaikohe study area.

Of the 41 LUC units identified, five completely new units were established: 4w5, 6e20, 6w4, 6w5, and 7s1.

- LUC units 4w5 and 6w5 encompass the undulating (4−7°) and rolling (8−20°) slopes associated with Mottled Orthic Allophanic and Mottled Orthic Brown Soils, and Typic Orthic Gley Soils (in swales) on hill country underlain by melange derived from sedimentary rocks.
- LUC unit 6w4 encompasses flat to rolling slopes and swales with deep, poorly drained Acid Orthic Gley Soils associated with Ultic Soils, predominantly on hill country underlain by crushed argillite and melange.
- LUC unit 6e20 encompasses steep hill slopes on weathered crushed argillite and massive sandstone with deep, imperfectly to moderately well drained Mottled Orthic Brown Soils with a potential for moderate shallow soil slip, and moderate sheet and gully erosion.
- LUC unit 7s1 encompasses rolling to undulating basaltic lava flows with non-arable, very stony or extremely stony and boulder, well drained, very shallow Typic Orthic Allophanic Soils. These occur as part of soil map unit LOT_3 with topsoil stone contents of >70%, and common surface boulders which severely limit production.

The subdivision of the 26 existing units into their major components was determined primarily on soils at the sub-group level.

5.4 Assigning LUC from extended legend

5.4.1 Assigning LUC from extended legend – method

As described in the previous section, no fundamental changes to LUC and how it is defined were proposed. LUC units were defined conventionally during development of the extended legend, which was based on the Northland extended legend (Harmsworth 1996), modified to deal with the NZSC soil classification and to accommodate the change to farm-scale.

Assignment of LUC unit codes to polygons was carried out through a simple rule-based code implemented in ArcGIS. Based on the inventory factors (specifically rock, erosion, soil and slope) an LUC unit was assigned to each polygon. For example, LUC Unit 4e7b is described as 'rolling to strongly rolling (C, D, B, A) slopes on downlands underlain by weathered greywacke with deep, imperfectly to moderately well drained Mottled Orthic Brown Soils which have a potential for moderate to severe sheet, rill and gully erosion when cultivated'.

This description is turned into an IF>THEN rule.

> IF Rock = Gw, or Gw+Us AND Slope < E AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (i or mw) [any drainage] AND Depth = deep [any depth] THEN LUC = 4e7b

These rules are coded into a simple series of sequential SELECT and CALCULATE functions, which find all inventory polygons that match the rule specification and assign the LUC code accordingly.

This has the advantage that all LUC rules are explicitly recorded, and map unit LUC codes can be reliably coded according to their inventory. Any unmatched polygons are quickly identified because they are not assigned an LUC, and adding new units or correcting/adjusting rules to accommodate unexpected inventory combinations is straightforward. LUC assignment is done progressively through the rule set, making the process of LUC assignment objective, transparent, consistent, and fast.

5.4.2 Assigning LUC from extended legend – results

Once set-up is complete, reassigning LUC codes for almost 4,000 polygons takes less than a minute. The complete inventory and LUC data set is available online at https://LRis.scinfo.org.nz/layer/553-mpi-slmacc-northland-property-scale-luc/.

Table 6: Summary table of LUC units, their frequency of occurrence, and size statistics for digital LUC mapping for the Kaikohe study area

LUC class	LUC unit	Count	Area (ha)	Mean (ha)
Luc Class 2	2e1	34	193.16	5.68
	2e1c	199	384.37	1.93
	2s1b	34	122.08	3.59
LUC Class 3	3e1	12	45.36	3.78
	3e1b	191	528.80	2.77
	3e3	160	336.79	2.10
	3s1	73	508.54	6.97
	3s3a	58	115.33	1.99
	3w1a	68	170.93	2.51
	3w1b	159	339.07	2.13
	3w2	150	419.59	2.80
LUC Class 4	4e12a	138	266.60	1.93
	4e2b	61	95.06	1.56
	4e6a	202	1,113.29	5.51
	4e6b	85	144.95	1.71
	4e7a	240	661.31	2.76
	4e7b	105	143.23	1.36
	4s1	6	7.80	1.30
	4s4a	41	133.04	3.24
	4w1a	2	2.02	1.01
	4w1b	36	74.02	2.06
	4w5	45	83.19	1.85
LUC Class 5	5s1	128	507.52	3.97
LUC Class 6	6e17a	6	7.73	1.29
	6e17b	111	353.45	3.18
	6e19a	296	956.35	3.23
	6e20	178	244.71	1.37
	6e4	16	69.14	4.32
	6e4b	146	253.31	1.73
	6e7a	315	668.12	2.12
	6e7b	13	15.46	1.19
	6e9a	32	55.12	1.72
	6e9b	57	83.44	1.46
	6s1	85	206.25	2.43
	6s5b	12	69.53	5.79
	6w1a	19	81.90	4.31
	6w1b	159	353.50	2.22
	6w4	98	141.07	1.44
	6w5	21	20.18	0.96
LUC Class 7	7e8	98	201.84	2.06
	7s1	43	164.75	3.83
	Total	3,932	10,341.92	2.63

6 Traditional LUC Mapping

MWLR contracted LandVision Limited (LV) to carry out a business-as-usual traditional farm-scale LUC mapping exercise for a subset of 10% of the Kaikohe study area. There were lengthy discussions regarding what constituted business-as-usual LUC mapping. In the view of MWLR this meant the LV team would carry out their traditional mapping as if MWLR were not also digitally mapping the area. Both mapping teams would have access to the same legacy data (e.g. Sutherland et al. 1980), but the LV traditional mapping team should not have new information being collected by the MWLR digital mapping team, since under business as usual this would not exist. The aim was to ensure that both mapping teams started with the same legacy data and acted as far as possible independently from that point on.

The exception to this was that the orthophoto set was supplied to LV to ensure both teams were working from the same imagery date, particularly in terms of erosion.

Specific discussions were held about access to LiDAR data. Again, it was the view of MWLR that if LV would not usually use LiDAR in their farm-scale mapping process, even where it was available, then use of LiDAR would not constitute business as usual. If LV did use LiDAR whenever it was available, its use would constitute business as usual practice. In this case, where LiDAR was being acquired as part of the digital mapping project, LV were given the option of mapping with or without LiDAR data but were advised that a reasonable cost of acquisition would be factored into the cost comparison between the two approaches. Given this choice, LV chose not to use the LiDAR data.

LV also advised that business-as-usual farm-scale mapping involved mapping properties, not arbitrary square or rectangular areas. Agreement was reached to map seven properties (Figure 21), part properties or adjacent groups of small properties, to ensure the business-as-usual principle was not compromised. The parcels used were selected by MWLR using LINZ property data and were selected to include a fair range of the terrain, geology, soils, and vegetation of the wider Kaikohe study area. Some of the parcels selected were areas where MWLR had collected field soil data; other properties were chosen because minimal or no soil data had been collected.

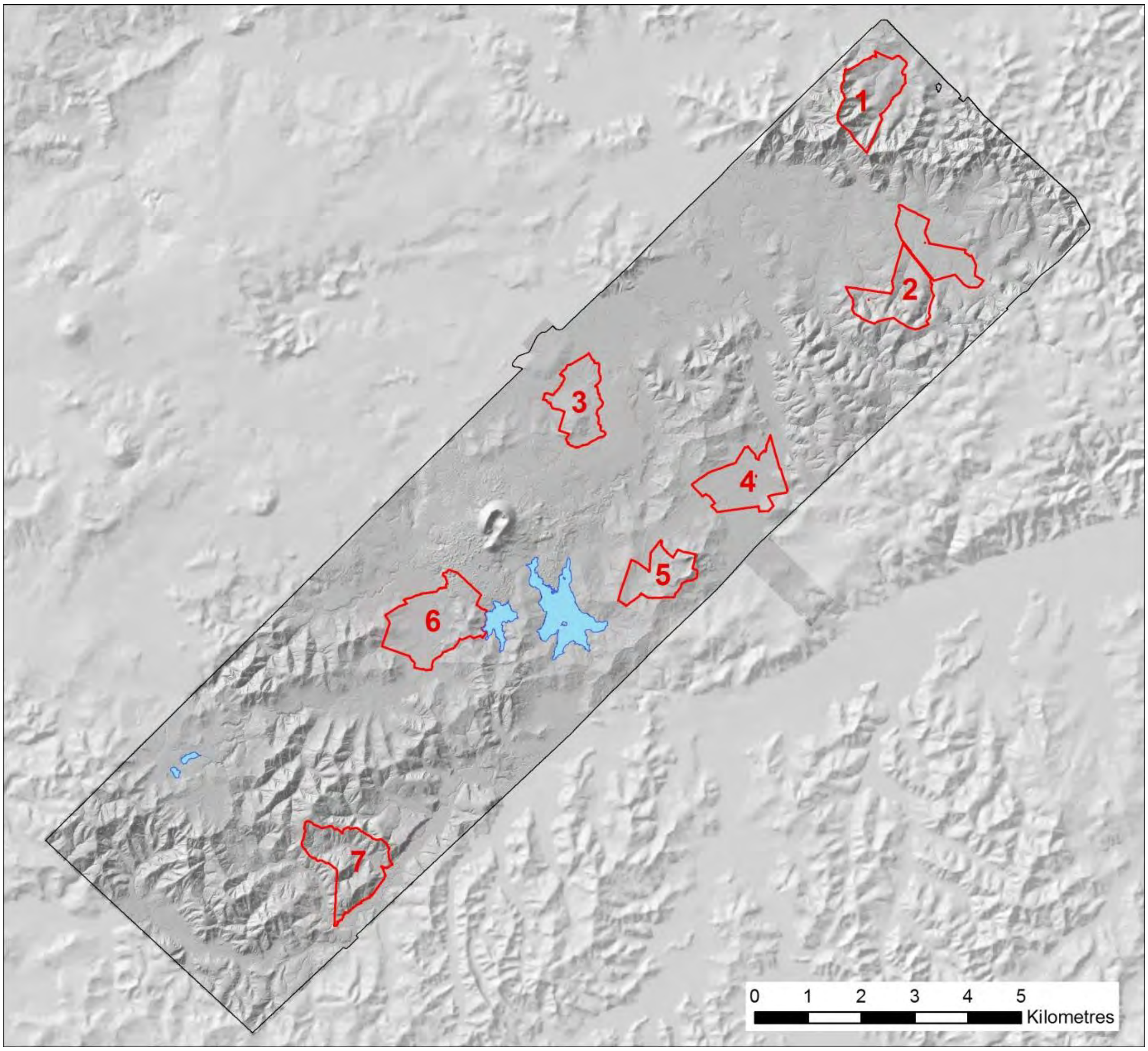

Figure 21 The properties/blocks mapped using traditional LUC techniques by LandVision Limited.

6.1 Traditional LUC mapping – methodology[4]

The traditional LUC mapping team from LV carried out their farm-scale LUC field survey in late 2016, and LV summarised their mapping methodology in their report as follows.

- The mapping was treated as a commercial job, with the aim to be as efficient as possible.
- The field work was undertaken as per the LUC handbook.
- Prior to the mapping we did prepare paddock maps of the areas of interest for the ease of mapping. This way it is easier to locate your position on the map.
- The contract was to map at 1:10,000 scale with the smallest map unit about the size of the old 'one cent piece' on a 1:10,000 scale aerial map. Generally, the mapping scale

[4] Section 6.1 is provided as closely as possible in the words of LandVision from their report and communications.

for pastoral units was around 1:7,000-10,000 whilst this stretched out to about 1:15,000 for forested or indigenous bush/scrub with limited access.

- In undertaking the mapping, we were generally looking for changes in the LRI for another polygon to be drawn.
- Rock type was generally assessed when digging holes and looking at track or bank cuttings along with consideration of the physiographic position in the landscape.
- Soil assessment made as per physiographical position in the landscape plus changes in vegetation type present. Continuously using the auger to confirm extent. The soils were described using traditional soil survey techniques and generally labelled 1, 2, 3… Local names were not given to them in the field and we tried to give them a local name in the office based off old MWLR descriptions. Our level of confidence for some of these names, or more so the correlation with our descriptions varied significantly.
- Slope determined from eye assessment and a clinometer (used also to calibrate the eye assessment). Generally, slopes were looked at from at least two different angles to remove the bias between assessing from up-slope versus down slope positions.
- Vegetation determined from the dominant vegetation type present. The vegetation in the large areas of indigenous bush and exotic forestry were often determined from a high advantage point.
- Erosion mapped as present. We created a new erosion type for ‘pugging and treading or compaction damage’ and this was based on the surface erosion degree and severity methods and overall the areas with pugging damage were extensive. It was felt this resulted in significant production loss through reduced soil drainage and soil moisture holding ability. There was also a potential increase in surface wash into waterways. There was very little evidence of any ‘avoid, remedy or mitigate’ measures for this in the Kaikohe study area.
- All the inventory collection occurred in the field and no pre-field work mapping was undertaken. The regional scale LUC/LRI was looked at briefly prior to mapping but generally not used in the mapping process.
- Observation points were marked on the field sheets during the mapping process.
- In drawing the polygons consideration was often given to management practicalities.
- The large areas of indigenous bush and exotic forestry were mapped.

With reference to LUC classification for traditional mapping, LV provided the following comments on methodology:

- This was determined in the office from the LRI factors unless it was quite obvious in the field.
- We used the strict definitions for the LUC class and sub class descriptions before determining the LUC unit. For example, the difference between 3w, 4w and 6w would have been determined by depth to mottling or gleying along with vegetation species present if ‘w’ was the major limitation.
- Several new units were devised where there was not a ‘good fit’ for the existing regional units. Priority was to first use the existing regional units where possible. In total four additional units were used beyond the Northland LUC suite as it was felt that the detail from paddock scale mapping was not being separated out adequately. These included IIIw5, IIIe6, Ve1 and VIe20 units.

Other comments provided by LV regarding mapping methods were that the aerial photographs were considered of inferior quality despite the high resolution (“they were quite flat”). Furthermore, there was very little ‘overhang’ of the aerials for some properties. This meant that it was difficult to assess the ‘bigger picture’ in terms of land forms. DEMs and recent soils information were not made available to LV, despite asking for it. The only soils information that was made available was the very old information, which lacked detail.

6.2 Traditional LUC mapping – results

LV delivered a shapefile of their inventory and LUC mapping, and a PDF file containing an LUC legend for the farm-scale mapping carried out on the seven test properties representing approximately 10% of the Kaikohe study area (see Appendix 1 for LV maps of each property and Appendix 3 for the LV LUC legend).

LV supplied map data as a shapefile, which has 451 mapped units (polygons). LV mapped 34 different LUC units:

- one Class IIe
- nine Class III (three each of IIIe, IIIs and IIIw)
- eight Class IV (five IVe, one IVs and two IVw)
- one Class Ve and one class Vs
- eleven Class VI (eight VIe, one VIs and two VIw)
- three Class VII (one VIIe and two VIIw)[5].

The attribute table supplied with the shapefile (Table 7) illustrates the basic inventory factors and LUC, as specified in the *Land Use Capability Survey Handbook* (Lynn et al. 2009).

Table 7 The farm-scale LUC for seven properties was supplied by LV as a shapefile with the following attribute columns. (Note that only a sample of the first 14 rows of the table is shown, and the block name and mapper are not shown for space reasons.)

LUC	Rock	Soil	Slope	Vege	Area	GenSoil	Erosion
IIIe3	Lo/Sm+Mm	RAI	B	gI	2.783	9	0
IVw1	Al	YU	A	gShR*	0.274	4	0
IIIs3	Lo+Al	KR	A+B	gI	0.373	5	0
IIIs3	Lo+Al	KR	A+B	gI	0.927	5	0
VIe20	Al+Gr	YA+Br	E+D'	gSfO*hR*	0.581	7+Br	1Sb
IIIe3	Lo/Sm+Mm	RAI	B+C	gI	0.630	9	0
IVw1	Al+Co	KR+YUy1	A+B	gShR*	0.238	4+11	0
IIIs3	Lo+Al	RAI	A	gI	4.279	9	0
IIIw1	Al	WF	A+B	gI	0.222	10	0
IIIw1	Al	WF	A	fOgS*	0.056	10	0
IVw1	Al+Co	KR+YUy1	A	gShR*	0.218	4+11	0
IIIs3	Lo+Al	KR	A+B	gIhR*	1.951	5	0
VIe20	Al+Gr	YA+Br	E+C'	gSfOefR*hR*	1.732	7+Br	2Sb
IIIs3	Lo+Al	MR+KR	A+B	gI	4.009	1+5	0
……	……	……	……	……	……	……	……

[5] Note LandVision uses Roman numerals for LUC class, which does not follow recommendations in the 3rd edition handbook (page 48).

6.3 Comparing traditional and digital LUC mapping – results

The process of combining inventory layers through segmentation processing emulates the manual process of drawing polygon boundaries, within which LUC can later be assigned to that polygon entity. The overall result seems to produce broadly comparable maps to the traditional maps prepared by LV.

Generally, the digital polygons tend to have more precise boundaries because of the fine-scale slope mapping derived from the LiDAR DEM. This gives an initial impression of greater mapping precision from the digital method. However, it is interesting to note that for the seven properties mapped using traditional mapping techniques, LV mapped a total of 451 polygons in a little under 1,000 ha, with an average polygon size of 2.09 ha, a maximum polygon size of 25 ha, and some 106 polygons less than 0.2 ha. By contrast the digital mapping workflow produced 530 polygons in roughly the same area (some of the properties extended outside the DEM area slightly), with a mean polygon size of 2.04 ha, a maximum polygon size of 37 ha, and only 68 polygons less than 0.2 ha, almost all of which were edge polygons created when clipping out the farm boundaries from the larger digital data set for the Kaikohe study area. While the boundary definition in the digital LUC maps may have greater resolution, the overall mapping scale and degree of spatial differentiation are effectively similar.

7 Comparing Automated Digital and Traditional Mapping

This section aims to provide some insights into the strengths and weaknesses of the traditional and digital LUC mapping approaches. Comparing results between the two mapping approaches is difficult because they diverge with respect to soil classification method and also have some differences in LUC legend. Statistical differences alone do not tell the whole story. Visual comparison of the traditional and automated digital maps demonstrates both strong visual similarities and some important differences (see Appendix 1).

7.1 Boundary delineation and accuracy of polygon mapping

There are clear differences in boundary delineation between the two mapping approaches. Generally the automated digital mapping based on the LiDAR DEM slope data produces more complex spatial patterns and is more complex and precise than the traditional mapping. This effect is not as noticeable in the number of polygons and polygon size statistics (Table 8), but it is clear in the dimensional perimeter:area ratio of the polygons that the traditional manual mapping produces less complex polygons. A circle has a ratio of 1, and more complex polygons have a lower ratio as a more complex (longer) boundary encompasses the same area. Although the average ratio is not very different, the average perimeter length of the polygons in the traditional mapping is 66% of the digital mapping, and the maximum ratio for a traditional polygon is nearly 400% of the maximum for a digital polygon.

Table 8 Statistics for polygon dimensions. A higher perimeter:area ratio confirms the visual impression that the polygons of the digital LUC maps have greater boundary detail than the polygons of the traditional LUC map

Mapping method	Number of polygons	Mean area (ha)	Perimeter length (m)	Length:area ratio (mean)	Length:area ratio (max)
Traditional	451	2.09	823	0.088	0.90
Digital	530	2.04	1274	0.081	0.24

Visually, exceptions to this seem to be wetland areas, some channel features, and some erosion features, which the traditional mappers have delineated with much greater precision than other features. All these are clearly visible features that a mapper can identify and delineate relatively easily. By contrast, the digital LUC mapping, working with the inventory factors alone (e.g. rock, soil, and particularly slope), may not always recognise a feature that is visible to an observer. Even when it does, the settings for ignoring small areas may mean these features are grouped in with the surrounding terrain.

7.2 Agreement of inventory factors

The level of agreement between unique combinations of inventory factors and LUC classification is discussed using a visual assessment of the seven traditional mapping windows (see section 7.3). In this section we provide statistics from 650 randomly distributed points in the areas mapped by both teams to highlight the degree of similarity between the digital and traditional LUC mapping techniques.

7.2.1 Rock

Differences largely relate to the level of spatial complexity of geology and the presence or absence of tephra. Generally, the maps produced by the traditional and digital LUC techniques agreed more often on the less complex crushed argillite and greywacke hill country and in areas with fine alluvium (40% of random point sample), but elsewhere agreement was poor. Some of these differences are less significant (e.g. mapping Sc+Vo versus Vo on bouldery volcanic deposits), but some areas of Us/Gw according to MWLR were mapped as Lo/Sm+Mm by LV, and LV did not seem to recognise the Af/Vo valley floors that MWLR did. Independent verification of parent material may be required to resolve some of these issues.

7.2.2 Soil

It is difficult to compare soil mapping because of the difference in soil classification and naming conventions used. However, based on MWLR's Fundamental Soil Layers (FSL)[6] and its assignment of Northland soil series to NZSC classes, the result is 41% agreement between soil mapping for the random point sample at the soil order level (i.e. Allophanic − L, Brown − B, Gley − G, Recent − R and Ultic − U). At the soil group level (e.g. Orthic Brown – BO) the level of agreement dropped below 20%.

7.2.3 Slope

It is again difficult to objectively compare different polygons with slope class assignments of the MWLR and LV maps, because the different boundary means the average or modal slope will be different. Taking a random sample of points and comparing slopes from the traditional and digital data sets shows poor agreement for this reason. Some comments from visual assessments are made in Appendix 1, but the accuracy of traditional slope mapping was tested by calculating a ZONAL HISTOGRAM for the LV polygon data set and the LiDAR-based slope map, assigning the dominant slope using the method outlined in section 4.2.1.

Based on this analysis, the traditional mapping agrees with the DEM-based slope classification for 44% of the mapped polygons. But traditional mapping appears to under-estimate dominant slope relative to LiDAR DEM slope in 33.48% of polygons, which is more often than it over-estimates slope (22.39%). While in 78% of the polygons classified slope agrees within ±1 class, under-estimates by 2 or more classes occur in 16% of polygons compared to only 5.5% over-estimates of not more than 2 classes (Table 9).

[6] Fundamental Soil Layers (FSL) (https://lris.scinfo.org.nz/layer/48136-fsl-north-island-all-attributes/)

Table 9 Agreement of slope between LiDAR and traditional mapping, where 0 difference means the dominant slope class agrees; −1 implies traditional mapping under-estimates slope by one class; and +1 implies traditional mapping over-estimates slope by one class

Slope difference	Frequency	Percent
–5	1	0.22
–4	6	1.33
–3	8	1.77
–2	59	13.08
–1	77	17.07
0	199	44.12
+1	76	16.85
+2	25	5.54
Table totals	451	100%

7.2.4 Present erosion

To compare erosion, the MWLR erosion that was mapped as current (i.e. age = 0) was used to compare with LV erosion mapping. Using the same random sample points and comparing erosion recorded by both MWLR and LV has much higher levels of agreement (between 50 and 75%), but this level of agreement may be misleading. There is a 50% agreement of sample points in polygons that have negligible present erosion according to both surveys, but the level of agreement where both mapping teams recorded some erosion was less than 10%. Yet again, much of this disagreement may relate to the degree to which the different polygon boundaries used caused erosion features to be counted as occurring in an adjacent area. Almost 9% of the random sample points fell in polygons where LV mapped slight present erosion (severity = 1) but MWLR identified negligible present erosion. Less than 8% of the random points fell in polygons where LV identified that present erosion was negligible and MWLR mapped slight present erosion.

Another 25% of sample points were deemed to contain pugging by LV, something that MWLR didn't map because it was outside the scope of the project.

7.2.5 Vegetation

As explained in section 4.5.1, the MWLR team used LCDB version 4.1 to map vegetation, so there is an expectation that the match between the two mapping exercises may be poor. Based on the sample of random points, and looking only at dominant vegetation class, there is only a 30% agreement between MWLR and LV mapping. This seems to be skewed somewhat by the LCDB identifying all pasture in the traditionally mapped areas as improved pasture (gI), whereas the LV mappers recorded considerable semi-improved and some unimproved pasture. If the improved and unimproved pastures are combined in the LV mapping, agreement rises to over 75%.

This high level of agreement is also skewed by the large amount of pasture present within the seven properties being compared. As noted in section 7.1, areas of wetland herbaceous vegetation in some valley bottoms are identified more precisely by the LV mapping than in the LCDB. Similarly, shelter trees and small patches of woody vegetation are mapped in more detail by LV, and there are some discrepancies between areas mapped as indigenous forest and mānuka, which may reflect either scale differences in mapping or a common misidentification of taller scrub. It is also notable that significant areas of production forest have been felled, and in some cases replanted, in the Kaikohe study area between the most recent LCDB4 satellite coverage (i.e. 2012/13) and the orthophotos flown for this project in 2016. This time difference leads to some obvious but explicable differences in vegetation between the LV mapping and the LCDB data.

7.2.6 LUC classification

Generally, the agreement of LUC as assessed from the random point sample has similar results to the inventory factors, with an agreement of about 45% at the LUC class level and 74% within ± one class. The LUC class maps appear similar visually in most cases. At LUC subclass (limitation) level (e.g. IIIe to 3e matches), agreement drops to 36%. At the level of the LUC unit (e.g. IIIe3 to 3e3 matches), agreement drops to 17%.

We also assessed areas mapped in each LUC class (Table 10 and Figure 22), which highlight differences in the amount of Class 6 mapped by the two approaches.

Table 10: Comparison of areas (hectares) of each LUC class mapped by traditional and automated digital approaches

LUC class	Traditional	Digital
2	0.00	720.68
3	1,023.29	2,058.65
4	3,394.34	2,990.39
5	65.05	511.34
6	5,651.00	3,712.20
7	675.77	367.59

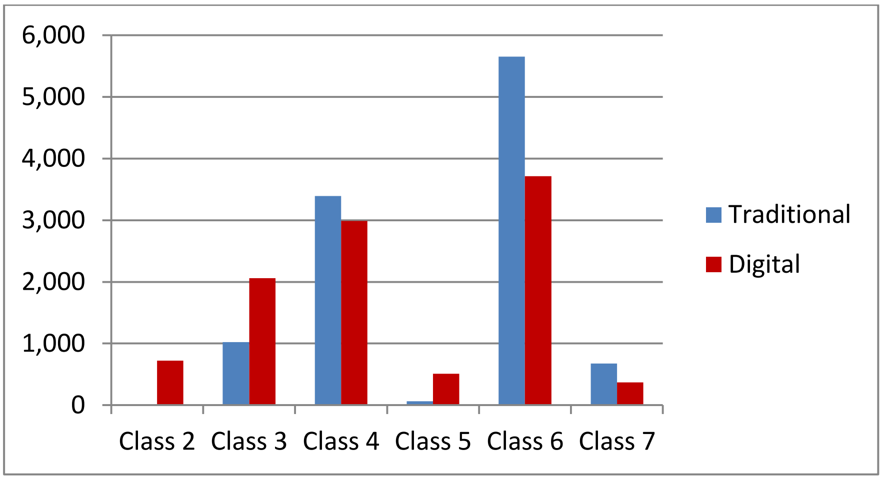

Figure 22 Graphic representation of differences in areas (hectares) of each LUC class mapped by traditional and digital approaches.

7.3 Visual comparison of the traditional and digital mapping in seven test 'properties'

Appendix 1 contains the LUC and inventory maps produced by the traditional and digital LUC mapping techniques, and associated comments for each of the comparison windows. Figure 21 shows the locations of the comparison windows within the Kaikohe study area. Visually discernible similarities and differences are discussed in the tables following each set of maps in Appendix 1. Summary comments are presented here.

Where the LV mapped soils series are related to the NZSC classification, this is by MWLR according to the Fundamental Soil Layers (FSL) data set.

Variation in the interpretation of rock type was largely confined to the identification and recognition of a tephra component, when present, intermittently mantling the non-igneous terrain. The presence of tephra is significant, because it affects soil properties and hence LUC class assignment. In Property 2, patchy loess cover was mapped extensively on massive sandstone and mudstone by LV and assigned LUC Classes 3 and 4. MWLR identified and mapped a tephra component to the soils over much of this window and therefore assigned LUC Classes 2 and 3. Much of this area was mapped as Marua soil (≈ UYM) by Sutherland et al. (1980), which is characterised by neither tephra nor loess.

Characterising and mapping soils by soil series as they appear in the legacy soil maps, as opposed to determining and mapping the soil characteristics in the field and classifying them by the NZSC, has led to a number of differences in LUC mapping between the traditional and digital mapping. This relates to LV's efforts to relate soils observed in the field to the soil series available from the legacy maps, and the subsequent implications for assigning LUC map units to the soil series.

For example, Ultic Soils with poor soil physical properties were mapped by LV as Rangiora (≈ UEM) and therefore identified as LUC unit 3s2. The MWLR mappers sampled the same area and mapped the soils as LOM and assigned LUC unit 2e1c. In fact, no Ultic Soils were mapped in this landscape position by MWLR, but had they been, MWLR would have assigned these units to a LUC Class 4 (e.g. 4s4a).

Using the DEM to determine slope and then using slope as the main determinant of the digitally derived polygon boundaries has led to slopes being distinguished with greater precision. Using the traditional mapping techniques LV has both under and overestimated slope on both gentle and steep terrain.

7.3.1 Property 1

Variability centres largely on the recognition (or not) of the tephra component, and the follow-on effect this has on soil properties, soil classification, and LUC class assignment. MWLR identified and mapped LUC Class 2e1 and 3e1 on Mottled Orthic Allophanic Soils (soils with good physical properties) on the lower slopes of this property, in contrast to LV's use of Ultic Soils and a new LV-defined LUC unit, 3e6. MWLR also identified and mapped Brown Soils extensively on the steeper hill country terrain, whereas LV mapped the presence of Ultic Soils as depicted on the 1:100,000 soil map. Areas of Gley Soils and peat (Organic Soils) are more precisely mapped by LV, both in comparison to MWLR and relative to other LV polygons elsewhere on the property.

7.3.2 Property 2

Variability centres largely on a simple (MWLR) versus very complex (LV) depiction of the geology, and the failure to recognise the tephra component (mistaken as loess?) present. The presence of the tephra component affects soil properties which determine classification, of Allophanic or Brown Soils, and hence LUC class assignment. MWLR mapped LUC Class 2e1c and 3e1b on the Allophanic Soils, whereas LV mapped Ultic Soils and LUC Class 3e3. Steeper slopes devoid of tephra were similarly mapped, by both MWLR and LV, as Ultic Soils and LUC Class 4e.

7.3.3 Property 3

Major differences are present in the interpretation of geology on the rolling hill component. LV depict this as Vo (lavas and welded ignimbrite), whereas MWLR uses Ac+Sm, which follows the 'thin ash over siliceous and non-siliceous claystone' as presented by Evans (1993) in his 1:50 000 geology map. This difference in the rock type classification has led to a difference in the soils that are have been labelled in the map units, and consequently a difference in the LUC units assigned: UYM+LOM_2 for LUC 4e6a+2e1 compared with LOT/NXT for LUC 3e1 by MWLR and LV, respectively. Differences in the lava-filled valley (3s1 to 6s1, 7s1 to 5s1, 7s1 to 5w1, MWLR versus LV, respectively), and slope depiction, especially on the scarp edge and lava valley floor, are also evident.

MWLR had very limited training data intersecting this window. Ideally this site should be visited to validate both teams' rock type, soil, and LUC assessments.

7.3.4 Property 4

There were some differences in interpretation of rock type in the lava-filled valley: Af/Vo to Al+Vo and Vo+Sc; and on the downlands, Ac+Sm to Ac+Vo and Vo (MWLR v LV, respectively). This in turn leads to variation in soil identification (Allophanic to Granular, alluvial Brown to Granular), and subsequently to LUC class and subclass interpretation. MWLR uses 3s1 and 3w1b, whereas LV has used 4w1 and 3w2.

7.3.5 Property 5

Variability centres largely on a simple (MWLR) versus a complex (LV) depiction of the geology and the presence or absence of tephra on the sedimentary component of this window. In general rock type and soils related well, but some of the actual soils mapped by LV are questionable. LV mapped Granular Soils (Waitakere ≈ NOT) compared to MWLR's Allophanic Soils; Mottled Albic Ultic Soils (Rangiora UEM) compared to MWLR's UYM_1, and Mottled Densipan Ultic Soils (Hukerenui ≈ UDM) compared to MWLR's UYM_1. As a result there is some significant variation in LUC class assignment. MWLR consider the use of LUC class 3e3 on Mottled Albic Ultic Soils is questionable.

7.3.6 Property 6

Variability centres largely on a simple (MWLR) versus a complex (LV) depiction of the geology and the presence or absence of tephra on the sedimentary component of this window. MWLR found no evidence of tephra on the western downlands recorded as pMo/Mm+Ac by LV. MWLR found patchy tephra <30 cm thick present on the eastern downlands, but the soils still classified as Ultic (UYM), and not UDP, as no densipans were found. Small areas where the tephra is >30 cm thick on the eastern downlands were mapped as Allophanic Soils (LOM_2) by MWLR. The valley fill edges are difficult to determine. LV were more precise than MWLR, and were more precise in delineating gullies. There were major differences in LUC assessment for the valley-floor terrain, Kara soils (≈ GOT/GOO), which MWLR considered as LUC Class 6w1b because the soils have poor to very poor drainage, 20 cm of topsoil directly overlying an E, or a very strongly gleyed Br horizon, not 3w2, as assessed by LV. The allocation of UDM Soils as Class 3 by LV on the south-western downlands is also questioned.

7.3.7 Property 7

A simple rock type to landscape correlation was presented by both techniques. LV was more precise in distinguishing the valley floor terrain within the hill country than MWLR. MWLR recognised better-drained terrace surfaces, where LV did not, but overlooked the narrow valley floors. MWLR recognised Brown Soils, and a mix of UYM and UDP Soils on hillslopes. LV mapped a similar UYM and UDP complex but did not recognised any Brown Soils on the hills. There are also differences in mapped slope angles and the distribution of LUC Class 4 on steeper slopes, reflecting the variability of slope as determined by both techniques.

7.4 LandVision Limited comments on traditional mapping vs computer mapping[7]

General first impressions were that there was a reasonable fit for some areas of the LRI and LUC. On closer examination, the following observations were noted.

The mapping scale of the computer-generated maps appears to be at a more detailed scale than 1:10,000.

Rock type recordings between the two techniques are very similar on some properties or at least the patterns are. Where there is variation it may be just an interpretation issue. The greatest variations appear generally occurs around what we were calling Lo or pLo/Sm+Mm vs Gw or Ac and it could just be a weathering thing. The same thing applies to Al vs Af. We certainly have mapped more volcanic material and perhaps this should be Vo rather than pMo or Mo. The patterns on Property 1 are very similar except for the lower slopes in the gully system and to the northern part of the property where the computer map has not pulled out the distinctive differences. Maps for Property 7 are also very similar; however, we have extended the alluvium further up into the flat wide gully system compared with the computer map. For Property 3 the volcanics and scoria present on or just beneath the surface have been missed, with the computer map recording it as Af/Vo. Furthermore, the extent of the Vo over the undulating to easy rolling country has been missed. On Property 4 we had the benefit of a long discussion with the farmer who had used his own digger extensively throughout the property and knew exactly which areas had what parent materials.

For the comparison between the soil maps it is difficult to make an assessment without the extended legend from the computer maps. For some properties there is a reasonable fit for pattern, which is encouraging.

Often there is a discrepancy in slope classes between the two mapping techniques and it is generally over all slope classes. There are probably errors from both techniques, and for traditional mapping it is dependent on where the observations are taken. For the computer maps it can be hard to determine which perspective has been used to

[7] These notes are provided verbatim from LandVision's report

determine the slope. For Property 7, for example, there are large areas of forestry that have been recently harvested using a hauler that you would not drive a tractor over it (if in pasture) that have been classified as 7–15 degrees on the computer map. For Property 3 it was difficult to classify the slope of the indigenous bush in the north-eastern corner as there were no decent vantage points. However, I feel the slopes below the Property 3 farm house have been underestimated by the computer map. Other issues of slope from the computer map occur where there is a sudden change in slope class and there appears to be confusion as to which polygon it gets loaded into. An example of this is up one of the gully systems on Property 1 where the actual slope is probably E and the slope above it is C+D whilst below it is B. It has been lumbered in with the B slope.

There was no erosion or vegetation information provided by the computer maps and I am not sure whether this was recorded or not. If it wasn't then it is difficult to determine the LUC unit without all five inventory factors.

In terms of generating LUC units

The computer maps appear to 'over' or 'under' play the LUC class for land with a wetness limitation and generally make it higher or lower LUC class. An example of this is the Property 6 Block where we have allocated LUC class based on degree of limitation based on digging holes. This may reflect the soils attributed to the area for the two different approaches and possibly the lack of consideration of vegetation type present by the computer map. Furthermore, the computer map appears to over extend the 6w1 unit into areas that are clearly hill country.

The 5s1 on the Property 6 block from the computer map is a new LUC unit and can be correlated to the VIs1 mapped by LandVision Limited under the existing suite. A similar situation occurs with LandVision Limited calling the gully systems or waterways a new unit (6e20) due to scale.

The LUC unit differences in the Property 4 block probably reflect the differences in rock types and consequently the soil types between the mapping techniques.

The differences in the LUC units on Property 1 have come about by smaller polygons pulling out flatter slopes to give Class 2e1 land. Certainly, where the computer map has classified the gully system as 6w1 the greatest limitation is the steep banks and not the bottom of the gully for large parts of it. Where wetness is the biggest limitation, the vegetation is raupo and carex plus low fertility grasses and rush, we have classified this as VIIw1 rather than 6w1 with the computer map.

8 Comparison of Costs of Traditional Versus Digital Mapping

8.1 Semi-automated digital mapping

Total budget for this project was $500,000 to map 10,000 ha. A first approximation of the cost of automated digital LUC mapping would therefore be $50 per hectare. However, due to the R&D nature of this project its cost has been significantly higher than would be the case for an operational mapping project. With the methods and processes now developed, and assuming economies of scale in mapping larger areas, the model developed here could be extended to similar physiographic areas of Northland. Also, it is likely that other parts of New Zealand would be less difficult to map because the terrain is significantly more contrasting and soil parent materials more closely resemble the underlying rock types, which are also easier to observe in the field. This is due to higher rates of tectonic uplift and erosion, and less impact from deep chemical weathering than is found in the thermic zones of coastal Taranaki and Waikato, and much of Northland (Hewitt et al. 2010).

LiDAR acquisition was $35,000, and along with raw point cloud processing to DEM/CHM and creation of basic derived covariate layers and slope and slope segmentation analysis cost a total of approximately $50,000, or $5 per hectare. If suitable LiDAR data and DEM were already available, the slope segmentation step would cost approximately $10,000, or $1 per hectare. Current LiDAR coverage of New Zealand is patchy. Only three regions (Wellington, Auckland, and Bay of Plenty) have near total coverage, although Northland is soon to follow.

Rock type and the geomorphological knowledge associated with it (e.g. surface age) is problematic in the absence of operation methods for digital geological mapping equivalent to DSM or high-resolution radiometrics suitable for mapping at this scale. Manual mapping (digitising) at farm-scale using legacy data sets, terrain knowledge from LiDAR, and field observations during the soil survey cost an additional $2,500, or approximately $0.25 per hectare.

The soil survey and DSM work was the major component of the field work, including a preliminary reconnaissance visit, planning of the sampling and data collection campaign, main field visit(s) to acquire soil data, a data quality assurance assessment, and a database creation cost of approximately $250,000, or approximately $25 per hectare. It is worth noting that this exercise involved a fresh start (legacy data was of limited assistance) in a very complex geological and geomorphological setting. In a less complex geomorphological setting where soil patterns were easier to observe and predict, existing legacy data were of higher quality, and/or existing soil auger observation data of suitable quality were available, the cost of a field survey could be reduced. Nonetheless, this will remain a major project cost of good-quality farm-scale soil mapping.

The cost estimate for the DSM analysis is based on database creation for field data, defining map units based on classified soil observations, setting up and running R scripts for the random forest model, evaluating results, and iteratively improving the model. This cost approximately $20,000, or $2 per hectare.

The erosion mapping, as carried out in this test, was predominantly a visual digital assessment using LiDAR terrain data and the orthophotography delivered with the LiDAR. This manual remote-sensing approach was supported by two field trips, a reconnaissance visit before mapping, and a field validation of selected areas to assess the quality of erosion mapping. Overall the cost of erosion mapping was approximately $10,000, or $1 per hectare, but this might vary considerably depending on the nature of the terrain and susceptibility to erosion. Erosion remains one of the most difficult inventory factors to map, but developing an alternative erosion susceptibility classification could significantly reduce this cost and prove of more value than mapping present erosion (see the discussion in Basher et al. 2015)

Vegetation was mapped from LCDB and cost less than $0.10 per hectare. The cost of SCION forestry indices is similar, exclusive of any data and/or data delivery charges. Without further breakdown, SCION indices were $4 per hectare, but in the future we would hope to get improved resolution for this cost.

Combining these costs, the total digital LUC mapping cost is $38.45 per hectare (Table 11).

Table 11 Breakdown of LUC mapping costs for digital LUC mapping

Category	Cost $	Cost per ha
LiDAR	$50,000	$5.00
Soil survey	$250,000	$25.00
Rock type	$2,500	$0.25
Digital soil mapping	$20,000	$2.00
Erosion mapping	$10,000	$1.00
Vegetation mapping	$40,000	$4.00
Create LUC legend	$10,000	$1.00
LUC from inventory	$2,000	$0.20
Totals	$384,500	$38.45

Economies of scale and automated mapping

Hypothetically, the 24 LUC units represented in the 100 km^2 Kaikohe study area represent a physiographic region of over 5,000 km^2 (500,000 ha) of northern New Zealand. It would be extremely optimistic to suggest that the model developed in this study could be confidently applied across this much more extensive area with no additional effort (e.g. additional soil observations, preparation of parent material layer and erosion mapping). However, with all-of-region LiDAR soon to be available, making this assumption can place an upper bound on the potential for economies of scale with digital LUC mapping. At this coarse level of estimation this gives an indicative cost of $1 per hectare; i.e. the $500,000 spent on this project could, with minimal additional cost, assist in mapping 50 times the area. This indicates that mapping costs per hectare for digital LUC mapping of large areas may be able to be achieved at a significantly lower cost per hectare than in this project.

8.2 Traditional mapping

Table 12 Breakdown of time and costings (excl. GST) for traditional LUC mapping supplied by LandVision Limited

	Description	Quantity	Cost	Total
Expenses	Travel	1900 km × $0.95/km	$1,800	
		1 flight return to Wanganui	$750	
	Accommodation	3 nights × 2 people × $130/night	$780	
	Sub-total for expenses			**$3,330**
Work	Field work	2 days × 8 hours × 2 people × $120/hr	$3,840	
	Post field work/report writing	16 hours × $120/hr	$1,920	
	Sub-total for LUC mapping			**$5,760**
Total				**$9,090**

LV reported that their costs associated with the mapping component of 1,084 ha were $5,760. This equates to $5.31 per hectare. However, MWLR note that the evaluation in the previous section does not attempt to separate expenses from field effort. Adding LV's 'Expenses' and 'Work' allows a clearer comparison. Note also that while LV do record travel expenses, they do not appear to record travel time while positioning staff as a cost. The total LV figure of $9,090 equates to $9 per hectare.

8.2.1 Summary of cost analysis

Currently MWLR's digital LUC mapping, as carried out for this project, cost over 400% of the cost of LV's business-as-usual traditional LUC mapping. Costs have been itemised to give an indication of where different the major costs occur. Approximately 66% of the cost of digital LUC mapping is in the data collection of soils field data for DSM, and about 13% in the cost of LiDAR acquisition. The difference in staff charge-out rate is also very significant, with the MWLR charge-out rates approximately three times greater than the LV charge-out rate. Other practitioners have indicated that traditional soil and LUC mapping, in terms of effort per hectare, would result in costs in the $30–$40 per hectare range if MWLR comparable staff charge-out rates were used (e.g. R Hill, LandSystems Ltd., pers. comm.).

9 Discussion and Conclusions

The following section summarises the strengths and weaknesses of both methods.

9.1 Traditional mapping

9.1.1 Strengths

- This is a well-established, tried-and-true method for recording inventory and assessing LUC to an accepted national standard.
- It has simple logistics, and can be undertaken by an individual mapper at farm-scale.
- It involves field work across as much of the mapped area as possible, during which the mapper can check inventory factors like rock type, erosion, and vegetation for accuracy and temporal currency.
- It allows greater access to farmer and landowner knowledge, and farmer greater interaction.
- The manually prepared map is digitised into GIS and checked to ensure it is accurately transferred and logically consistent in terms of inventory and LUC.
- One mapper has an overview of how inventory relates to LUC classification.
- Approach and mapping scale can be adjusted to target specific issues (e.g. mapping pugging and detailed wetlands extent).
- It is cost effective at the individual farm level at $5 per hectare.
- It targets the farm operation, so farm management issues can be addressed easily.

9.1.2 Weaknesses

- It is compiled by a single person, which means mapping is subjective, and different mappers may have variable capability and local expertise (e.g. variable mapping quality of inventory factors).
- Mapping accuracy is difficult to explicitly state.
- It may be limited by legacy data conceptually (e.g. where only older, small-scale soil series maps are available).
- The LUC legend may need revision for farm-scale mapping, and mappers' ability to make a case for new units is variable and not supported by a national overview (correlator).
- Because it is hand drawn on to topographic or photo map base, line positioning is subjective, not repeatable, and not scalable to mapping large areas.
- The mapping process creates single layer of 'polygons' that is inflexible and costly to repeat.
- The mapping of geology, geomorphology, lithology and recompilation of inventory from coarser-scale legacy data is subjective and *ad hoc*.
- It involves reconnaissance-style mapping, where it is not clear how field sampling is recorded or archived. The only data are the map/GIS polygons.
- Single-person manual mapping is difficult to scale up to regional level. This either requires a much bigger operation (many field mappers) or a lot of time. Even at $5 per hectare ≈ $7.5 million for the whole of Northland, using a large mapping team introduces challenges of quality control and much more complex logistics (the single person advantage is lost).

9.2 Digital LUC mapping

9.2.1 Strengths

- It combines the knowledge of multiple domain specialists.
- It is based on field data, explicitly defined modelling, and acknowledgement of uncertainty. This can help target areas that need additional data collection or improved modelling, either in the current project or in planning for a future one, which is important in an increasingly regulatory environment for land users.
- The mapping process involves individual raster (or polygon) inventory layers that can be compiled separately by domain experts who are not usually constrained conceptually by legacy knowledge (i.e. there is more capacity to question, review, and replace or improve inferior-quality legacy knowledge).
- It involves a mix of field data collection and use of best available legacy and/or remotely sensed inventory, some of which delivers the potential for a step-change in mapping precision of some inventory factors (e.g. LiDAR slope data).
- Boundaries are derived automatically using objective methods.
- Polygons are assigned dominant (modal) inventory attributes automatically from underlying raster inventory layers.
- There is greater consistency of mapping quality and the ability to make an objective accuracy statement for inventory layers.
- The mapping processes are well defined and produce consistent results. Segmentation processing and assignment of LUC classification mean mapping is reproducible given a fixed set of mapping parameters (e.g. minimum polygon size in segmentation processing).
- Wherever inventory mapping practice uses site-specific field observations, a subset can be held back from the analysis to provide a statement of mapping accuracy.
- Remapping has much lower marginal costs because individual components of the mapping process can be improved in isolation. Site-based field data can be supplemented with additional data, and/or new covariate layers, and/or new modelling procedures can be introduced individually or together. New inventory layers can be generated, and combined into a revised LUC product reliably and quickly.
- There is potential for significant 'economies of scale' when extending automated digital mapping across large areas of similar parent material, soil, and terrain.
- The process codifies the experience, skills, and knowledge of the domain experts.

9.2.2 Weaknesses

- Using multiple experts requires a coordinated approach and more complex logistics in terms of availability and managing field work campaigns.
- The standardised approach, in terms of classification structure, cannot easily be adjusted/reworked to address specific issues (e.g. pugging or leaching issues).
- It is harder to work across different scales if required (e.g. you can't choose to focus on wetlands and map them at higher resolution than other areas without potentially increasing costs).
- A digital land inventory and LUC mapping require greater levels of expertise in data management and analysis than traditional mapping.
- Digital mapping requires a greater level of technology to implement.
- Digital LUC mapping is costly over small to moderate areas ($35/ha) due to the high costs of field work and the involvement of domain experts.

- Digital LUC maps produce different results from traditional maps because they are modelled. Even if the accuracy has been demonstrated to be higher than a traditional LUC map through comparisons with field auger observations, there is a perception that digital mapping doesn't involve field work and hence the result is likely to be inaccurate.

In summary, the traditional and digital mapping approaches have both produced what appear to be acceptable farm-scale maps. Neither mapping approach has produced clearly superior maps in all respects. The soils mapping of LV, not least because in this case it was constrained within the conceptual framework of the older soil series, is arguably of lesser quality than the NZSC-based DSM soils mapping by MWLR. The key point here is that the LUC mapper must be more of a generalist and is most likely to recompile the existing soil map (using the existing soil series concepts), while the soil experts in the digital approach is a specialist who will collect new data to review and rethink the soil concepts being mapped where necessary.

Even where S-map data exists, the digital approach would need to consider re-scaling the data by collecting new data and carrying out DSM to meet the scale requirements of farm-scale mapping. Similarly, the slope mapping of LV, while based on direct field measurements, involves orders of magnitude less intense sampling than the LiDAR slope assessment, which delivers 40,000 slope estimates per square kilometre. Both mapping teams found the complex geological setting of Northland challenging, but the LV traditional mappers benefited from physically visiting all field areas, while the MWLR digital mappers were forced to rely on available data.

Although LV raised some issues (see section 7.4), much of the discussion regarding the outcome of the digital LUC mapping has focused on the accuracy of the map content, inventory and LUC data, rather than on the quality of the mapping. The method developed for converting the raster inventory layers to a combined vector LUC polygon product works well. The project illustrates how single-factor inventory mapping with an automated workflow to combine inventory into an LUC layer creates the opportunity for rapid update. When this is allied with properly documented and managed field data (e.g. soil auger observations), well managed covariate data layers, and well-documented models, the ability to improve individual inventory layers at much lower cost than original mapping offers a clear advance in the repeatability and cost-efficiency of LUC mapping.

This project has also demonstrated the potential for combining single-factor maps of best available environmental data to map concepts like land vulnerability or land suitability using more rigorous and repeatable methods. This capability may be of interest to well beyond the scope of the current project.

9.3 Meeting project objectives

In section 2.2 a number of objectives were identified. How well did we achieve against these objectives?

9.3.1 Did the project deliver accurate inventory layers at farm-scale?

Answer: Yes.

Both the traditional and digital inventory layers have strengths and weaknesses, and it is unclear whether one method is clearly superior to the other in terms of accuracy. The digital methods are arguably better at slope and soil mapping, the traditional methods at rock type and vegetation. Traditional mapping is a well-established method that is cheap and efficient at mapping individual farms, while digital methods for generating inventory factors such as rock type and erosion severity (or susceptibility) need more research, and the current costs of acquiring suitable soil auger observations to support DSM to the required level of accuracy and precision are high.

The ability demonstrated to more objectively derive inventory layers using automated and repeatable methods that make better use of existing data and can be implemented over substantial areas with explicit statements of accuracy has the potential to advance farm-scale LUC mapping to a new level.

9.3.2 Did the project deliver LUC maps that are fit for purpose?

Answer: Yes.

The digital LUC maps are similarly fit for purpose as the traditional LUC maps. Both maps would be a substantial improvement over the regional data set for farm management. However, it is recognised that business-as-usual farm-scale mapping does normally include farm management analysis that was not attempted as part of this project.

9.3.3 Could digital methods reduce the overall cost per hectare of LUC mapping?

Answer: Yes, though not at the individual farm-scale.

The digital mapping at 400% the cost per hectare of traditional mapping was clearly not lower cost in this study, but the following should be noted.

- Over larger areas the cost differential would diminish. Mapping at farm-scale for much larger areas would introduce logistic difficulties that suggest the method would not scale well. Digital mapping has more potential for mapping larger areas.
- Working in areas with less complex landscapes could well see the differential in mapping decrease, particularly over larger areas.
- Working in areas with better legacy data (e.g. S-map coverage fully or partially completed) and/or covariate data (e.g. whole-o- region LiDAR aLReady available) would be expected to significantly reduce the cost per hectare of digital mapping.
- The MWLR digital mapping team also believe there should be significant scope to reduce costs if the digital approach were operationalised. This was a first attempt at digital LUC mapping, and the experience gained indicates scope for improvement.

9.3.4 Are digital LUC mapping procedures more quantitative / less subjective?

Answer: Yes

While there is more work required in terms of the development of the rock type and erosion inventory layers, the workflow developed through this project represents a major step forward in introducing more objective and quantitative procedures to both inventory and LUC mapping. The LiDAR and slope mapping algorithms are well established, mature, and accurate measures of slope that are completely objective. The DSM approach to mapping soils not only leverages the LiDAR slope data and other DEM-based covariates, but also allows the mapper to focus more strongly on objective data collection through auger observation, with more subjective interpretation confined to soil classification decisions and defining map units. The DSM process of using the auger observation and covariate data to generate the raster soil inventory layer is both a major advance in objectivity and provides a measure of map accuracy through the confusion matrix.

Similarly, the whole automated workflow around combining raster inventory creates a single multifactor vector layer (polygon), and assigning LUC codes according to an explicitly coded rule-set introduces a far more quantitative and more objective process for drawing lines on maps and assigning appropriate LUC codes.

The process is not perfect, but there are many options for further development and refinement of the segmentation process, indicating there is considerable room to improve.

9.3.5 Are digital LUC mapping procedures more repeatable?

Answer: Yes

The increased automation of the workflow for creating both inventory layers and the LUC map enable rapid deployment of the results of additional field work, updates to inventory or covariate layers, and/or refinements in the segmentation process. During the latter phase of the project, for example, an improved soil inventory layer was created by DSM. It took a few hours to reprocess the whole workflow and generate a new LUC map. Although that new LUC map was completely reprocessed, those areas where inventory was unchanged were indistinguishable from the previous version. This ability to exactly reproduce the results of mapping from the same source data is a quantum advance in repeatability of mapping.

9.3.6 Would remapping of LUC be less costly using digital methods?

Answer: Yes

For the reasons stated in 9.3.5, this clearly must be the case. The cost of new soil field work will be a significant issue in some cases. However, the use of DSM methods can re-use existing soil data alongside any new soil data and will be more efficient and allow soils knowledge to be incrementally improved. This re-use of existing data alongside new sampling should also be a factor when scaling up to map adjacent areas.

9.3.7 Was a method established for comparing traditional and digital map products?

Answer: Yes

It is not difficult to assess statistical differences between the two approaches, but the complexity of the mapping processes and the nature of the map content (both inventory factors and LUC units) make objective assessment challenging. Agreement between the maps was generally moderate but variable, with the possible exception of the slope inventory and vegetation, and the nature of, for example, soil makes unequivocal statements of map accuracy a challenge. The fact that the critical soil inventory layer also involved different mapping classifications meant some differences were expected and would be propagated through to LUC.

A subjective visual assessment remains a valuable method for comparing the two mapping techniques. Independent field checking might also have assisted with comparisons, but in order to maintain the independence of the mapping teams would have involved an additional independent expert, plus significant challenges in terms of methodology to avoid yet further questions regarding the objectivity of the field check.

10 References

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Appendix 1 – Traditional Versus Digital LUC Maps

This appendix provides property-by-property maps, summary tables and comments for comparing inventory and LUC mapping using both traditional and digital methods. These support the discussion in Section 7 of this report.

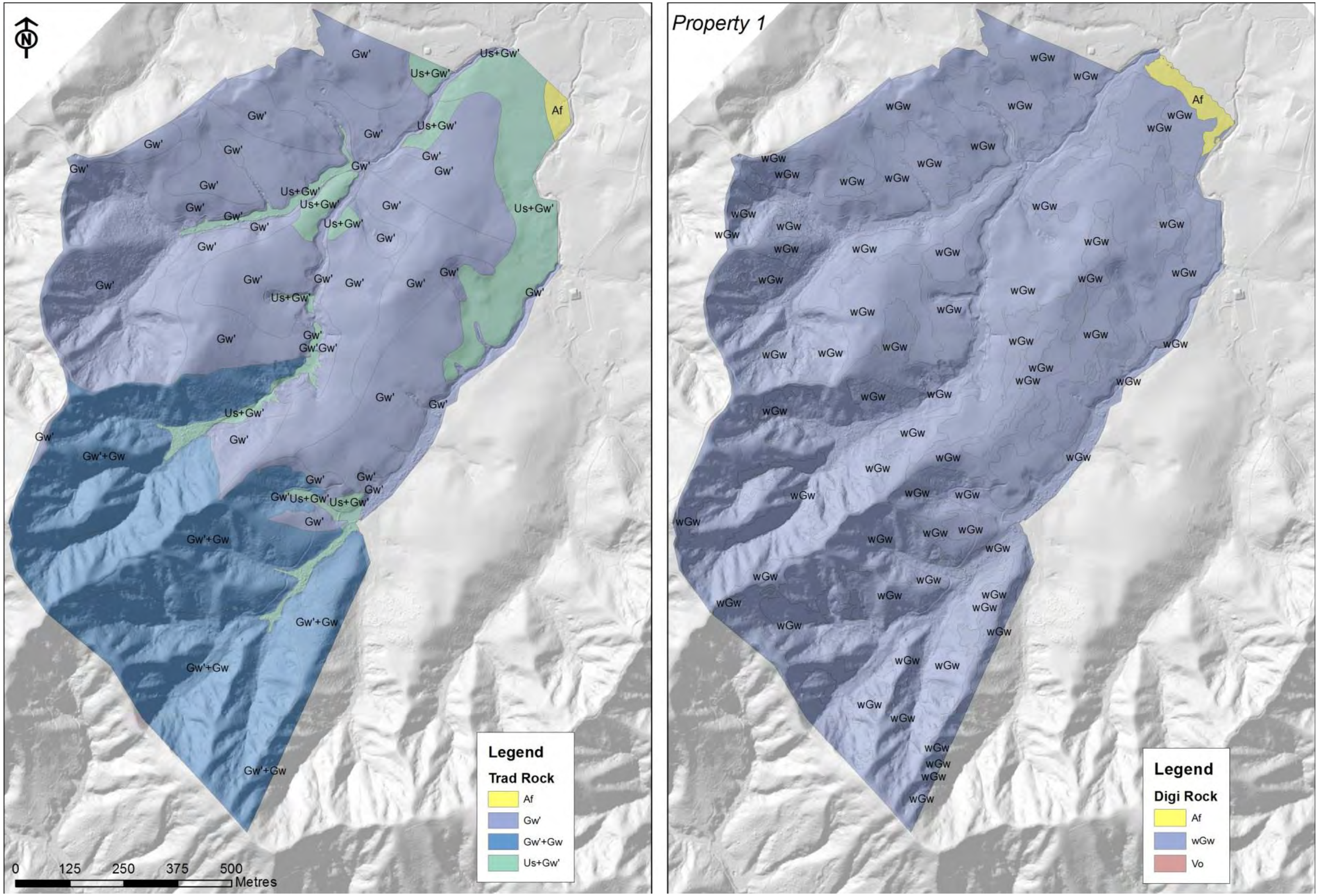

Figure 23 Comparison of traditional parent material and digital parent material mapping for Property 1.

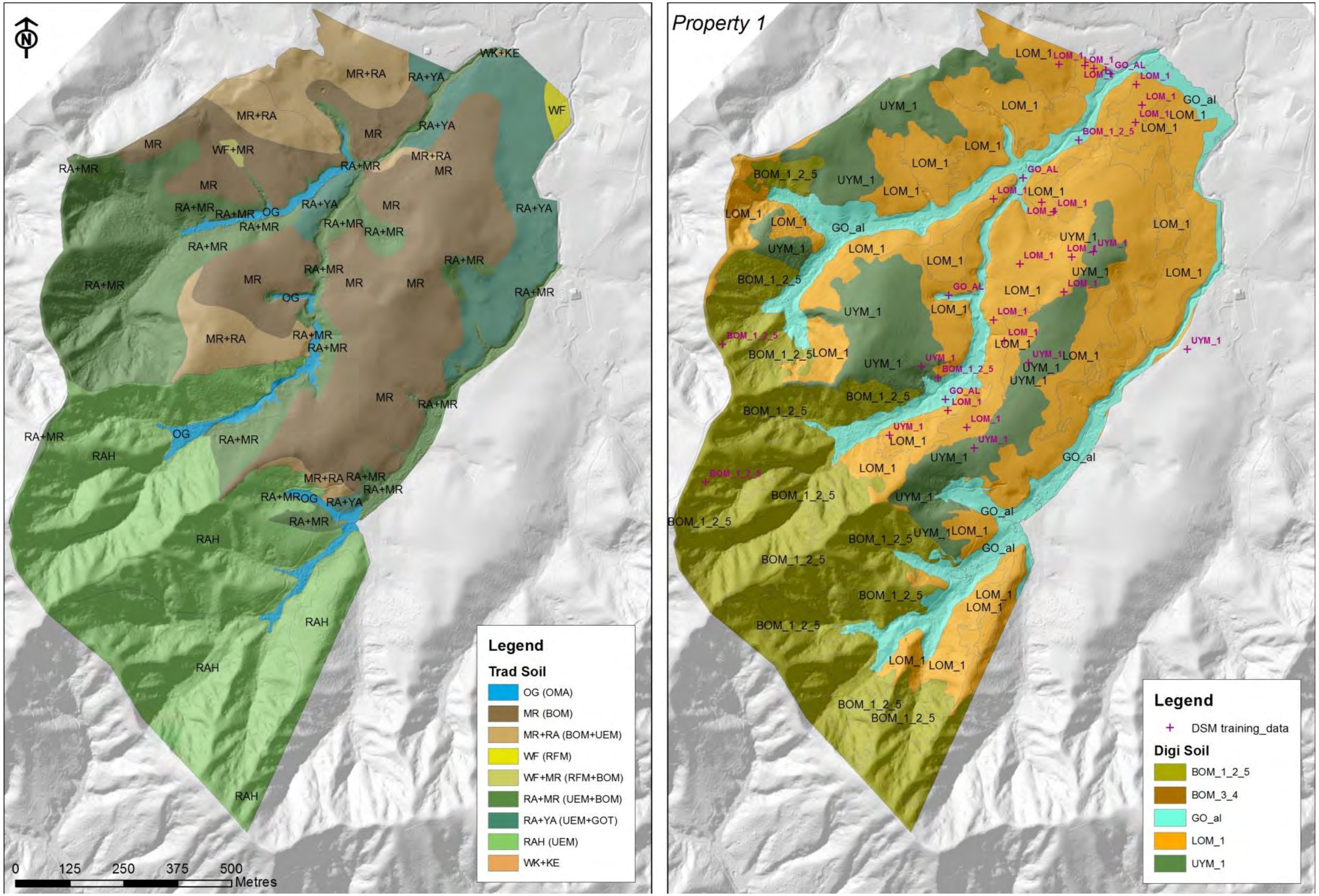

Figure 24 Comparison of traditional soil mapping and digital soil mapping for Property 1; soil observation locations in red.

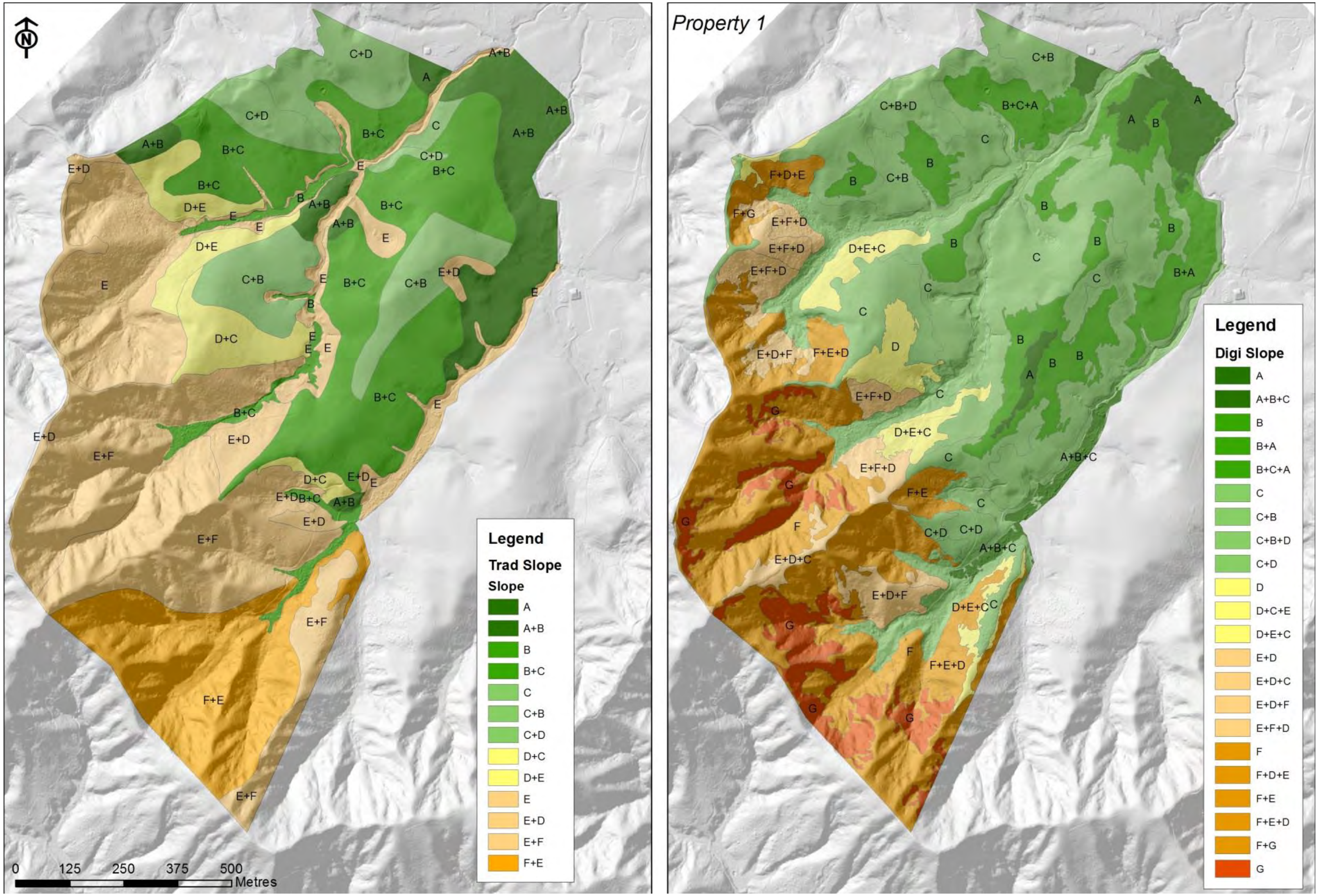

Figure 25 Comparison of traditional limited slope mapping and LiDAR-derived slope mapping for LUC units on Property 1

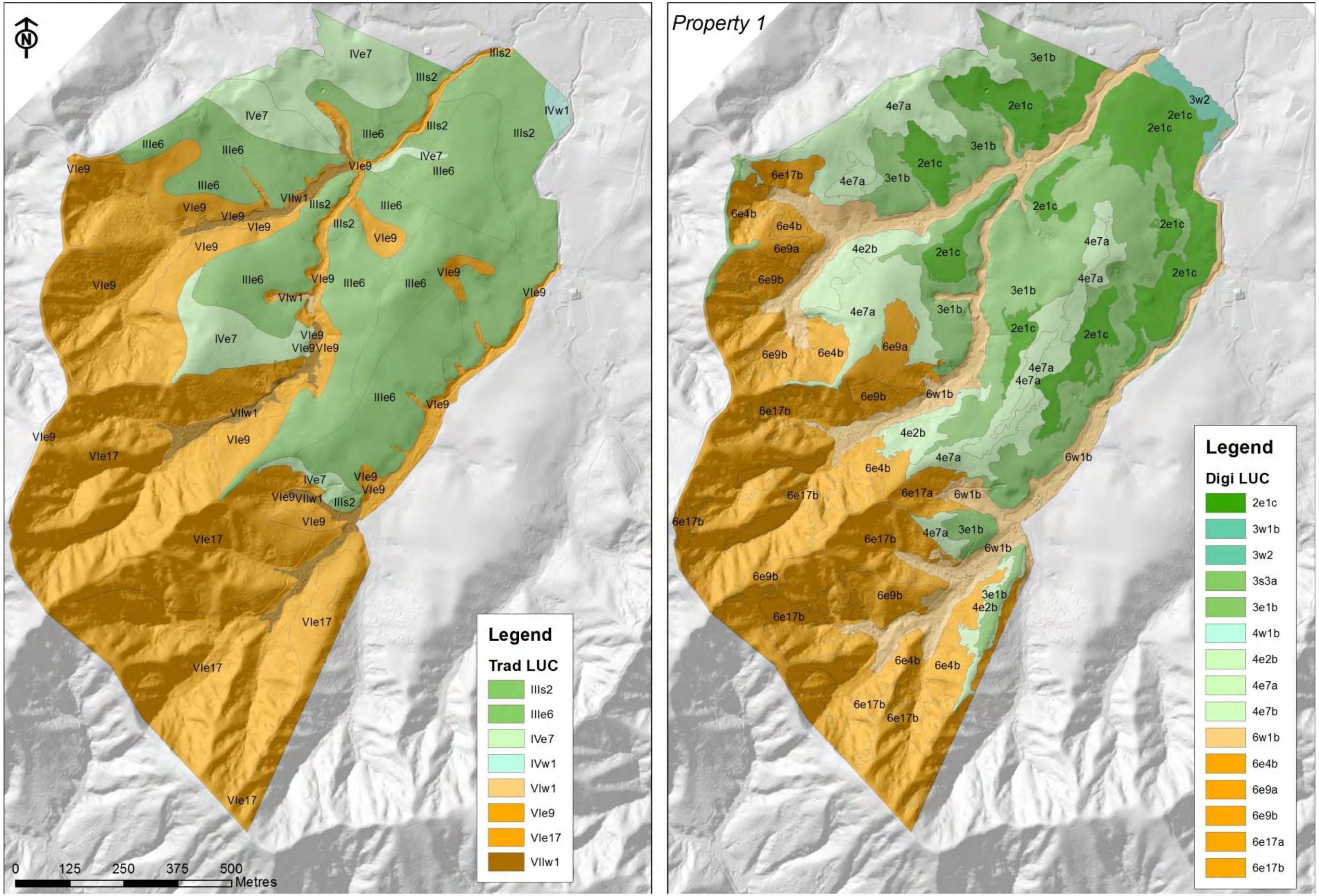

Figure 26 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 1.

Comments: Property 1

	Traditional	Digital
Geology / rock type	Used the weathered symbol Gw′, and Us+Gw	Very similar depiction by both parties; greywacke and alluvium.
Soils	Significant differences: • Mapped Marua series on lower slopes (Ultic Soil UYM), and a new LUC unit 3e6 was defined that does not mention a tephra component. • Mapped Rangiora soils (Ultic Soil UEM). • Areas of Gley Soils and peat are very precisely mapped.	• Identified Allophanic Soils [LOM] on the lower slopes of the property and the presence of tephra. Brown Soils on the steeper component. • Preserving the gully floor Gley soil component has led to it being exaggerated.
Slope	• Underestimated both easy and steeper slopes • B+C • E+F	More detail than conventional method • C+B • F+E
LUC	Mixed: • 3e6, new unit that does not mention a tephra component, which is assigned an Ultic Soil • 4e7, 3e6 new • 6e9 • 3e6, 4e7 • 6e17 • 7w1 • Used a new 3e6 on Ultic Soils, which is questionable.	• 2e1c (LOM Soils) • 4e7a, 3e1b • 6e9 & 6e17, more detail • 4e7, 4e2 • 6e17b, 6e9 • 6w1b – valley floors may be exaggerated • 3e1b (+4e7a) recognise the presence of tephra (LOM Soils) and 2e1c on B+A slopes
Summary comment	Variability centres largely on the recognition (or not) of the tephra component, and the follow-on effect this has on soil properties and classification, and on LUC class assignment.	

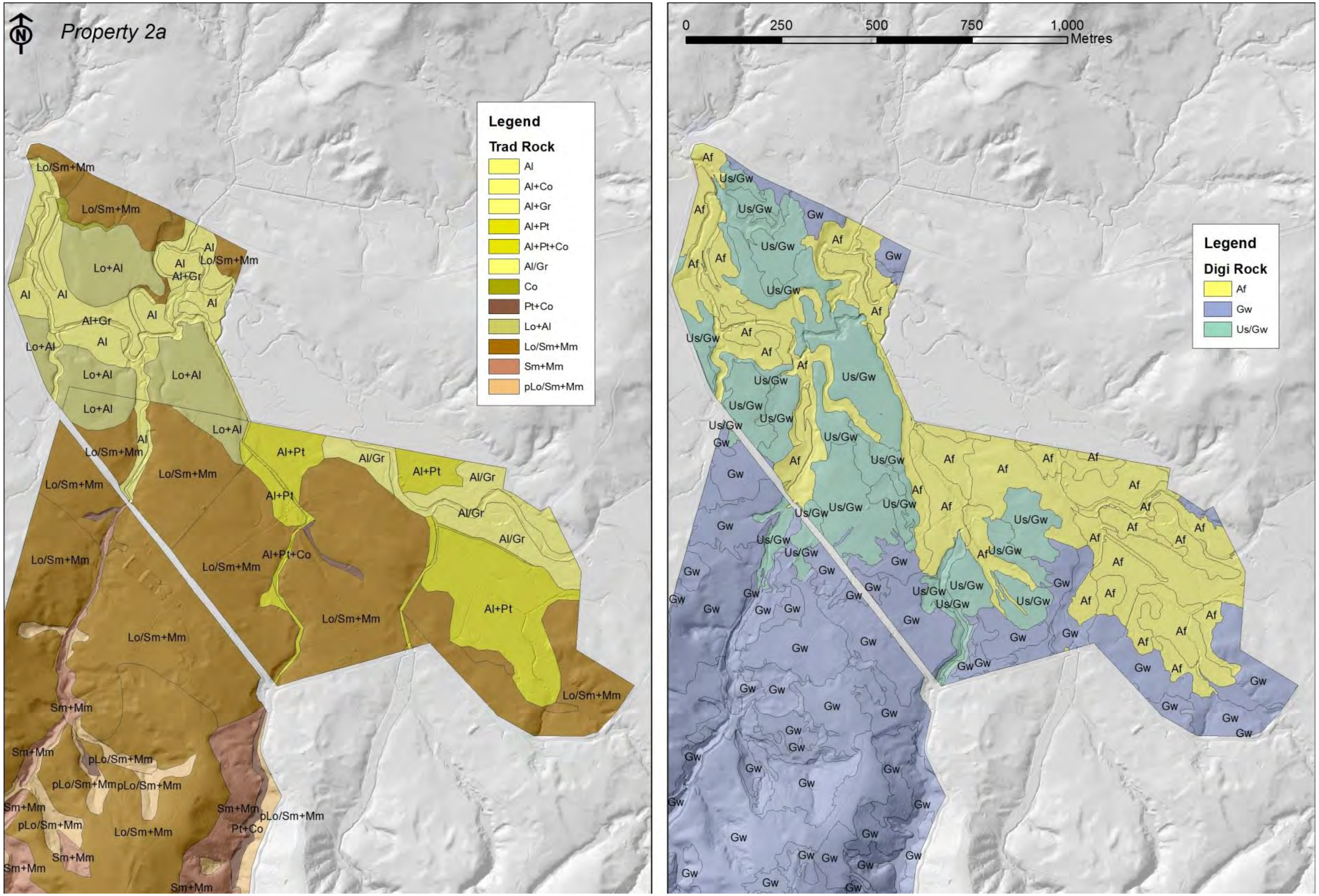

Figure 27 Comparison of traditional parent material and digital parent material mapping for Property 2a.

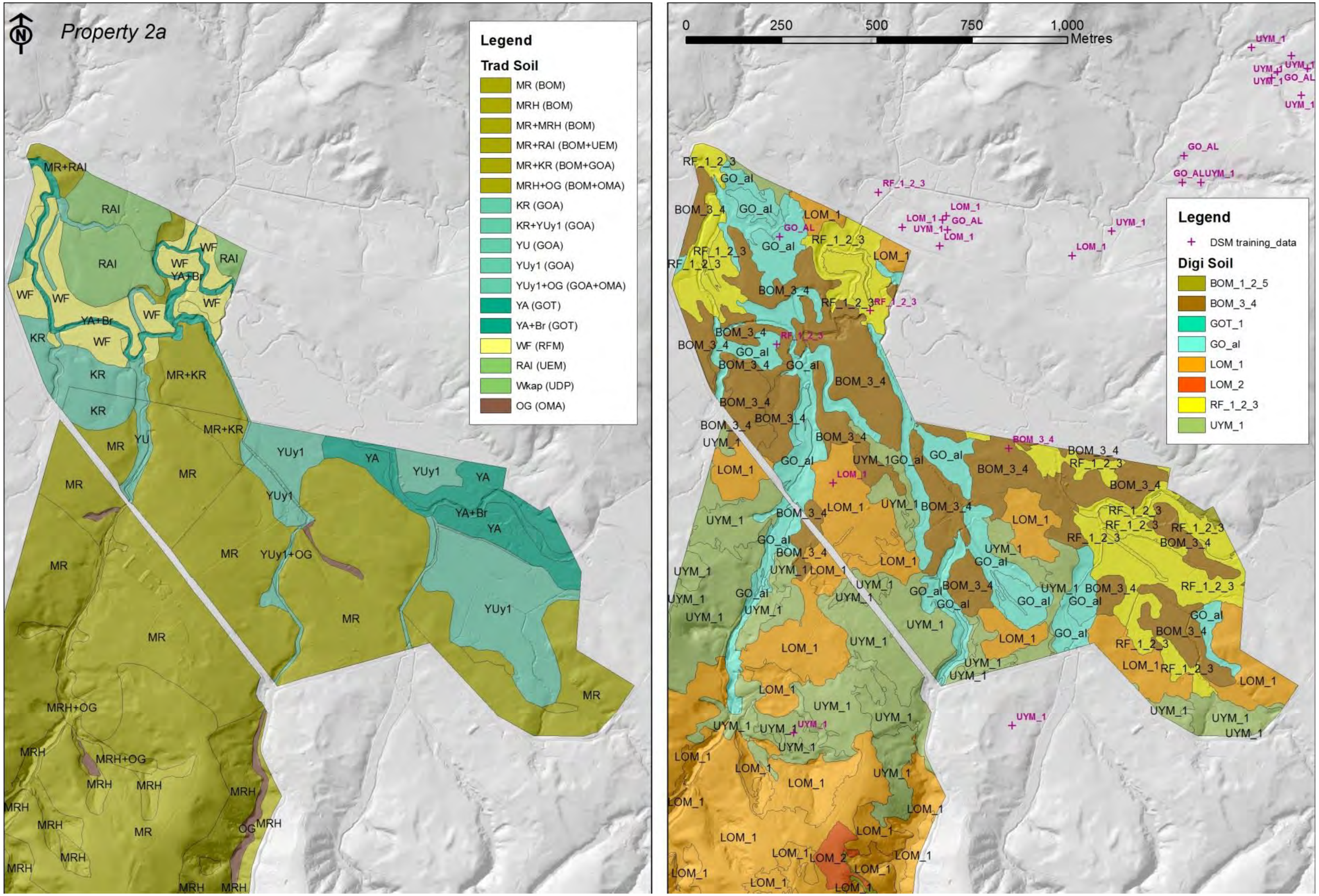

Figure 28 Comparison of traditional soil mapping and digital soil mapping for Property 2a; soil observation locations in red.

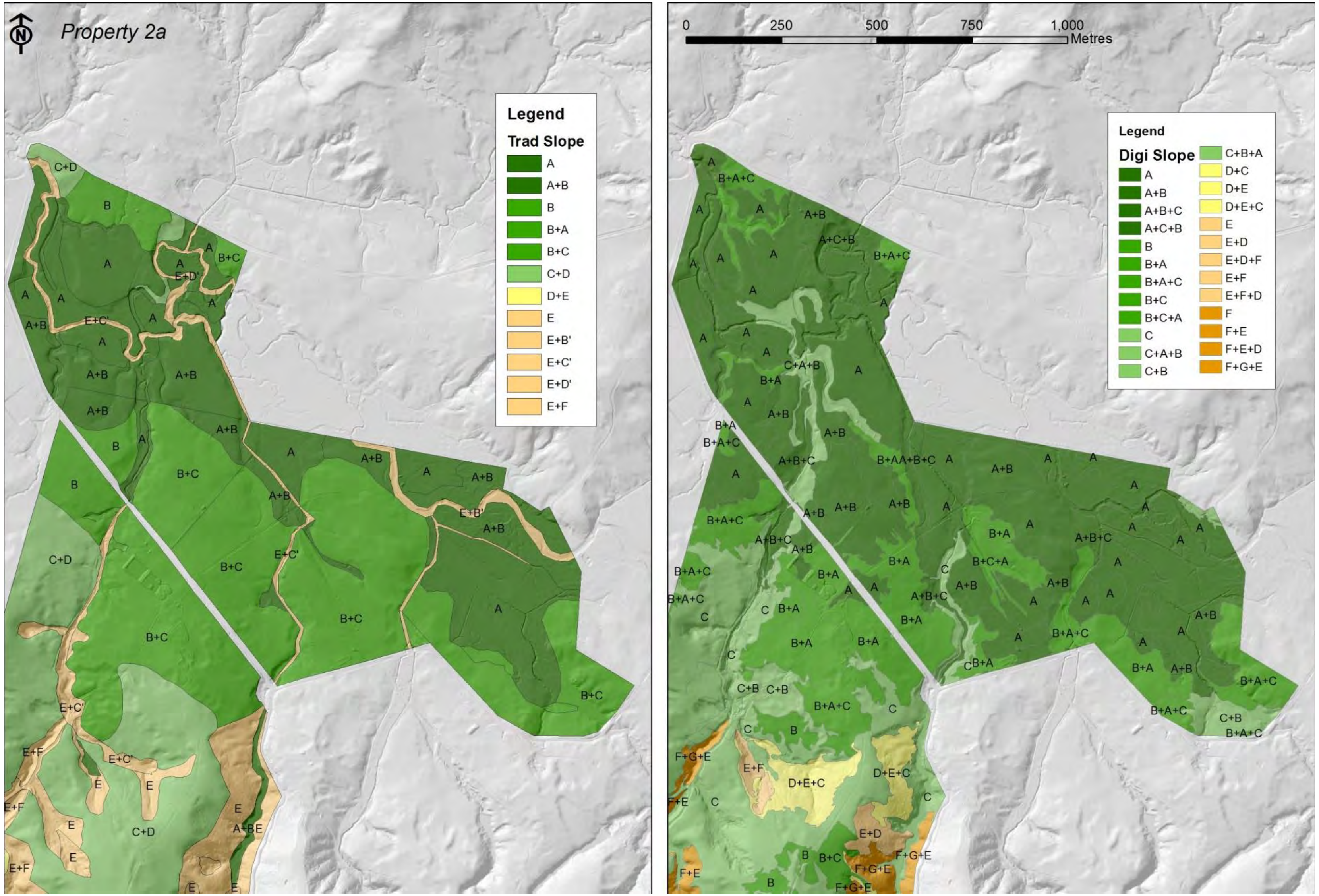

Figure 29 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 2a.

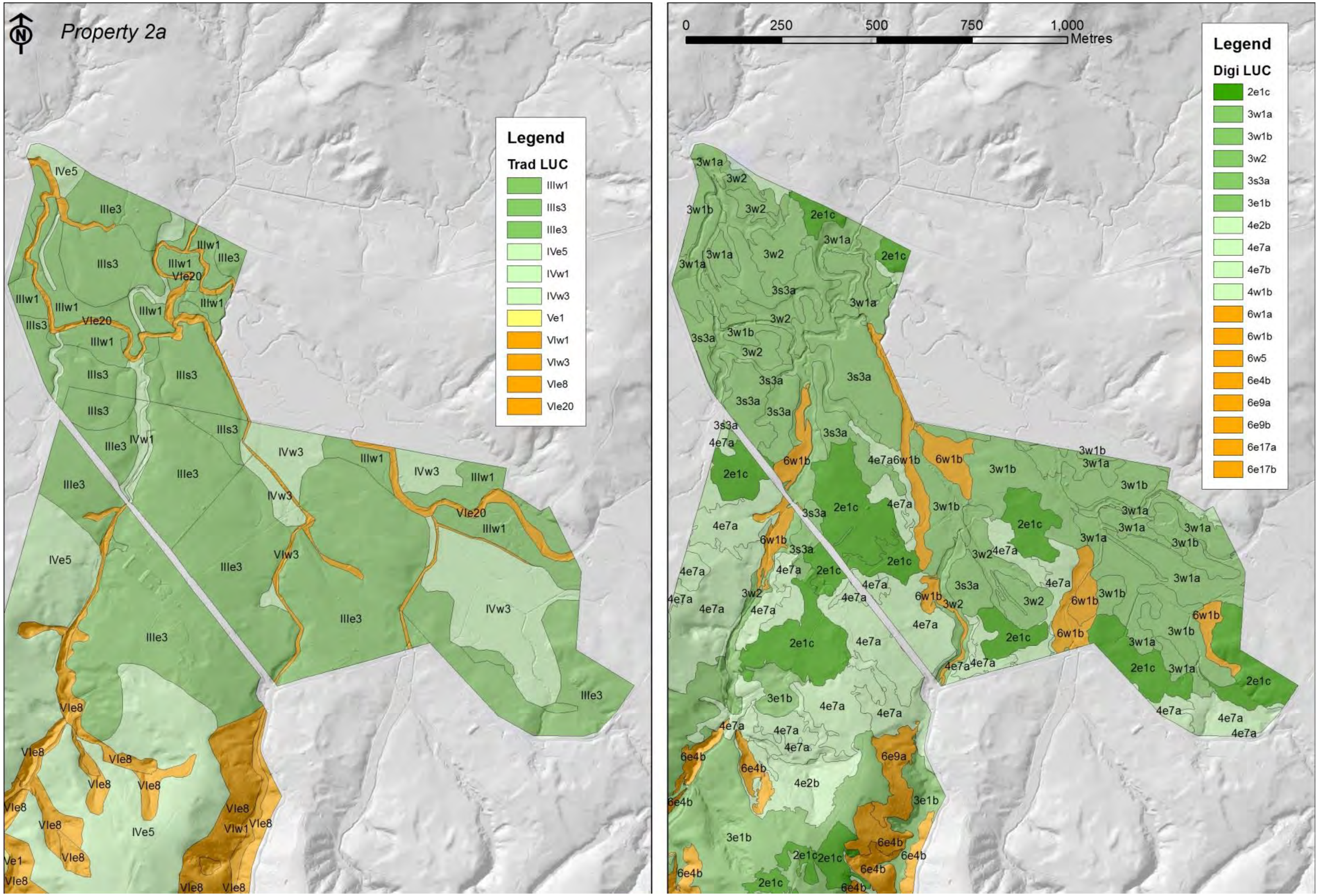

Figure 30 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 2a.

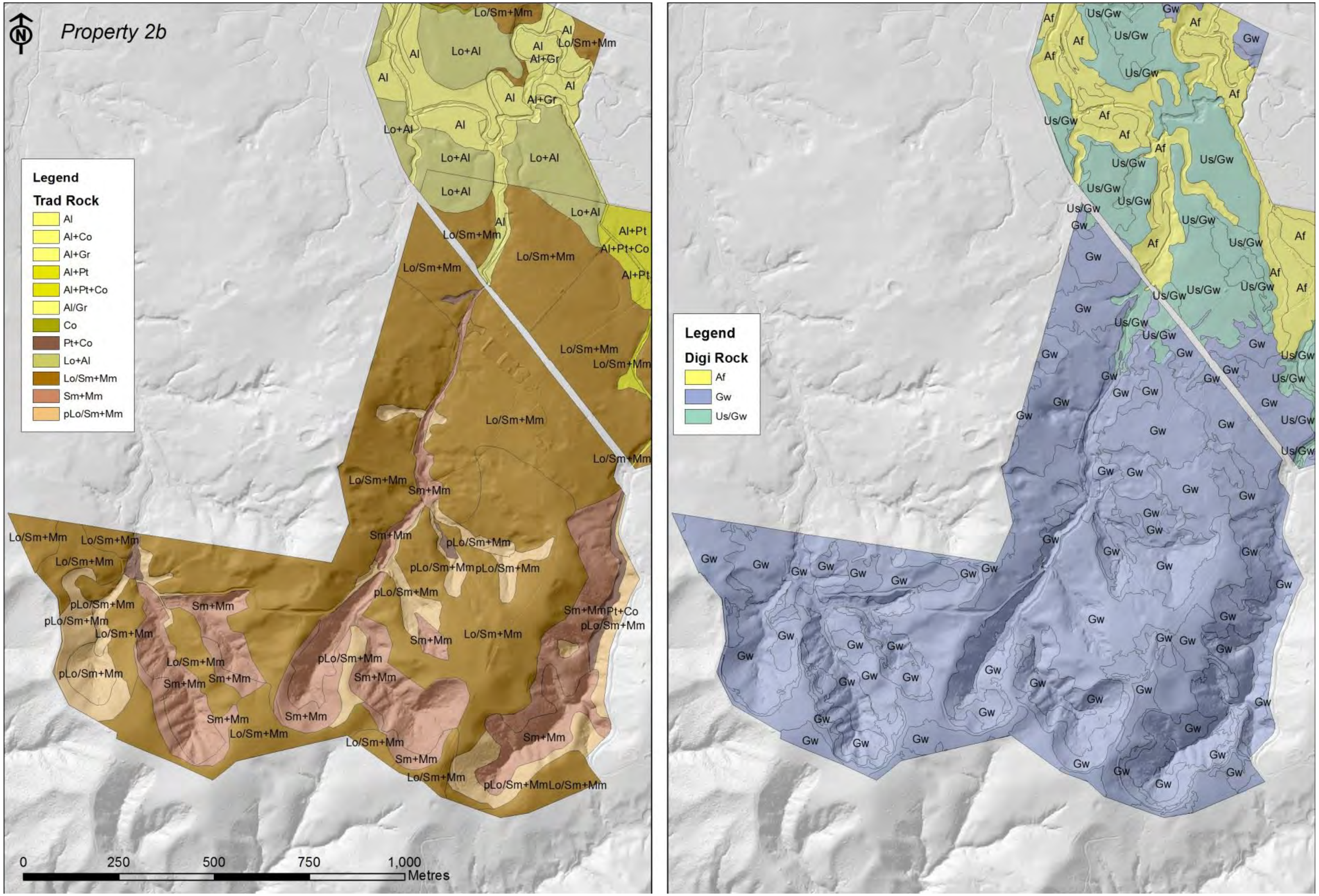

Figure 31 Comparison of traditional parent material and digital parent material mapping for Property 2b.

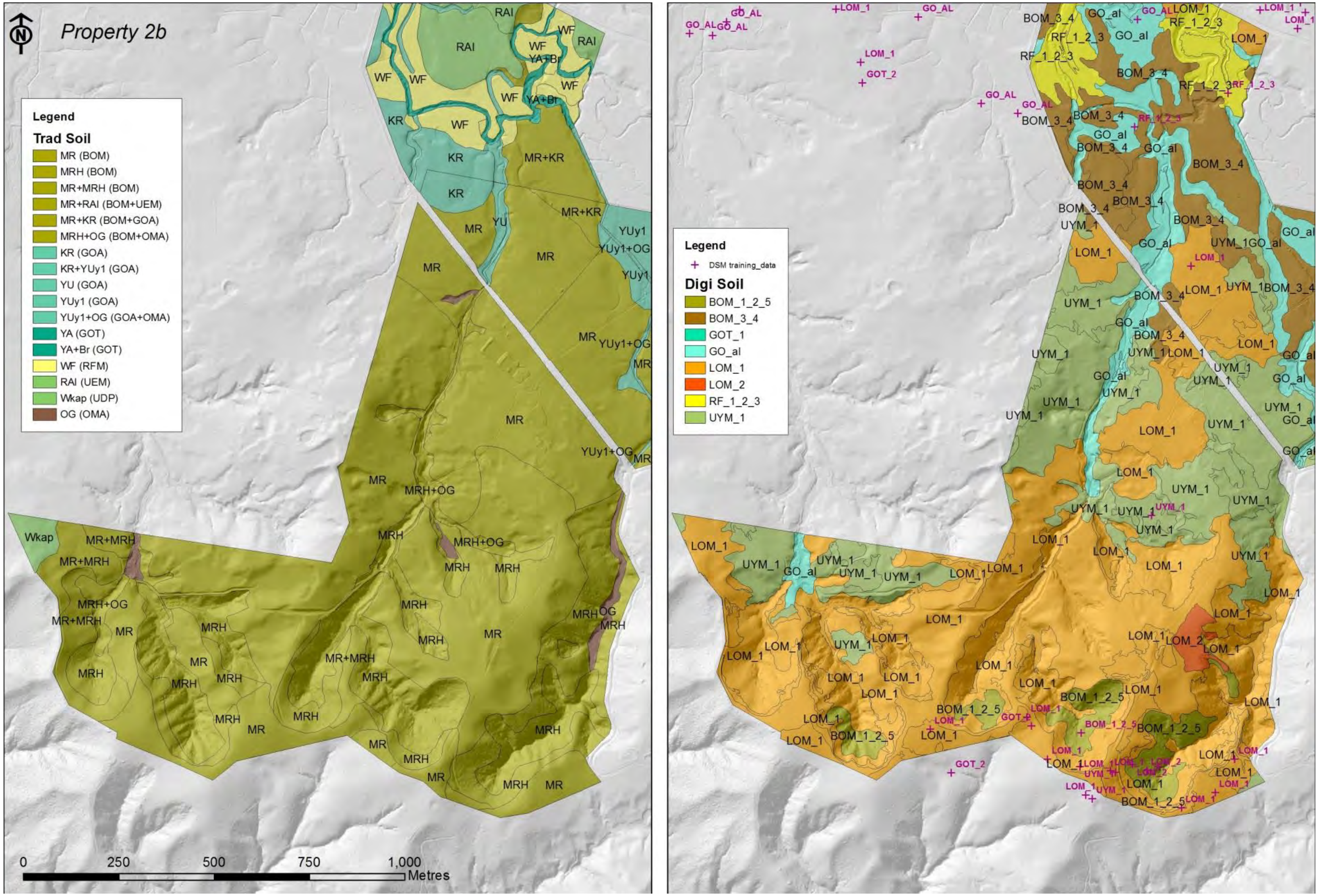

Figure 32 Comparison of traditional soil mapping and digital soil mapping for Property 2b; soil observation locations in red.

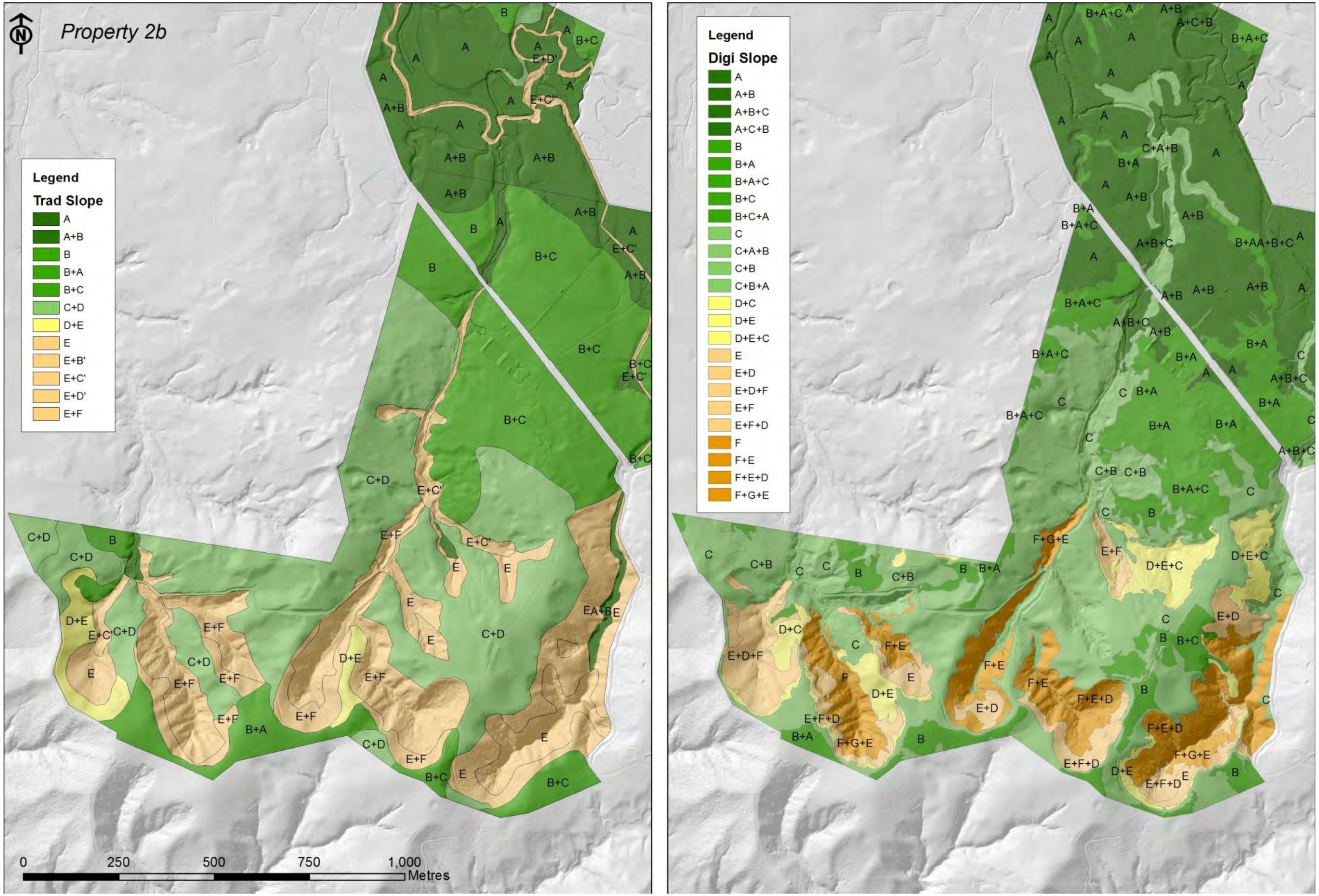

Figure 33 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 2b.

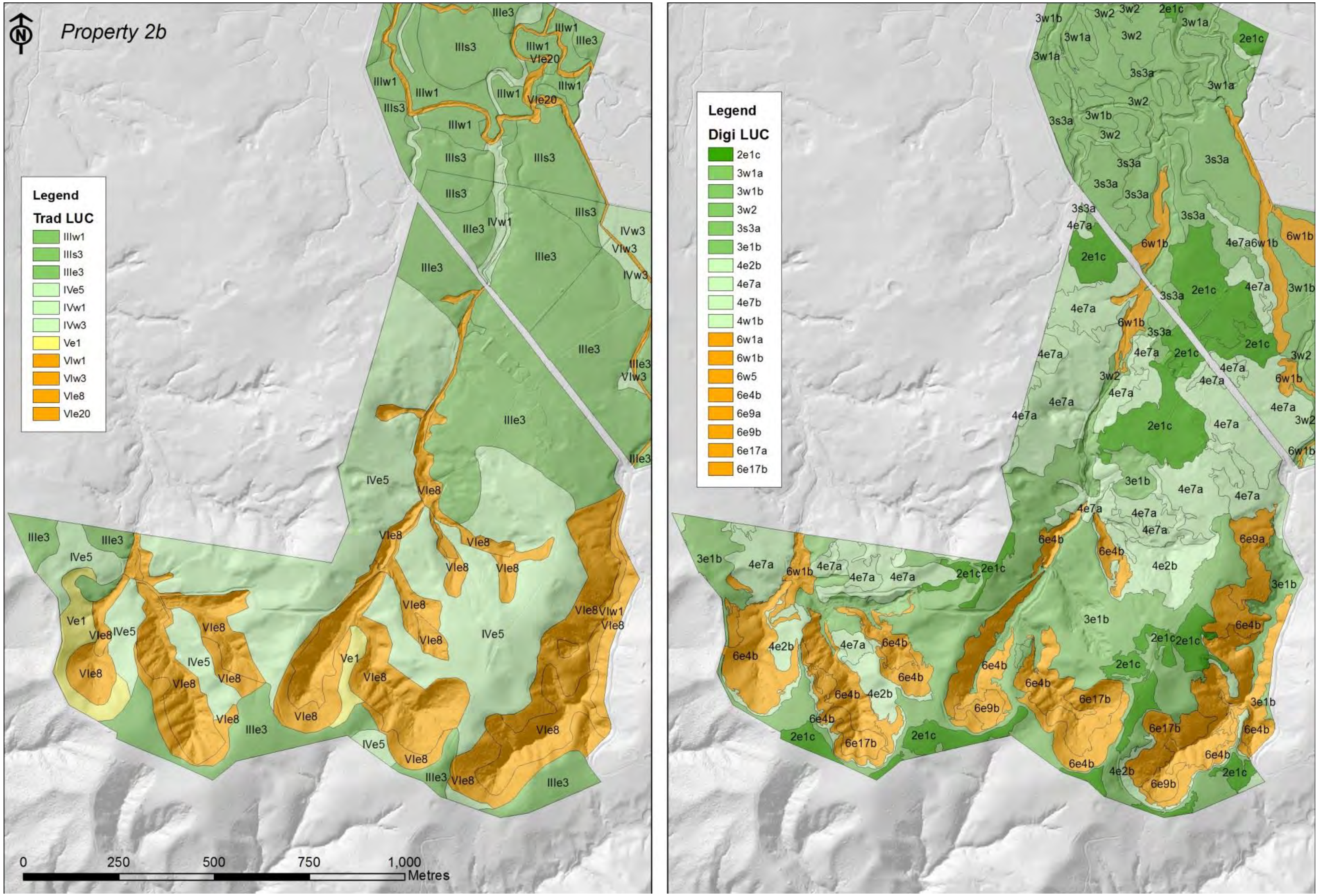

Figure 34 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 2b.

Comments: Property 2

	Traditional	Digital
Geology / rock type	Significant differences Multiple rock types depicted: 6 variations and combinations of alluvium mapped; a significant and patchy loess cover on massive sandstone and mudstone mapped extensively.	Simple depiction – alluvium, unconsolidated sands and gravels over greywacke, and greywacke on valley fill, downlands and hill country respectively. *No loess* mapped. The extensive presence of tephra is indicated by the mapping of Mottled Orthic Allophanic Soils.
Soils	Significant differences • Mapped as a Marua series (Ultic Soil UYM). No mention of a tephra component. NB: the farmer knows these soils as Marua! • Northern high terrace mapped as Rangiora series (UEM). • Southern high terrace mapped as Rangiora series (UEM); DSM survey indicates BOM/LOT with GOT • Gley and Organic Soils (highly variable fluvial system) • High terrace/footslope mapped as Rangiora soils (UEM)	• Recognised a significant tephra component on the hills and footslopes (LOM soils). DSM survey found soils have good physical properties not associated with Ultic Soils. • Northern high terrace mapped as GO-al (have DSM data point) • Southern high terrace-footslope; GO_al +BOM_3_4, GO_al component appears to be enlarged, maybe BOM dominated • North-eastern valley fill, Recent and Brown Soils • High terrace/footslope either side of McIntyre Road, LOM_1
Slope	Mixed: under- and overestimated both easy and steeper slopes	Mixed: more detail-precision in slope mapping
LUC	Mixed; reflects variation in soil interpretation • 3e3 for Ultic soil? • 6e8 • 6e9 • 3e3 • 4e5 • 3s3 • 3e3 • 4w3 • 3e3 (on Marua series UYM – unlikely).	• 2e1c (LOM_1) • Gullies, 6e17b, 6e4b • Rounded spurs & shoulder slopes mapped as 2e1c • 4e7, 3e1b • 3w2, 3s3a • 3w2, 2e1c • 3w1a, 3w1b • 2e1c
Summary comment	Variability centres largely on geology and the failure to recognise the tephra component (mistaken as loess?), and the follow-on effect this has on soil properties and classification (the presence of Allophanic and/or Brown Soils), on LUC class assignment.	

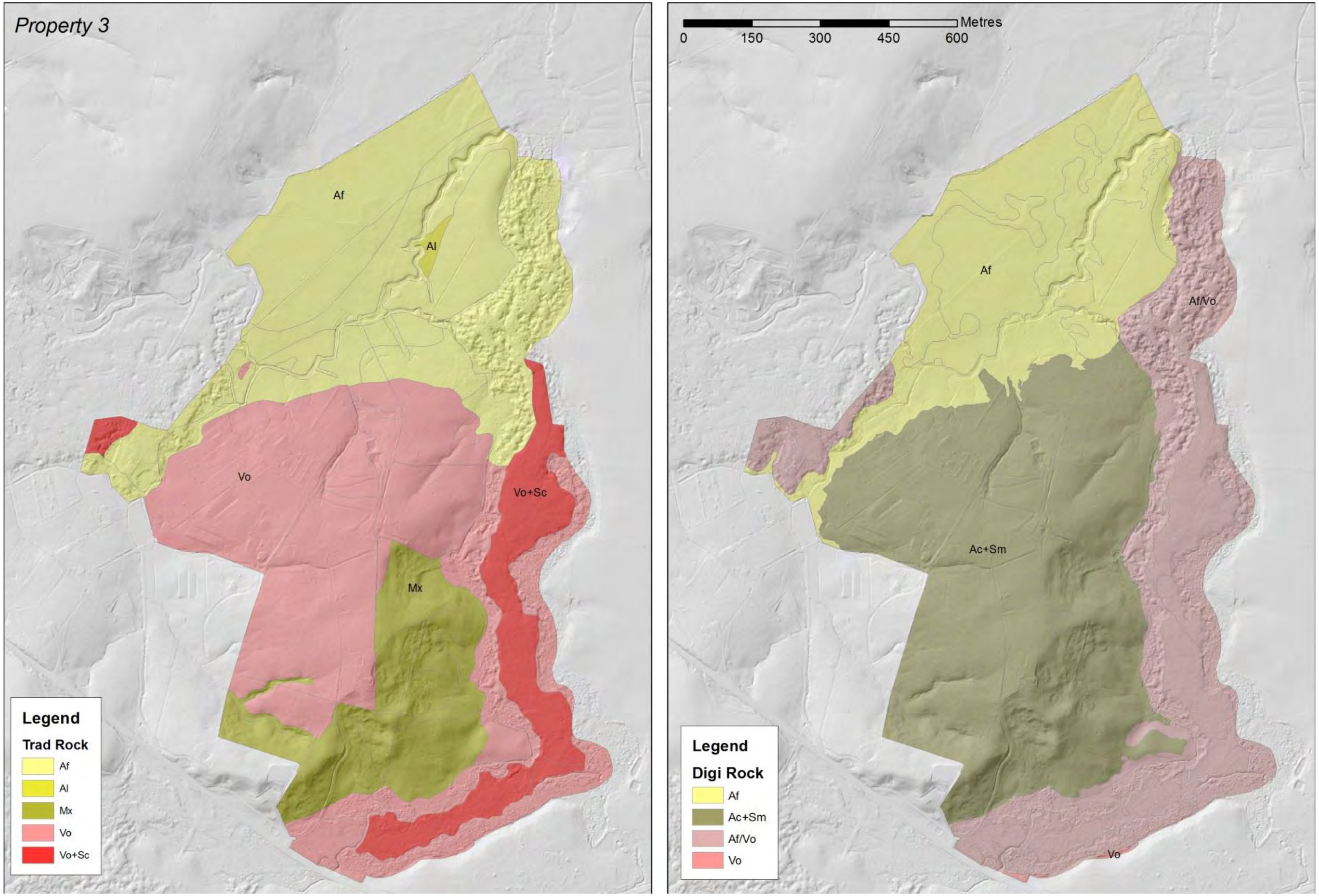

Figure 35 Comparison of traditional parent material and digital parent material mapping for Property 3.

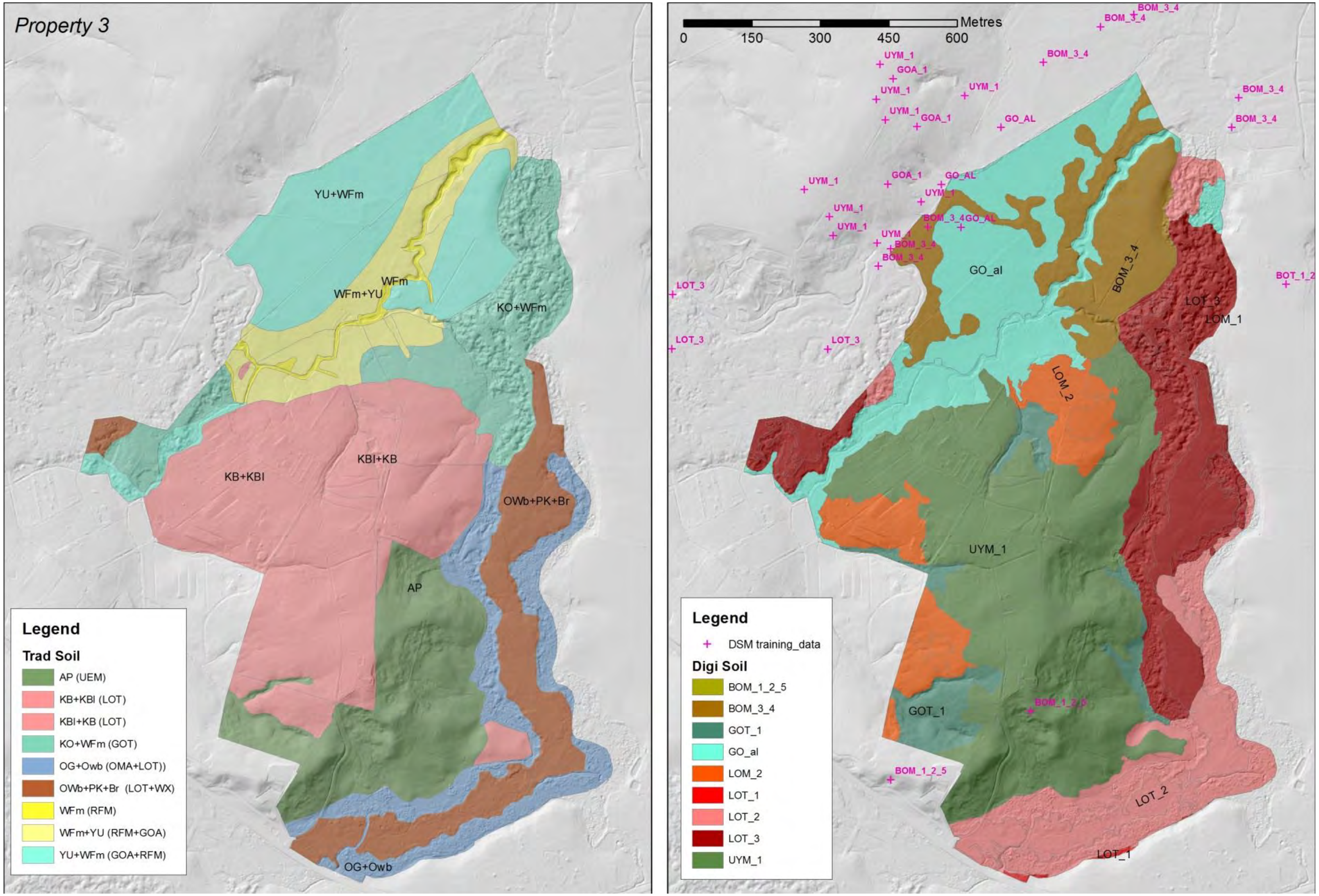

Figure 36 Comparison of traditional soil mapping and digital soil mapping for Property 3; soil observation locations in red.

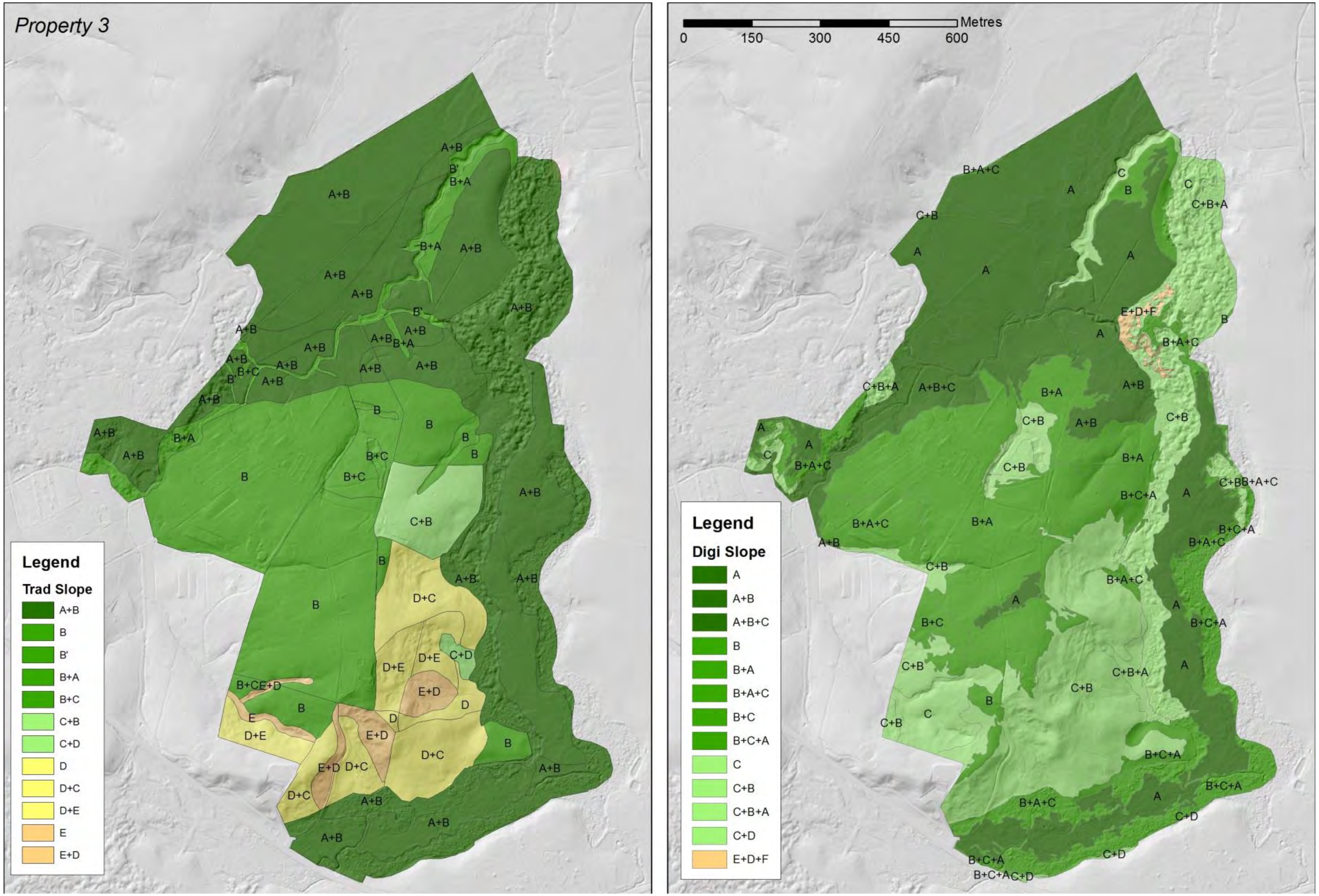

Figure 37 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 3.

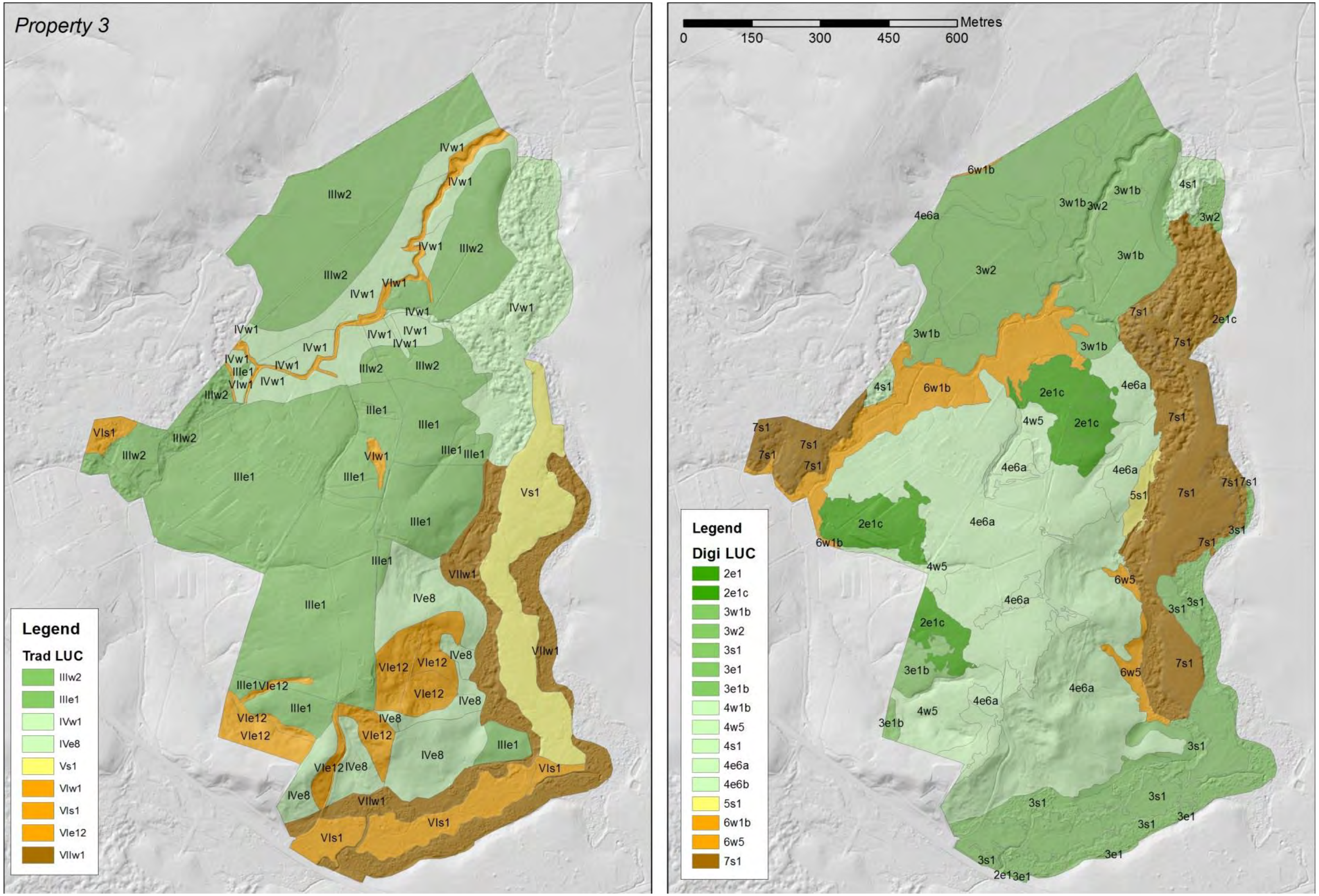

Figure 38 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 3.

Comments: Property 3

Significant differences are apparent. Note: MWLR had very limited training data intersecting this property.

	Traditional	Digital
Geology / rock type	Similar in parts and significant differences in others. Evans (1993) maps area depicted as Vo as 'thin ash over siliceous sandstone'. Mapped valley fills as Vo+Sc and rolling hill as Vo and Mx.	Similar distribution of alluvium (Af); significant differences in the distribution of valley fill lava and alluvium component (Af/Vo) *and* rolling hill component (Ac+Sm).
Soils	Significant differences; • Ohaeawai (LOT, wd) & Otonga (OMA, pd) • Kiripaka series (NXT) • Waipu (GOT/GOO) + Whakapara (RFM)	• Kahutoto Stm – LOM_2 & LOT_3 • Rolling hills – (thin ash/siliceous Sandstone) UYM_1 + LOM_2 • Alluvial valley fill – GO_al + BOM_3_4
Slope	Mixed, • very similar on flatter terrain A+B, B • D+C, E+D steeper elements recorded as much steeper • Valley floor all A+B	• A+B, B+A • Steeper hillscape & scarp edge C+B, C+D • Lava filled valley floor C+D 'rough textured terrain' and A+B smooth section
LUC	Mixed, with some marked differences in places; • 3w2 +4w1 • 3e1 LOT Soils • 4e8, 6e12 • 6s1 (stony/boulder basalts) • 5s1 • 5w1	• Alluvial valley fill (NW) similar 3w2 although stream channel way is exaggerated, 6w1 • Rolling hills – major differences, 3e3 – Ultic Soils • 4e6a similar reflecting differences in slope analysis • Lava valley – 3s1 • 7s1 • 7s1
Summary comment	Major differences in interpretation of geology on the rolling hill component feeds into soil identification UYM+LOM_2 versus LOT/NXT and LUC 4e6a+2e1 versus 3e1. Differences in the lava-filled valley 3s1 v 6s1; 7s1 v 5s1; 7s1 v 5w1, *and* slope depiction, especially on the scarp edge and lava valley floor. Note: digital soil mapping had very limited training data intersecting this property	

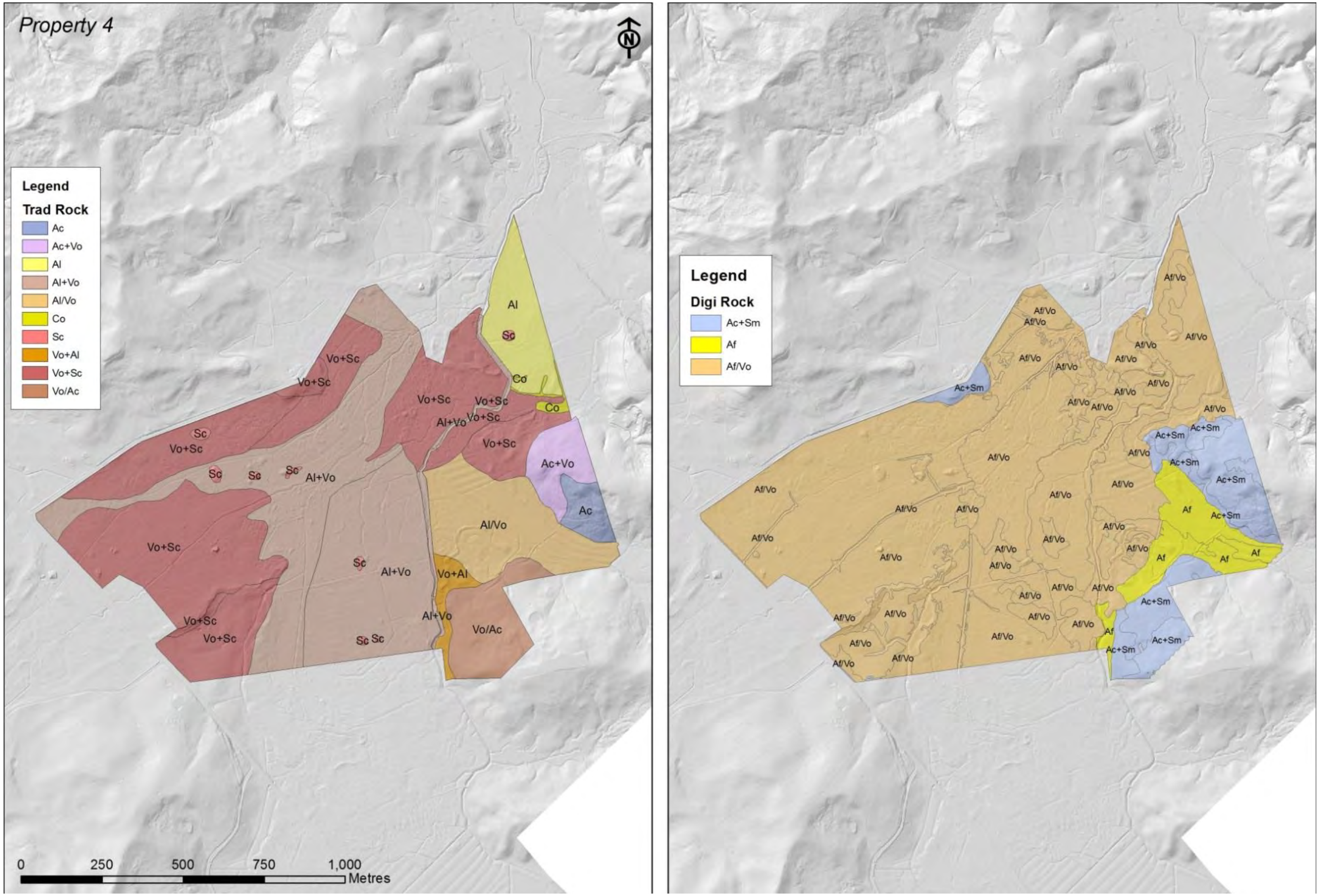

Figure 39 Comparison of traditional parent material and digital parent material mapping for Property 4.

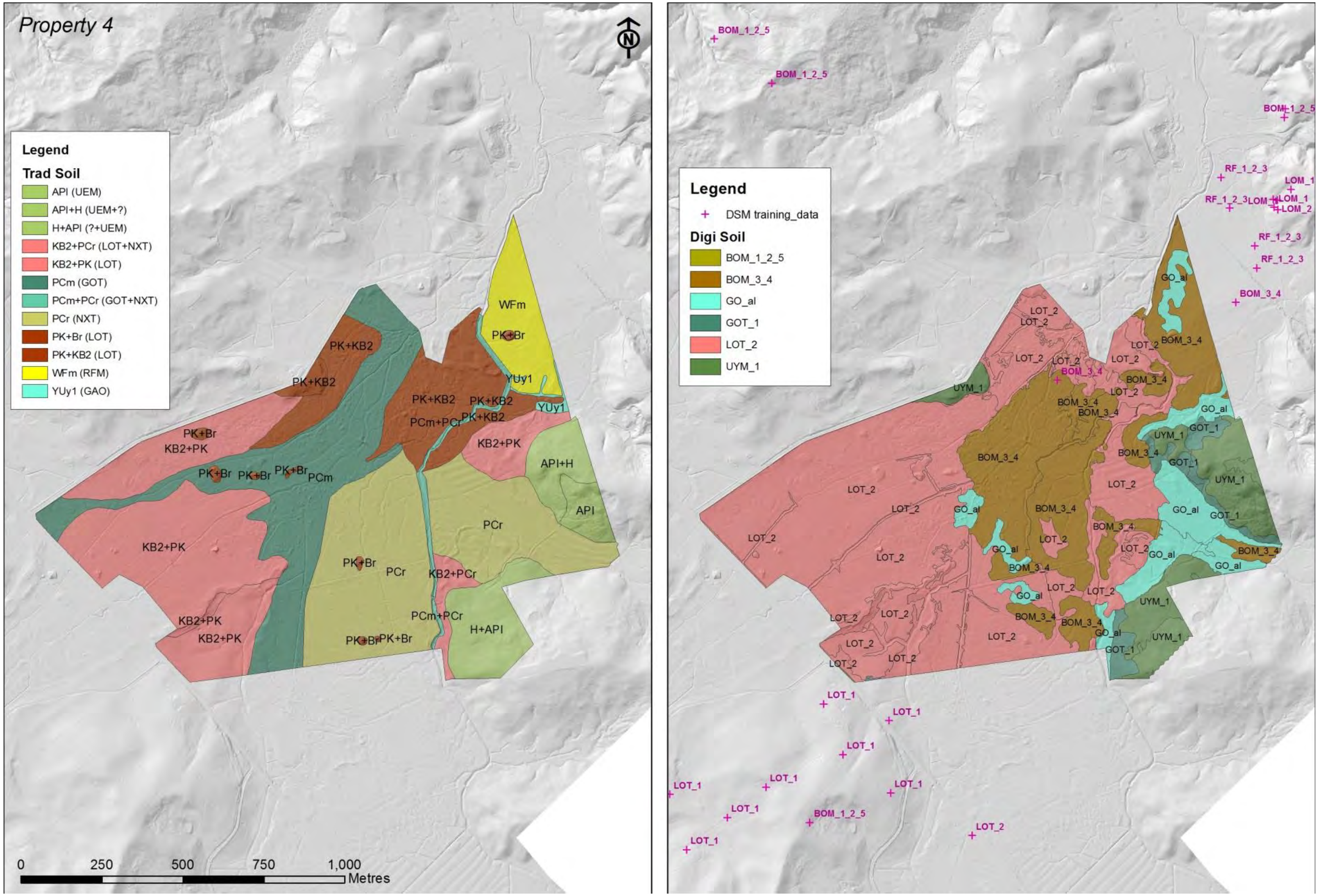

Figure 40 Comparison of traditional soil mapping and digital soil mapping for Property 4; soil observation locations in red.

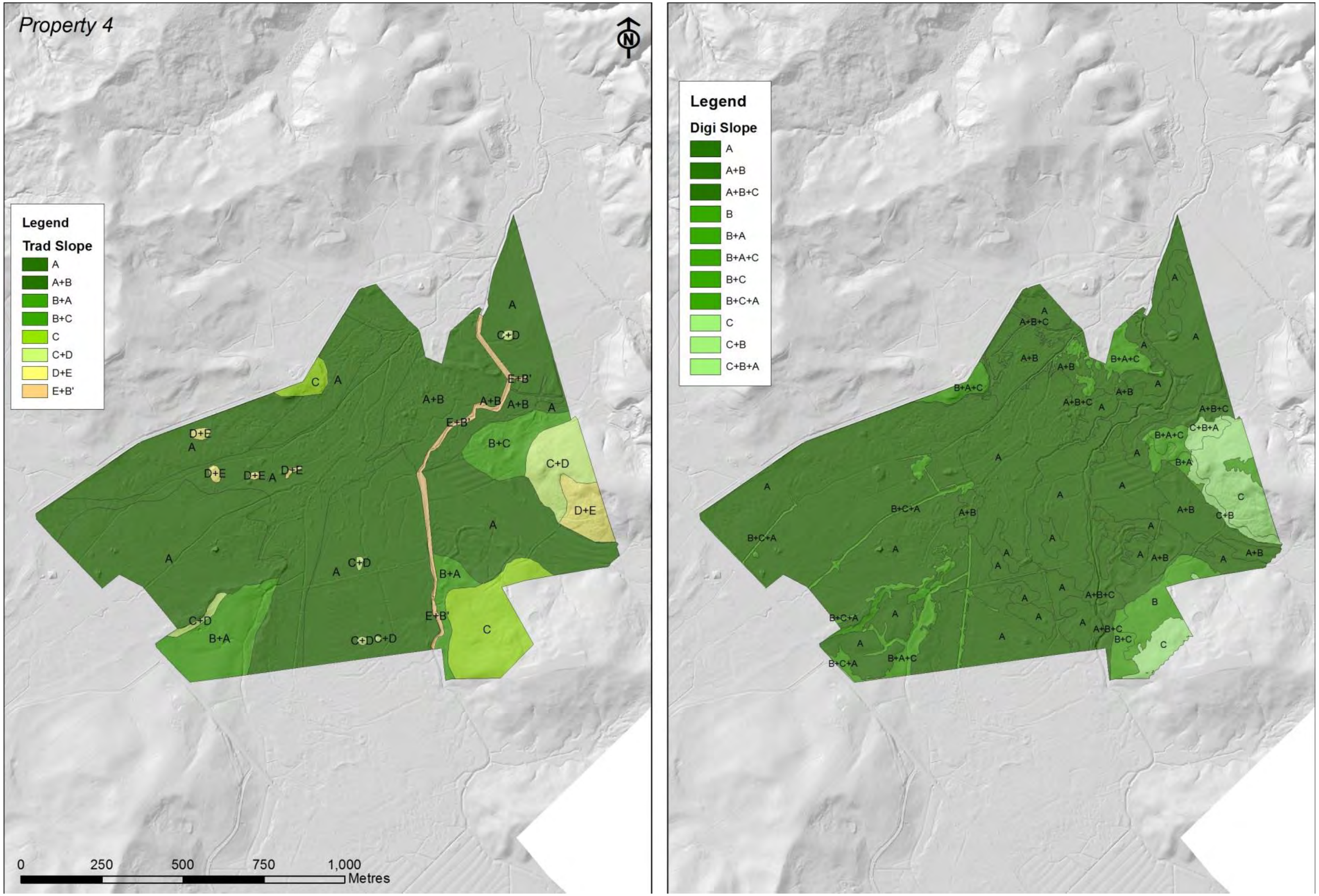

Figure 41 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 4.

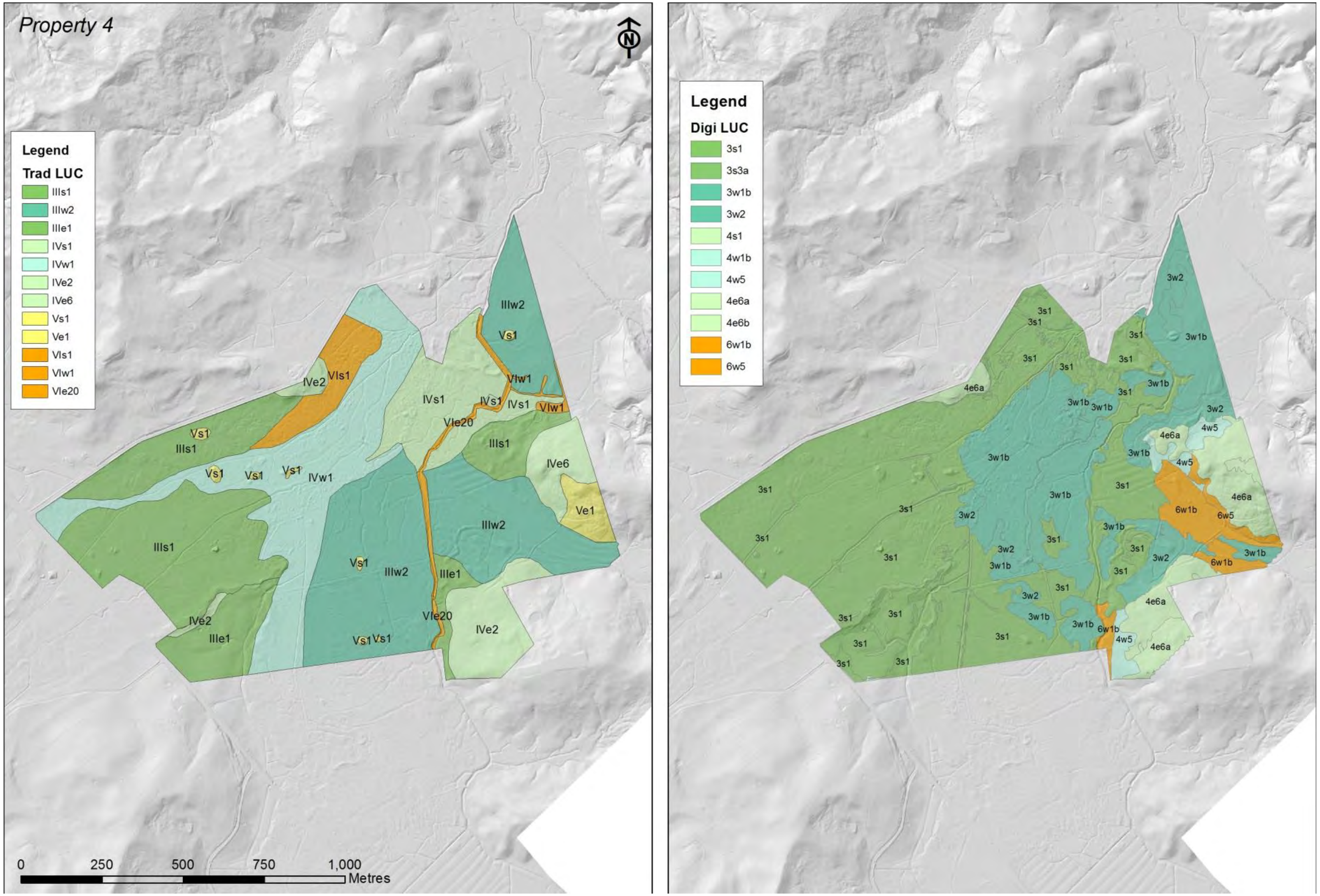

Figure 42 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 4.

Comments: Property 4.

	Traditional	Digital
Geology / rock type	Similar presentation: • Al+Vo • Vo+Sc • Mix of Ac+Vo, Ac	• Al/Vo • Af/Vo • Ac+Sm
Soils	Similar but some significant differences: • UDM+UYM (question the presence of densipan soils) • Granular Soils (NXT) • Pakotai series (Granular Soils NXT) • Whakapara series (Mottled Recent Soils RFM)	• Eastern downlands UYM • Western valley floor – Allophanic Soils [LOT_2] • Central valley floor Alluvial Brown Soils [BOM_3_4] • NE valley floor Alluvial Brown + GO al
Slope	Mixed: • C • C+D, D+E • A	• C+B • C+B • A+B
LUC	Similar interpretation: • Al+Vo • Vo+Sc • Mix of Ac+Vo, Ac	• Downlands 4e6a • Valley floor 3s1 • 3w1b
Summary comment	Some differences in interpretation of rock type in the lava-filled valley, Af/Vo versus Al+Vo, Vo+Sc; and on the downlands Ac+Sm versus Ac+Vo, Vo. Soils Allophanic versus Granular, alluvial Brown versus Granular, and LUC interpretation MWLR uses 3s1, 3w1b versus LV 4w1, 3w2 and 4w1.	

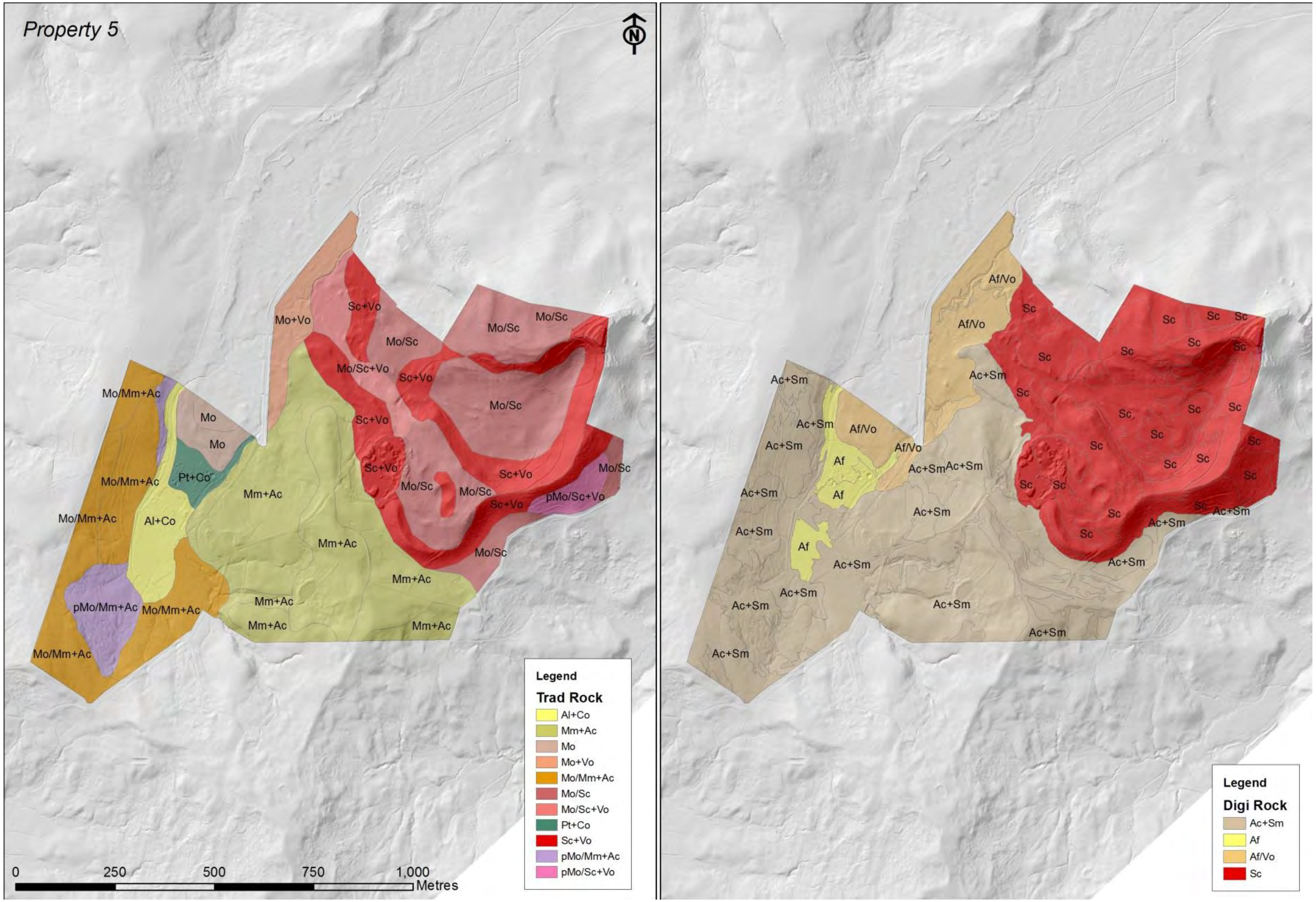

Figure 43 Comparison of traditional parent material and digital parent material mapping for the Property 5.

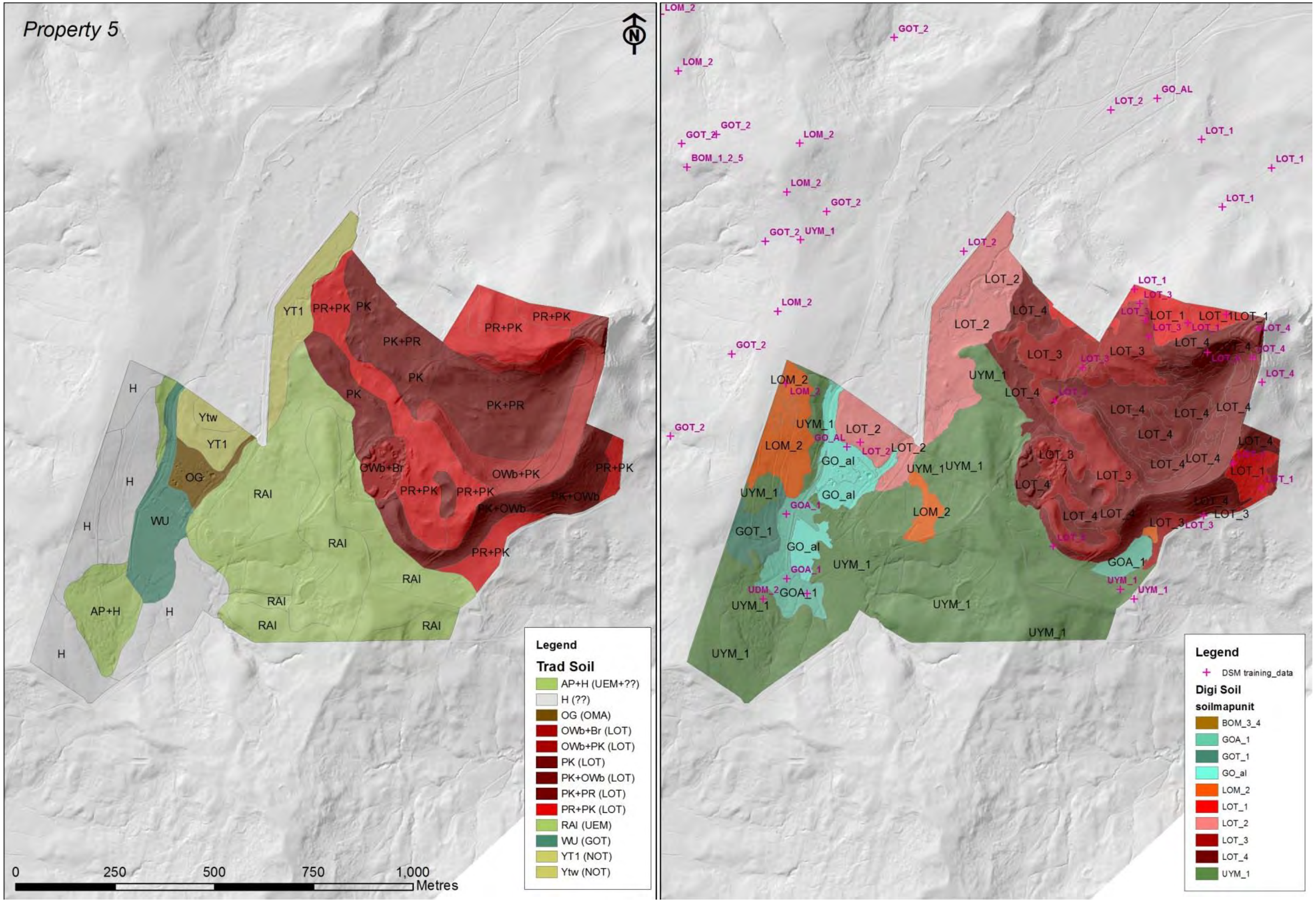

Figure 44 Comparison of traditional soil mapping and digital soil mapping for Property 5; soil observation locations in red.

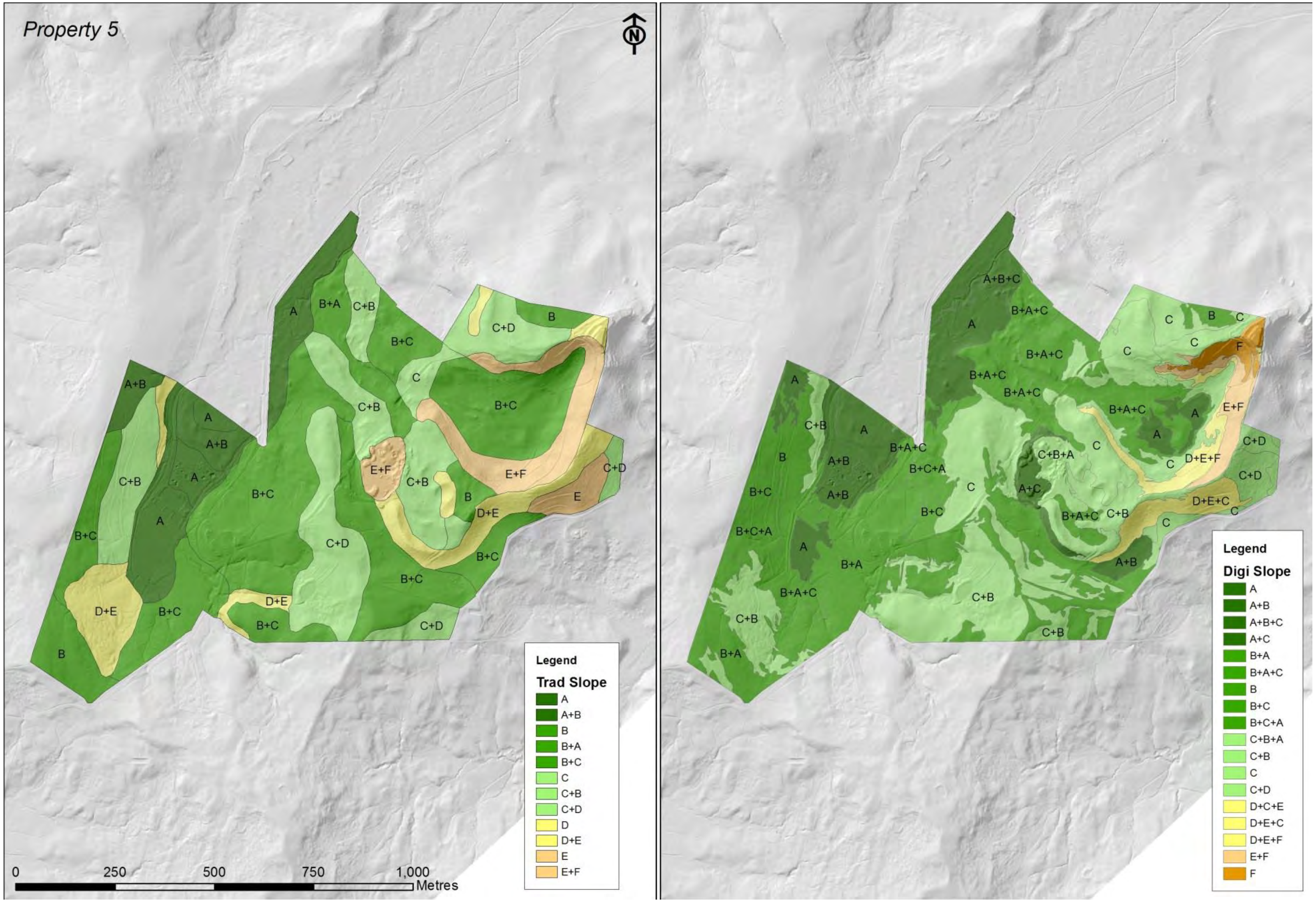

Figure 45 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 5.

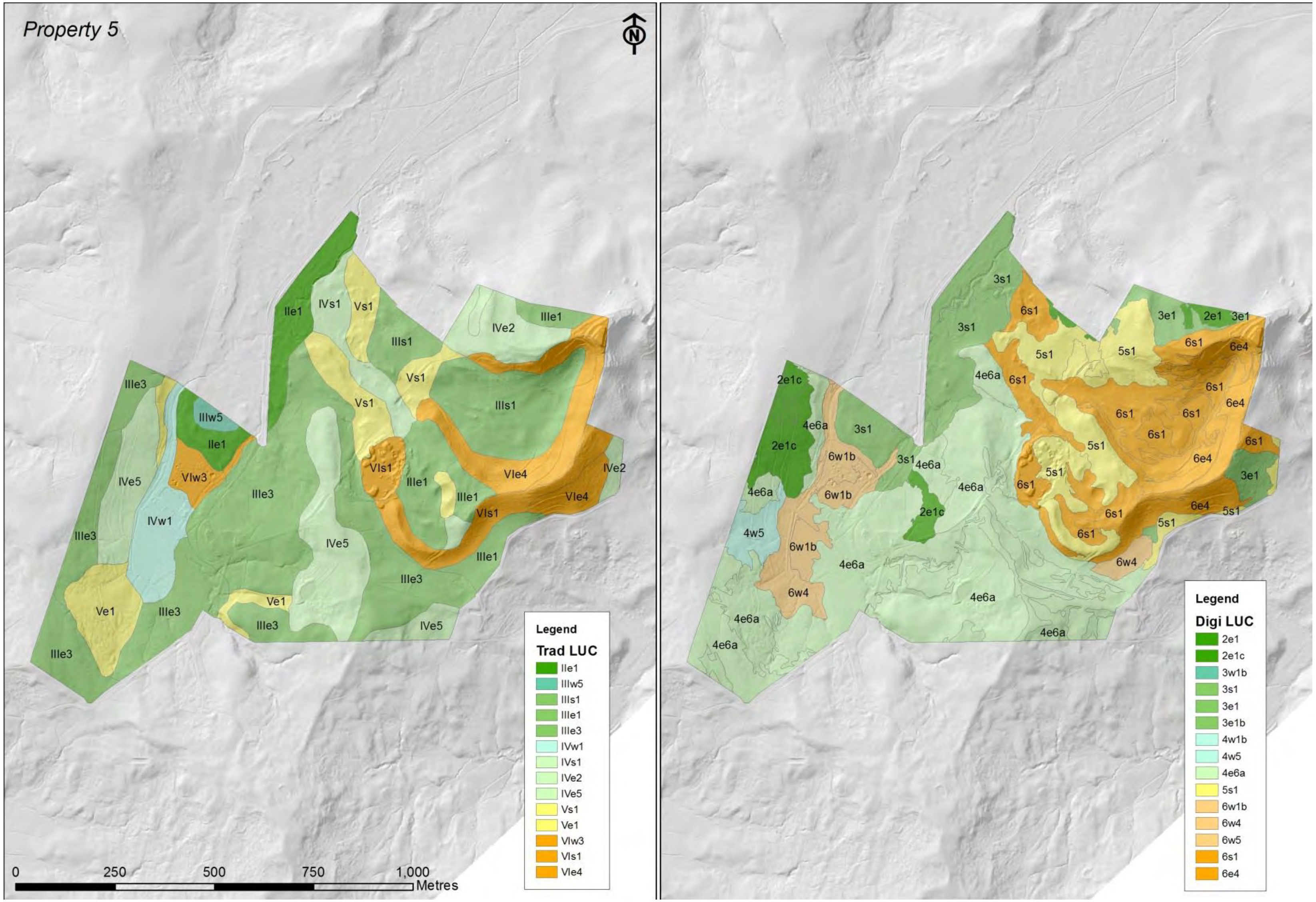

Figure 46 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 5.

Comments: Property 5.

	Traditional	Digital
Geology / rock type	Complex presentation, recorded a significant tephra component on the volcanic cone and surrounds • Mo/Vo • Al+Co • Mm+Ac and Mo/Mm+Ac	Differences – simple presentation • Sc • Af for valley fill • Ac+Sm for non-igneous region
Soils	Rock type and soils relate well, but the actual soils mapped by traditional method are questioned: • Waitaere series (NXT) • Rangiora (UEM) – question presence of E horizons here • Hukerenui (UDM) – question presence of densipan soils • Waipuna series (GOT) – same	• NW footslopes LOT_2 • Central sedimentary downlands UYM_1 • NW sedimentary downlands UYM_1 • Alluvial valley fill GO_al
Slope	Very similar: • B+C • B+C • E+F	• B+A • B+A • E+F
LUC	Variable interpretation reflecting differences in mapped soils: • 3s1 (yet surface boulders are clearly visible) • 3e3 on a Mottled Albic Ultic soil is most unlikely • 4w5 my view was that this was not arable	• Inside scoria cone 6s1 • Rolling country 4e6a (UYM) • 6w1b
Summary comment	Issues with actual soils mapped by LV: Waitarere (NOT) cf. LOT_2, Rangiora (UEM) cf. UYM_1, Hukerenu (UDM) cf. UYM_1 and hence LUC	

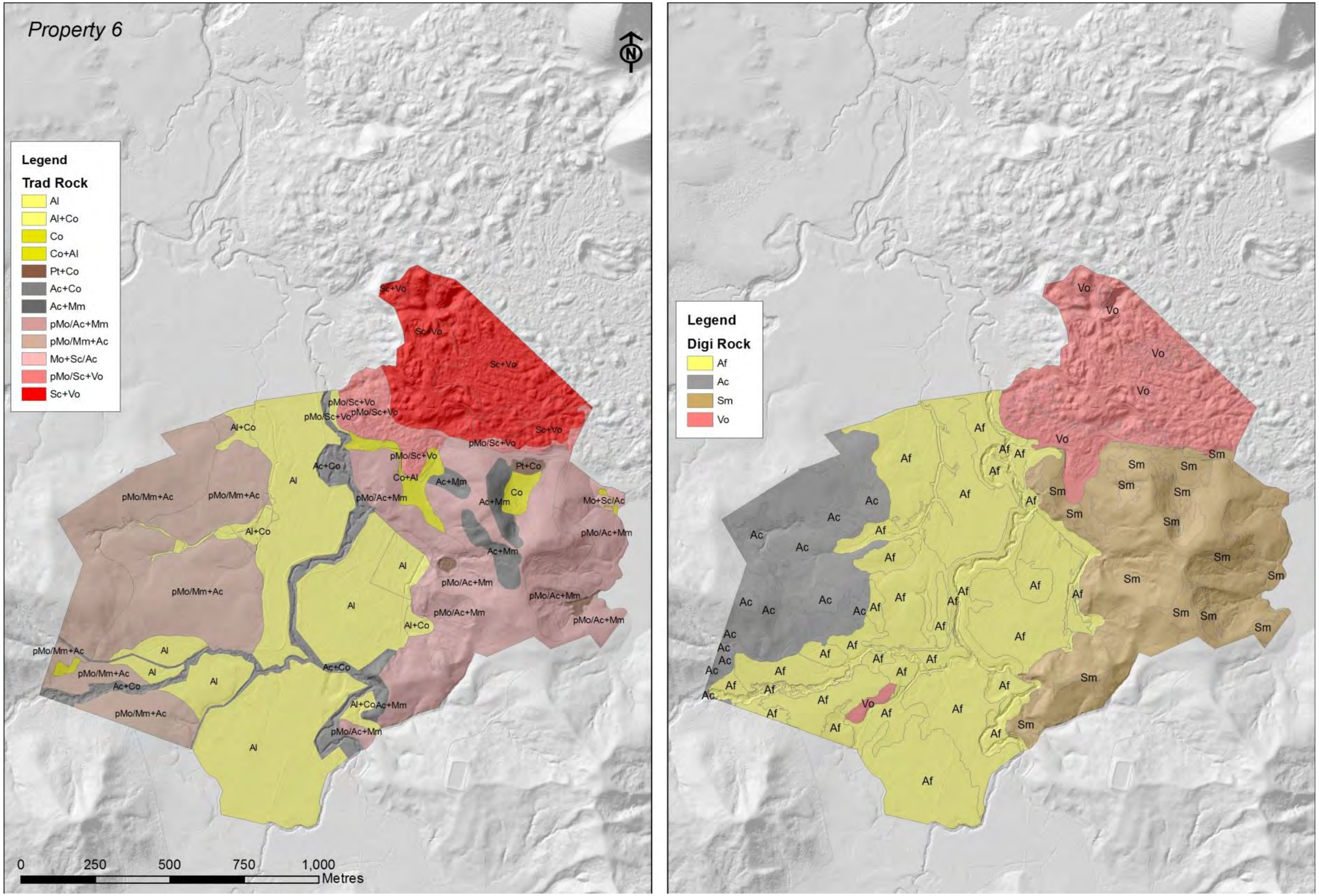

Figure 47 Comparison of traditional parent material and digital parent material mapping for Property 6.

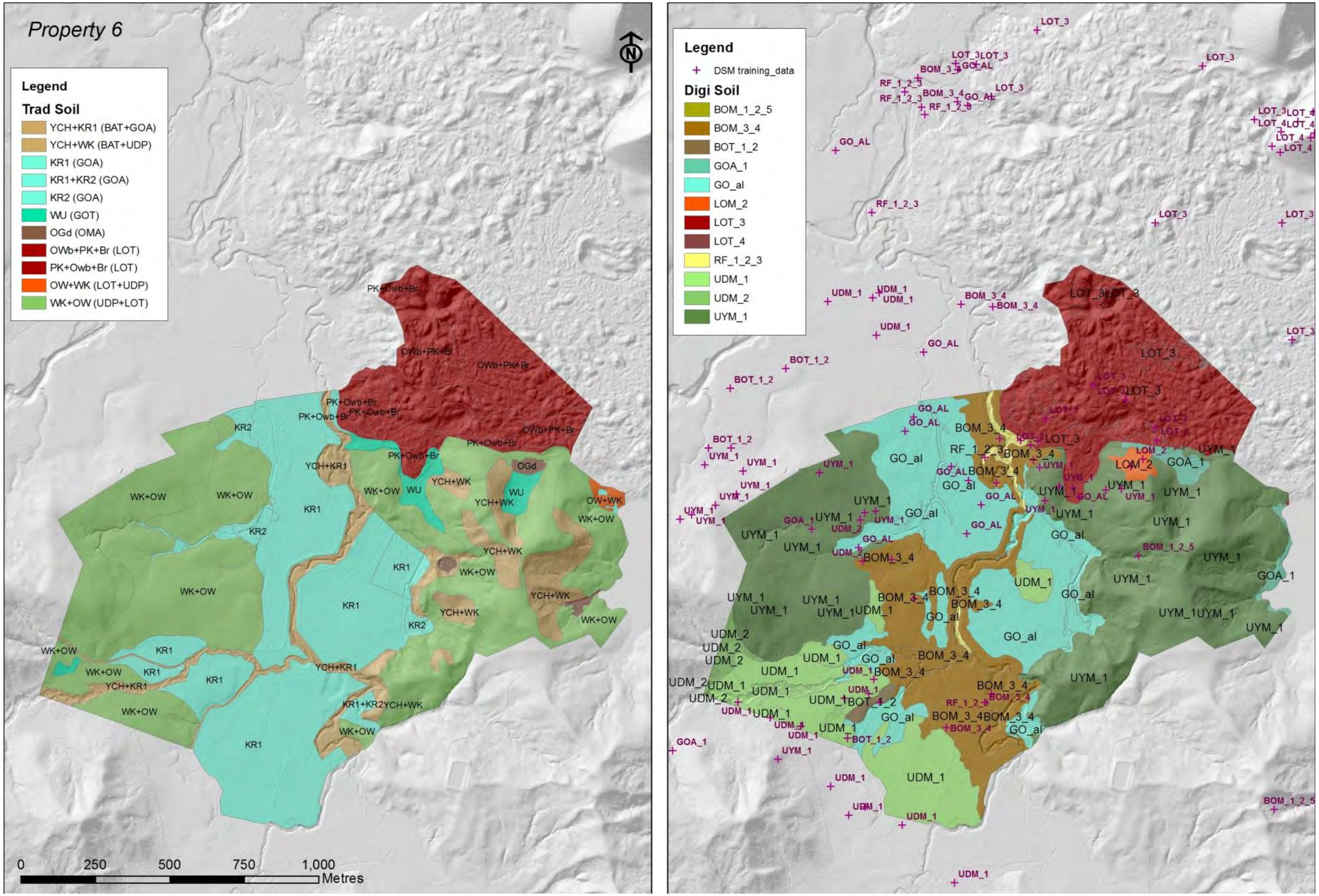

Figure 48 Comparison of traditional soil mapping and digital soil mapping for Property 6; soil observation locations in red.

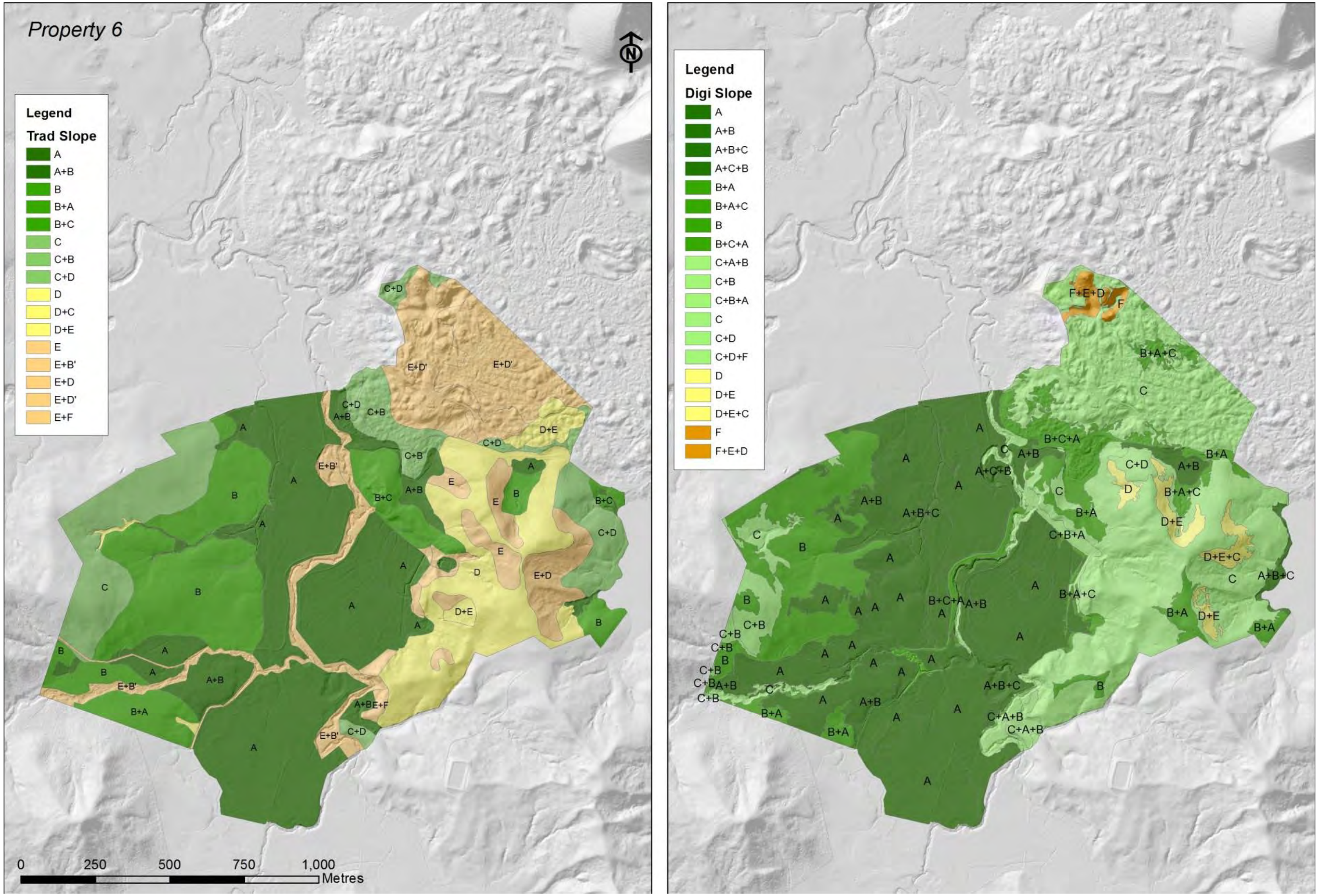

Figure 49 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 6.

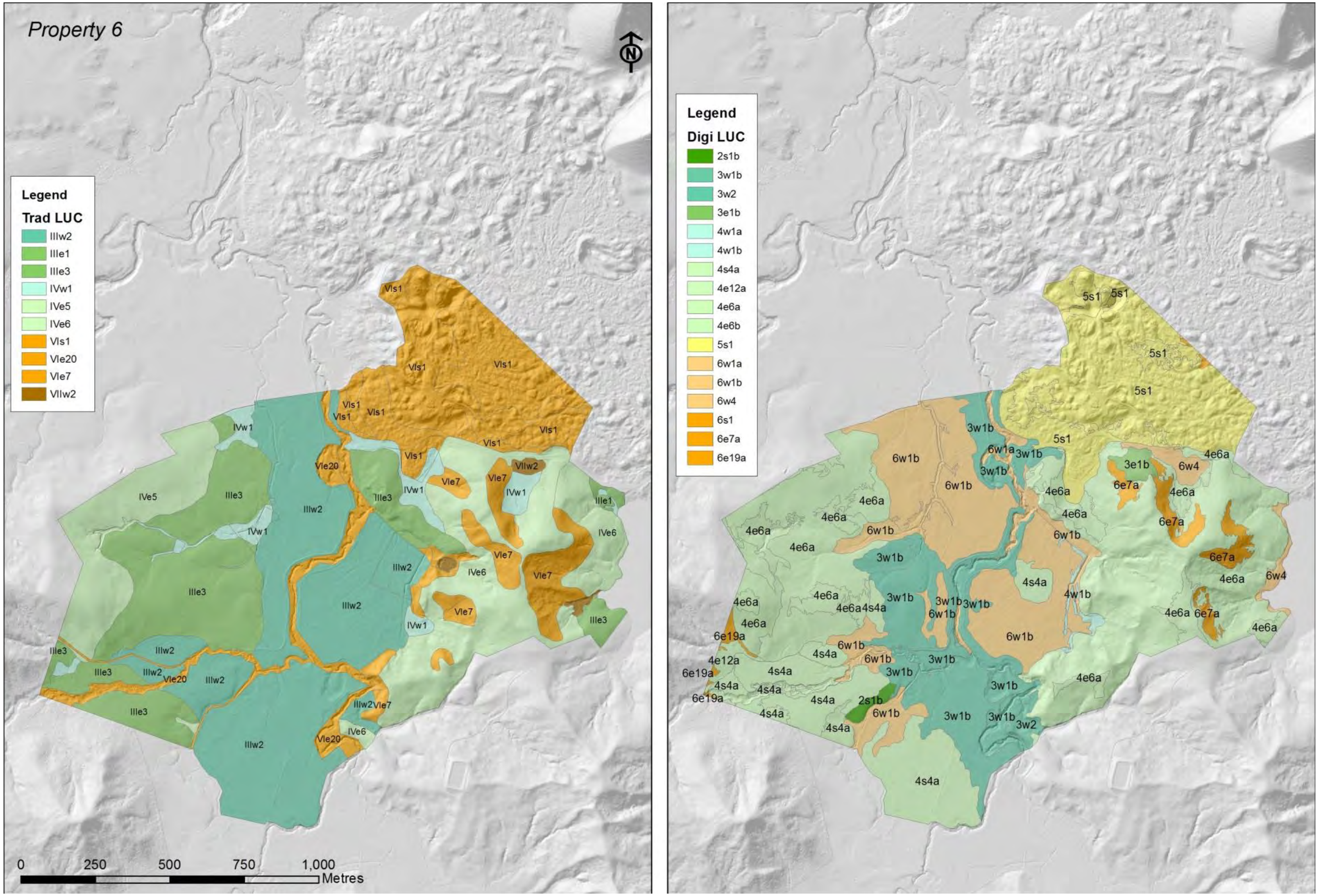

Figure 50 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 6.

Comments: Property 6

	Traditional	Digital
Geology / rock type	More complex presentation, recorded a patchy tephra component extensively • Both identified the volcanic terrain • pMo/Ac+Sm • valley fill – eastern boundary both agree • western boundary more precisely located • pMo/Mm+Ac	Differences – simple presentation • Both identified the volcanic terrain precisely • Eastern sedimentary hills – Sm • Valley fill – eastern boundary both agree • Valley fill – western boundary with old higher terrace has been 'lost' with polygonisation? • Western downlands – could find no evidence of tephra there, Ac
Soils	Reasonable correlation on the volcanics and valley fill; significant variability on other terrain • Ohaeawai + Papakauri series (LOT) • Kara series (GOT/GOO) • Wharekohe (UDP) + Ohaeawai (LOT) & Waiotira (BAT). DSM survey found no densipans here. • Wharekohe (UDP) + Ohaeawai (LOT). DSM survey found no evidence of tephra here. • Wharekohe (UDP) + Ohaeawai (LOT). DSM survey found no evidence of tephra here.	• Volcanics – LOT_3 • Valley fill – GO_al • Eastern sedimentary hill country UYM_1 + LOM_2, tephra recognised but generally <30 cm, therefore balance mapped as UYM • Northern western downlands UYM_1 (maybe better as YDM) • Southern western downlands UDM_1
Slope	Variable: • E+D • D • A • B • C	• C+B broken lava • C+B Sm hills • A+B valley fill • High terrace A+B • Western downland C+B

LUC	Variable interpretation reflecting the differences in mapped soils • 6s1 • 3w2 [definitely not arable, with moderate limitations to use] • not recognised • 4e6, 6e7 • 3e3 [unlikely on a UDP soil]	• Lava flows 5s1 [the key is that it is not arable & has a very low erosion risk, but level of production is unknown] • Valley floor – 6w1b [20 cm topsoil / E and/or very a strong gleyed horizon] • Freer-draining levees 3w1b [BOM_3_4] • Eastern hills – agree 4e6a, 6e7a • Western downlands 4e6a, 4s4a
Summary comment	The valley fill edges are difficult to determine. LV was more precise than MWLR and more precise in delineating gullies. MWLR didn't recognise tephra on the western downlands. Patchy tephra <30 cm thick is present on the eastern downlands, but the soils still classify as Ultic (UYM), and not UDP, as no densipans were found; MWLR did not find tephra on the western downlands. Major differences in LUC assessment exist for the valley floor terrain (see above), and the allocation of UDM Soils as Class 3 is questioned.	

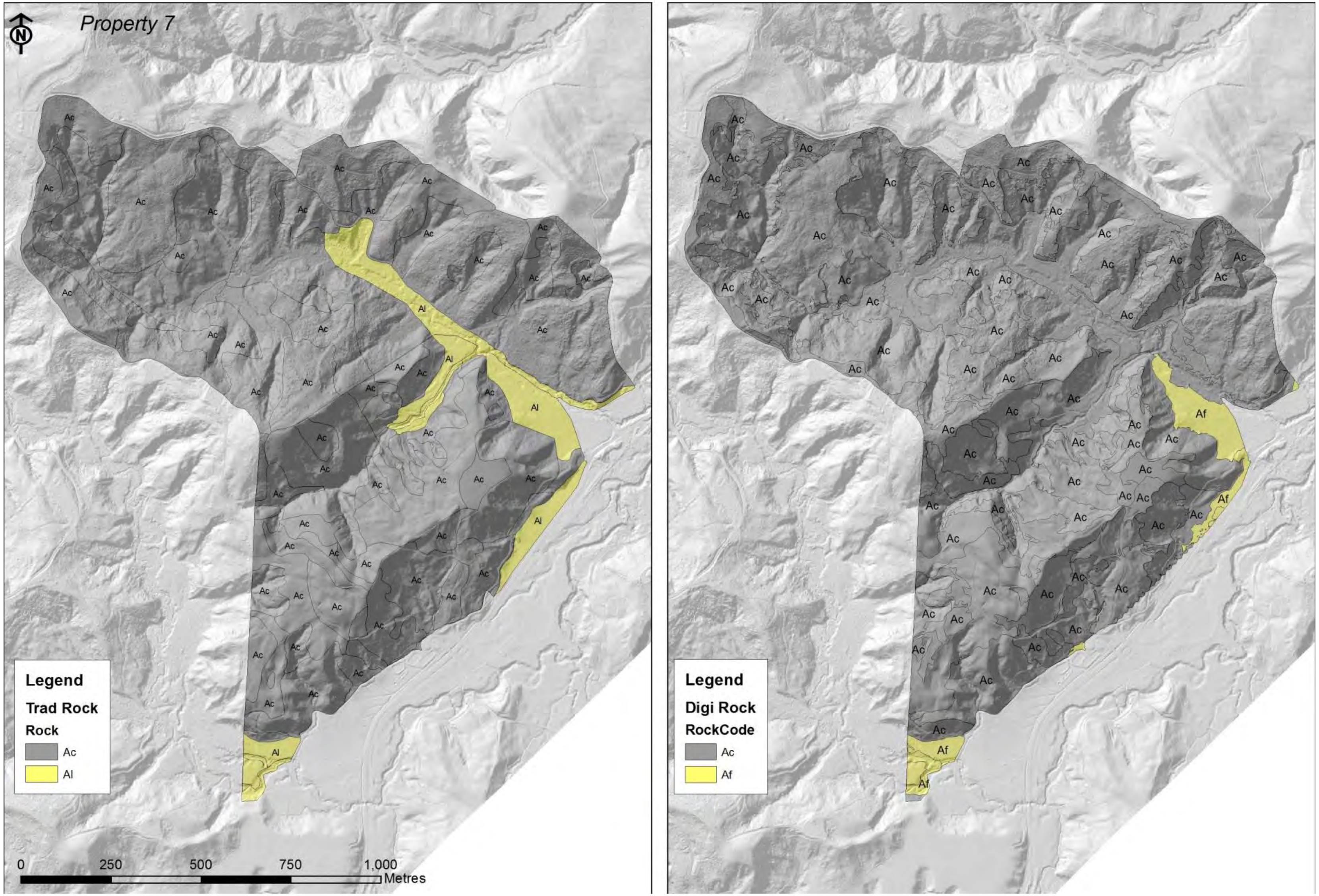

Figure 51 Comparison of traditional parent material and digital parent material mapping for Property 7.

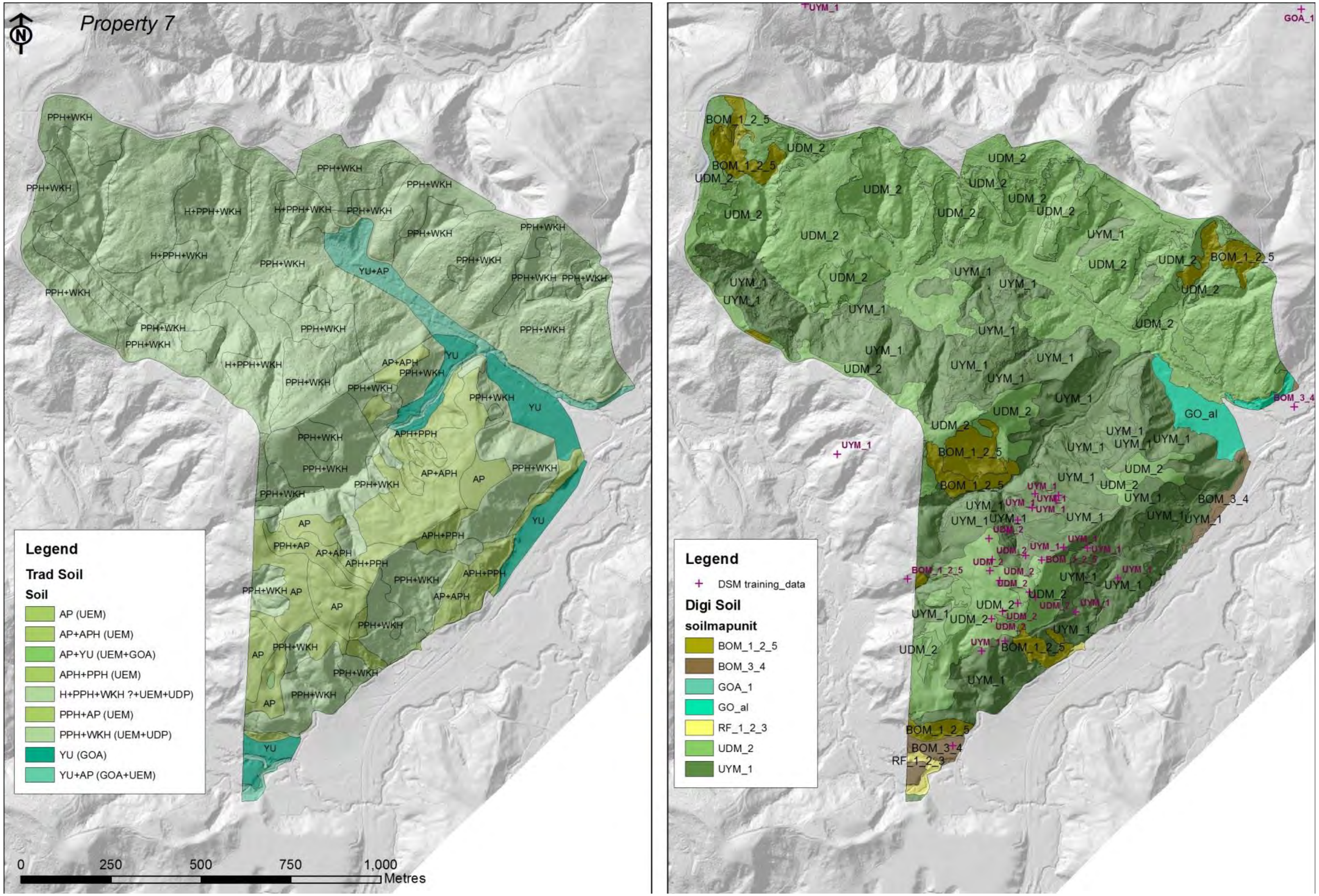

Figure 52 Comparison of traditional soil mapping and digital soil mapping for Property 7; soil observation locations in red.

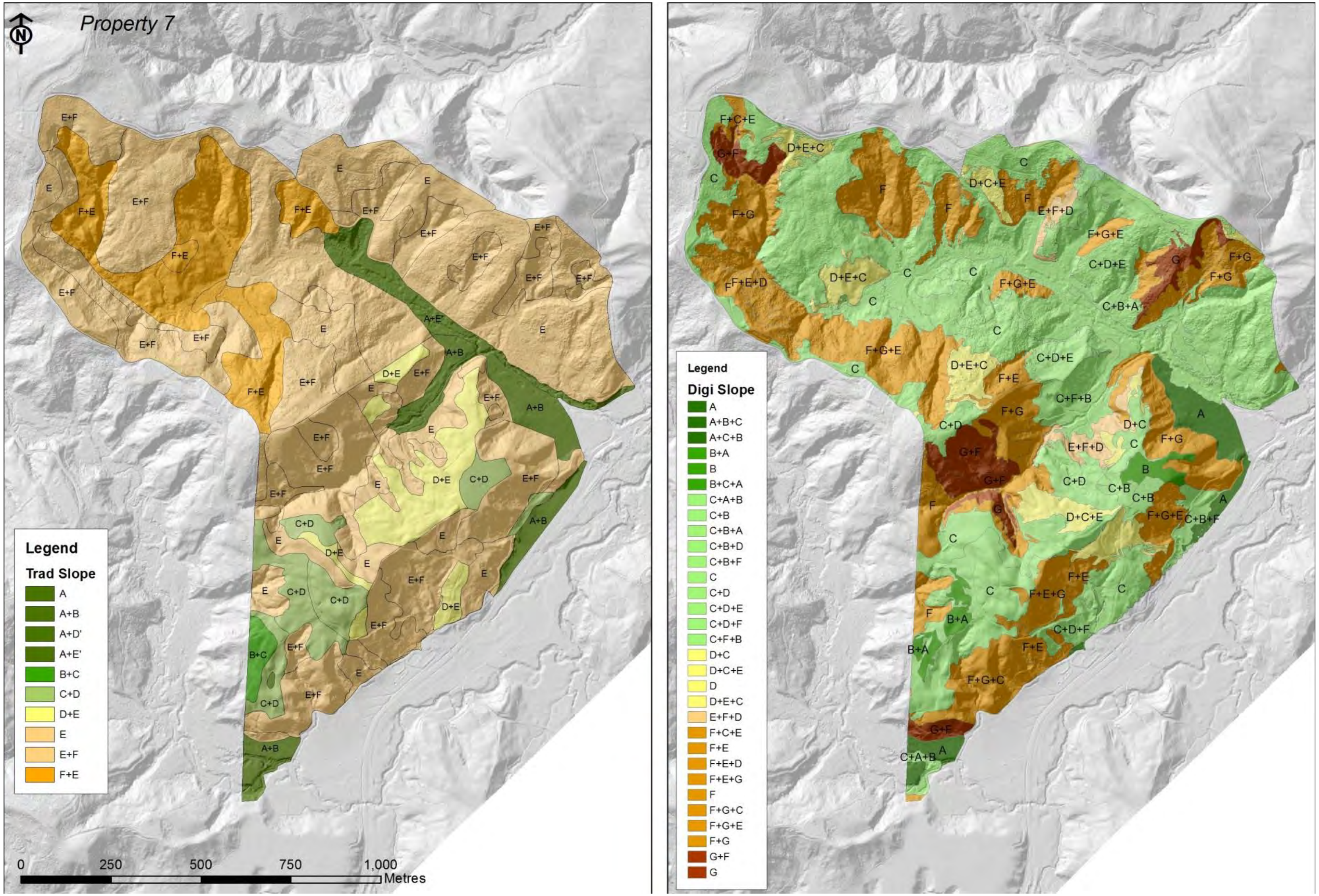

Figure 53 Comparison of traditional slope mapping and LiDAR-derived digital slope mapping for LUC units on Property 7.

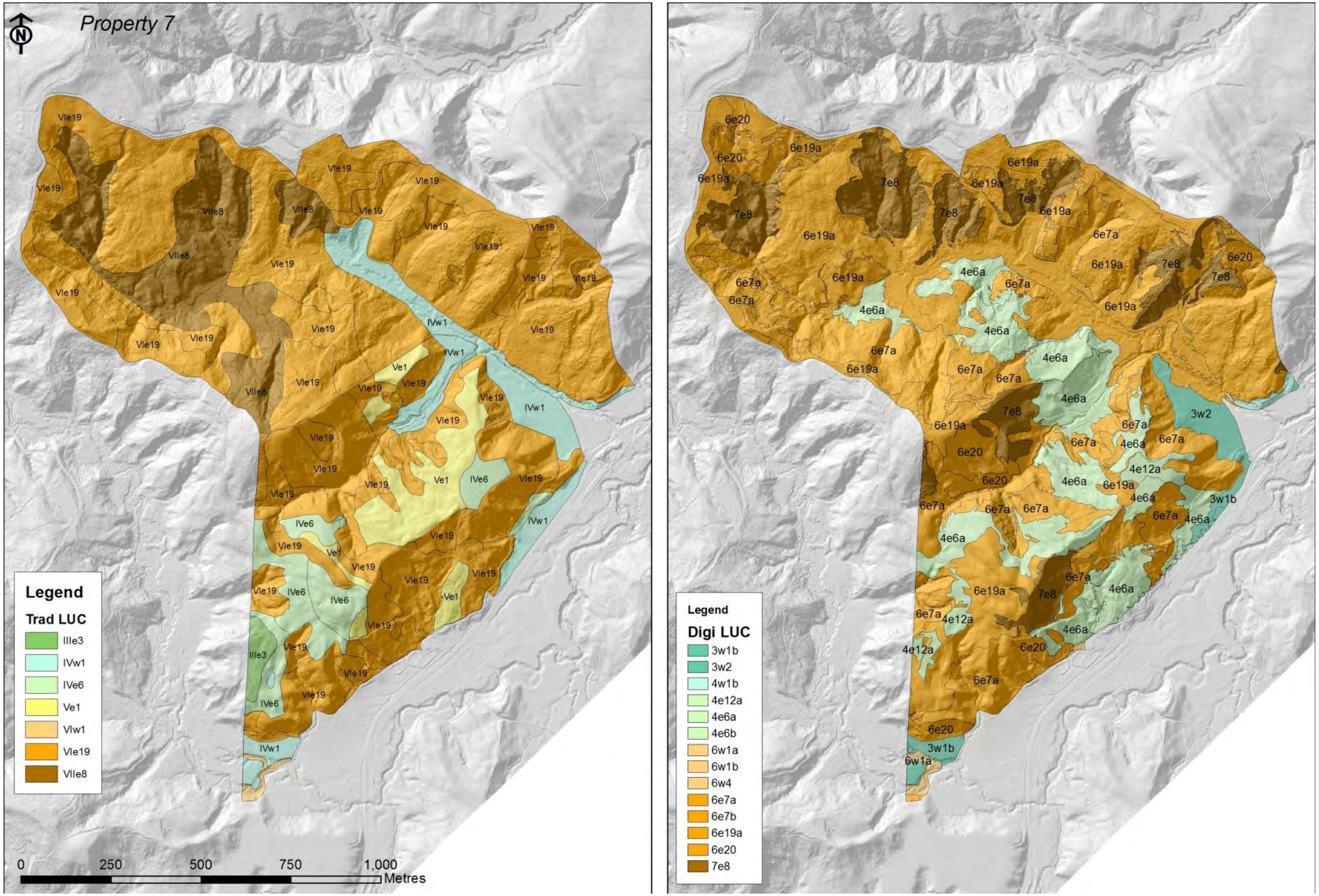

Figure 54 Comparison of traditional LUC unit mapping and digital LUC unit mapping for Property 7.

Comments: Property 7

	Traditional	Digital
Geology / rock type	A simple presentation from both methods. Valley floor terrain was more precisely defined, especially within the hill country.	Ac on the hill country and Af for the valley fill.
Soils	Reasonable correlation: • Waipu series (GOA) only. • Only recognised Ultic hill soils (UYM, UEM, UDP). • Recognised a complex of UYM and UDM Soils on the hills.	• Recognised free-draining terrace component, BOM_3_4 and GO_al. • Recognised a significant Brown hill soil component [BOM_1_2_5]. • Recognised a complex of UYM and UDM Soils on the hills.
Slope	Variable: • E+F, E • D+E • E+F • E • A+B	• Steep scarp face with slump on slump topography F+E, G+F. • Easy summit ridges D+C, C+C. • Steep slopes G+F. • Easy hill country C+D. • Within hill country valley floor (missed) C+B.
LUC	Variable interpretation: • 4w1 • 4w1 • 6e19 an 7e8 • 5e1 and 4e6	• Recognising the true flood hazard on the valley fill is difficult, 6w1b. • Missing minor valley floor components within the hill country part of 6e7a. • Bulk of the hill country, 6e19a and 7e8. • Easier sloping summits and spurs, 4e6a, 4e12a, 6e7a or 6e19a and 4e12a.
Summary comment	Simple rock type landscape correlation in both presentations. LV was more precise in distinguishing valley floor terrain within the hill country. MWLR recognised better-drained terraces but overlooked inter-hill valley floors. MWLR recognised Brown hillslope soils and a mix of UYM and UDP hill soils. LV mapped a similar UYM and UDP complex, but did not recognised any Brown Soils on the hills. There are significant	

	differences in slope determinations. The distribution of LUC Class 4 on steeper slopes reflects the slope variability determined by both parties.

Appendix 2 – SLMACC Northland Land Use Capability Legend Unit Descriptions and Rules for Assigning LUC

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6 June 2017

Map Unit 1: BOM_1_2_5 (1469ha)

Mottled Orthic Brown Soils on hills without tephra (includes Recent Soils on eroded hills)

Six LUC units differentiated, primarily on rock type (wGw versus the grouping of Ac, Sm and Ac+Sm (melange)) and slope; N4e7b, N4e6b, N6e9b, N6e17b, N6e7b, new 6e20.

N = Northland regional legend unit number; a, b, etc = subset of the regional unit.

Rock	Slope	Drainage	Depth	Other	LUC 4	LUC 6
wGw, wGw+Us	<E	I or mw	deep		4e7b	
	E	I or mw	deep			6e9b
	≥F	I or mw	deep			6e17b
Ac or Sm or Ac+Sm	<E	I or mw	deep		4e6b	
	E	I or mw	deep			6e7b
	≥F	I or mw	deep			6e20

LUC Unit 4e7b

Rolling to strongly rolling (C, D, B, A) downland slopes on weathered greywacke with deep imperfectly to moderately well-drained Mottled Orthic Brown Soils, which have a potential for moderate to severe sheet, rill, and gully erosion when cultivated.

IF Rock = wGw, or wGw+Us AND Slope < E AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (I or mw) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 4e7b

LUC Unit 4e6b

Rolling to strongly rolling (C, D, B, A) downland slopes on crushed argillite and massive sandstone with deep, imperfectly to moderately well-drained Mottled Orthic Brown Soils, which have a potential for moderate to severe sheet, rill, and gully erosion when cultivated.

IF Rock = Ac or Sm or Ac+Sm AND Slope < E AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (I or mw) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 4e6b

LUC Unit 6e9b

Strongly rolling to moderately steep (E) hill slopes on weathered greywacke, with deep, imperfectly to moderately drained Mottled Orthic Brown Soils with a potential for moderate shallow landslide, and sheet gully erosion (6e9b gentler than 6e17b).

IF Rock = wGw, or wGw+Us AND Slope = E AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (I or mw) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 6e9b

LUC Unit 6e7b

Strongly rolling to moderately steep (E) hill slopes on crushed argillite and massive sandstone with deep, imperfectly to moderately drained Mottled Orthic Brown Soils with a potential for moderate shallow landslide and sheet gully erosion.

IF Rock = Ac or Sm or Ac+Sm AND Slope = E AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (I or mw) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 6e7b.

LUC Unit 6e17b

Steep (F, G) hill slopes on weathered greywacke with deep, imperfectly to moderately drained Mottled Orthic Brown Soils with a potential for moderate shallow landslide, sheet, and gully erosion (a steeper version of 6e9b).

IF Rock = wGw, or wGw+Us AND Slope ≥ F AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (I or mw) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 6e17b.

LUC Unit 6e20

Steep (F, G) hill slopes on weathered crushed argillite and massive sandstone with deep imperfectly to moderately drained Mottled Orthic Brown Soils with a potential for moderate shallow landslide, sheet and gully erosion (steeper than 6e7b).

IF Rock = Ac or Sm Ac+Sm AND Slope ≥ F AND Soil = BOM_1_2_5, AND Drainage = imperfectly to moderately well drained (I or mw) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 6e20.

Map Unit 2: BOM_3_4 (805ha)

Mottled Orthic Brown Soils from alluvium

Two LUC units differentiated on rock type and drainage: N3w1b, 3s3a [*a potential 4w could also be defined if warranted]*

Rock	Slope	Drainage	Depth	Other	LUC 3	LUC 4
Af or Af/Vo	A, B, C	I or p	Deep or moderately deep		3w1b	
Af or Af/Vo	*A, B, C*	*p*	*Deep or moderately deep*			*potential 4w unit*
wGw+Us	A, B, C	I or mw or wd	Deep or moderately deep		3s3a	

LUC Unit 3w1b

Flat to gently undulating - dominant A, sub-dominant B and C slopes (A, (B, C)) floodplains and low terraces of sedimentary and volcanic derived alluvium with deep to moderately deep imperfectly drained Mottled Orthic Brown Soils. Runoff from the surrounding hills and moderately high water-tables increase the wetness limitation, areas are prone to occasional flooding, and slight to moderate streambank erosion and deposition.

IF Rock = Af or Af/Vo AND Slope < D AND Soil = BOM_3_4, AND Drainage = imperfectly drained (i) or (p) *[any drainage]* AND Depth = deep *[any depth]* THEN LUC = 3w1b

LUC Unit 3s3a

Flat to gently undulating (A, (B, C)) weakly dissected higher terraces and footslopes, primarily on weathered greywacke and alluvium, with deep to moderately deep imperfectly drained Mottled Orthic Brown Soils with minimal soil or wetness limitations and only slight to moderate erosion risk under cultivation.

If Rock = wGw+Us AND Slope < D AND Soil = BOM_3_4, AND Drainage = imperfectly drained (i) or mw or wd [*any drainage*] AND Depth = deep [*any depth*] THEN LUC = 3s3a

NB: 54 ha recorded as poor drainage, so there may be a need to also have a Class 4w unit.

Map Unit 3: BOT_1_2 (127ha)

Typic Orthic Brown Soils from volcanic parent material including tephra and lava flows, both stony and not stony

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Three potential LUC units: N2e1b / N2s1b, N3s1b

Rock	Slope	Drainage	Depth	Other	LUC
Vo	A, B, C	Mw or i	Deep	<5% topsoil stone	2s1b
Vo	A, B, C	Mw or i	Deep	>5 <35% topsoil stone	3s1b

LUC Unit 2s1b (2e1b)

Flat to undulating (A, B, (C)) tephra mantled lava flows with deep, moderately well-drained to imperfectly drained stone free (topsoil stones ≤5%) Typic Orthic Brown Soils suited to a wide range of crops with only slight limitations to arable use.

IF Rock = Vo AND Slope ≤ C AND Soil = BOT_1_2, AND Drainage = mw or i AND Depth = deep AND topsoil stones ≤5%; [topsoil FH are NOT tS** or tV**] THEN LUC = 2s1b

LUC Unit 3s1b

Flat to undulating (A, B, (C)) tephra mantled lava flows with deep, moderately well drained to imperfectly drained Typic Orthic Brown Soils with stones and topsoil stone content of ≥5 <35% suitable to a wide range of crops with moderate limitations to arable use.

IF Rock = Vo AND Slope ≤ C AND Soil = BOT_1_2, AND Drainage = mw or i AND Depth = deep AND topsoil stones ≥5 <35% [topsoil FH = tS**] THEN LUC = 3s1b.

Map Unit 4: GO_al (848ha)

Orthic Gley Soils from alluvium

Three potential LUC units differentiated on drainage and flood risk: N3w2 , N4w1b, N6w1b

Rock	Slope	Drainage	Depth	Other	LUC
Af	≤C	I	D		3w2
Af	≤C	p	D		4w1b
Af	≤C	p	D	Non-arable, higher flood risk	6w1b

LUC Unit 3w2

Flat to rolling (A, B, C) alluvial floodplains, valley floors and low terraces of sedimentary and volcanic-derived alluvium with imperfectly drained Orthic Gley Soils with a moderate wetness limitation for arable use, but can be effectively drained.

IF Rock = Af AND Slope ≤ C AND Soil = GO_al, AND Drainage = i AND Depth = deep THEN LUC = 3w2.

LUC Unit 4w1b

Flat to rolling (A, B, C) alluvial floodplains, valley floors and low terraces of sedimentary and volcanic-derived alluvium with poorly drained Orthic Gley Soils with continuing severe wetness or flooding limitation to arable use. Severe limitations to cropping because of runoff from adjacent hills, flooding of streams or high watertables. Potential for moderate streambank erosion and deposition.

IF Rock = Af AND Slope ≤ C AND Soil = GO_al, AND Drainage = poorly drained (p) AND Depth = deep THEN LUC = 4w1b [or 6w1b on flood risk).

LUC UNIT 6w1b

Flat to rolling (A, B, C) alluvial floodplains, valley floors and low terraces of sedimentary and volcanic-derived alluvium with poorly drained non-arable Orthic Gley Soils with a continuing severe wetness limitation. Subject to frequent flooding or a permanently high water table and assessed as requiring a community drainage scheme with an increased flood risk.

IF Rock = Af AND Slope ≤ C AND Soil = GO_al, AND Drainage = poorly drained (p) AND Depth = deep THEN LUC = 6w1b (on flood risk).

Map Unit 5: GOA_1 (241ha)

Acid Gley Soils associated with Ultic hill soils

One potential LUC unit; a new 6w4, associated with 6e7a, 6e7a, 6e17a.

Rock	Slope	Drainage	Depth	Other	LUC
Ac or Ac+Sm	≤D	P	D	Associated with 6e7a, 6e9a, 6e17a, 6e19a	6w4

LUC Unit 6w4

Deep, poorly drained Acid Orthic Gley Soils on flat to rolling (A, B, C) slopes and in swales associated with Ultic Soils on predominantly crushed argillite and melange hill country terrain.

IF Rock = Ac or Ac+Sm AND Slope ≤ D AND Soil = GOA_1, AND Drainage = p or i AND Depth = deep THEN LUC = 6w4

Map Unit 6: GOT_1 (213ha)

Gley Soils associated with tephric (LOM, BOM) soils on hills

Two new LUC units differentiated on drainage and slope, a new 4w and a new 6w, associated with 6e4, 6e9b, 6e17b.

Rock	Slope	Drainage	Depth	Other	LUC
Ac+Sm	≤C	i	D	Associated with 6e4, 6e9b, 6e17b,	4w5
Ac+Sm	≤C	p	D	Associated with 6e4, 6e9b, 6e17b,	6w5

LUC Unit 4w5

Imperfectly drained deep Typic Orthic Gley Soils on rolling and undulating (C, B, A) slopes and in swales associated with tephric Mottled Orthic Allophanic or Mottled Orthic Brown Soils (LOM, BOM) on melange hill country terrain dominated by sedimentary rocks.

IF Rock = Ac+Sm or Gw or Tc+Vo, AND Slope ≤ C, AND Soil = GOT_1, AND Drainage = imperfectly drained (i) AND Depth = deep THEN LUC = new 4w5.

LUC Unit 6w5

Poorly drained deep Typic Orthic Gley Soils on rolling and undulating (C, B, A) slopes and in swales associated with tephric Mottled Orthic Allophanic or Mottled Orthic Brown Soils (LOM, BOM) Soils on melange hill country terrain dominated by sedimentary rocks.

IF Rock = Ac+Sm or Gw or Tc+Vo AND Slope ≤ C AND Soil = GOT_1, AND Drainage = poorly drained (p) AND Depth = deep THEN LUC = new 6w5.

Map Unit 7: LOM_1 (1140ha)

Mottled Orthic Allophanic tephric Soils with up to 75cm of tephra over Ultic paleosol, P-retention predominantly <85%.

Four LUC units with tephra overlying primarily weathered greywacke differentiated by slope: N2e1c, N3e1b, (N3s1 if stony), N4e2b, 6e4b

Rock	Slope	Drainage	Depth	Other	LUC
wGw	A or B	I or mw	Deep		2e1c
wGw	C	I or mw	Deep		3e1b
wGw	D	I or mw	Deep		4e2b
wGw	≥E	I or mw	Deep		6e4b

LUC Unit 2e1c

Flat to undulating (A, B) tephra mantled slopes developed on greywacke and deeply weathered greywacke landscapes with deep, imperfectly to moderately well-drained Mottled Orthic Allophanic Soils with P-retention predominantly <85% overlying Ultic paleosols, suited to a wide range of crops, but with a slight erosion limitation under cultivation.

IF Rock = wGw AND Slope = A or B AND Soil = LOM_1, AND Drainage = I or mw AND Depth = deep THEN LUC = 2e1c.

LUC Unit 3e1b

Rolling (C) tephra mantled slopes developed on greywacke and deeply weathered greywacke landscapes with deep, imperfectly to moderately well-drained Mottled Orthic Allophanic Soils with P-retention predominantly <85% overlying Ultic paleosols. There are moderate limitations for arable use, largely due to the potential for slight to moderate sheet and rill erosion when cultivated and seasonal soil moisture deficit. Under cultivation the potential erosion on these slopes is regarded as the dominant limitation to use.

IF Rock = wGw AND Slope = C AND Soil = LOM_1, AND Drainage = I or mw AND Depth = deep THEN LUC = 3e1b.

LUC Unit 4e2b

Strongly rolling (D) tephra mantled slopes developed on greywacke and deeply weathered greywacke landscapes with deep, imperfectly to moderately well drained Mottled Orthic Allophanic Soils with P-retention predominantly <85% overlying Ultic paleosols, prone to summer moisture deficits and with a potential for moderate to severe sheet rill wind and gully erosion when cultivated.

IF Rock = wGw AND Slope = D AND Soil = LOM_1 AND Drainage = I or mw AND Depth = deep THEN LUC = 4e2b.

LUC Unit 6e4b

Moderately steep to steep (F, E) tephra mantled slopes developed on greywacke and deeply weathered greywacke landscapes with deep, imperfectly to moderately well drained Mottled Orthic Allophanic Soils with P-ret predominantly <85% overlying Ultic paleosols with a potential for moderate soil slip and sheet erosion.

IF Rock = wGw AND Slope ≥ E AND Soil = LOM_1, AND Drainage = I or mw AND Depth = deep THEN LUC = 6e4b

Map Unit 8: LOM_2 (152ha)

Mottled Orthic Allophanic tephric Soils with up to 75 cm of tephra over Ultic paleosol, P-retention predominantly >85%.

Potentially 2 LUC units differentiated primarily by slope: 2e1c, 3e1b

Rock	Slope	Drainage	Depth	Other	LUC
Ac+Sm	<C	I	Deep	P-ret > 85%	2e1c
Ac+Sm	=C	I	Deep	P-ret > 85%	3e1b

LUC Unit 2e1c

Undulating to flat (B, A) tephra mantled slopes developed on melange hill country terrain dominated by sedimentary rocks with deep, imperfectly drained Mottled Orthic Allophanic Soils with high (>85%) P-retention, overlying Ultic paleosols, suited to a wide range of crops but with a slight erosion limitation under cultivation.

IF Rock = Ac+Sm AND Slope = A or B AND Soil = LOM_2, AND Drainage = I AND Depth = deep THEN LUC = 2e1c.

LUC Unit 3e1b

Rolling (C) tephra mantled slopes developed on melange hill country terrain dominated by sedimentary rocks with deep imperfectly and moderately well drained Mottled Orthic Allophanic Soils with high (>85%) P-retention overlying Ultic paleosols. There are moderate limitations for arable use, largely due to the potential for slight to moderate sheet and rill erosion when cultivated and seasonal soil moisture deficit. Under cultivation the potential erosion on these slopes is regarded as the dominant limitation to use.

IF Rock = Ac+Sm AND Slope = C AND Soil = LOM_2, AND Drainage = I AND Depth = deep THEN LUC = 3e1b

Map Unit 9: LOT_1 (209ha)

Deep, moderately well to well-drained Typic Orthic Allophanic Soils without stones.

NB: 75% are recorded as imperfectly drained.

Potentially 2 LUC units differentiated by slope: N2e1, N3e1

Rock	Slope	Drainage	Depth	Other	LUC
Vo or Ac+Sm	A, B	I or mw	Deep		2e1
Vo or Ac+Sm	C	I or mw	Deep		3e1

LUC Unit 2e1

Flat to gently undulating (A, B) tephra mantled slopes underlain primarily by basaltic lavas with deep, imperfectly to moderately well-drained stone-free Typic Orthic Allophanic Soils suited to a wide range of crops but with a slight erosion limitation under cultivation.

IF Rock = Vo or Ac+Sm AND Slope = A or B AND Soil = LOT_1, AND Drainage = I or mw AND Depth = deep THEN LUC = 2e1.

LUC Unit 3e1

Rolling (C) tephra mantled slopes underlain primarily by basaltic lavas with deep, imperfectly to moderately well-drained stone-free Typic Orthic Allophanic Soils with moderate limitations for arable use, largely due to the potential for slight to moderate sheet and rill erosion when cultivated and seasonal soil moisture deficit.

IF Rock = Vo or Ac+Sm AND Slope ≥ C AND Soil = LOT_1, AND Drainage = I or mw AND Depth = deep THEN LUC = 3e1.

Map Unit 10: LOT_2 (483ha)

Typic Orthic Allophanic stony soils on lava flows

Two arable LUC units differentiated on topsoil stoniness: N3s1 N4s1.

Rock	Slope	Drainage	Depth	Other	LUC
Af/Vo	A, B	wd	Deep to md	Topsoil stone <35%, FH=tS**	3s1
Af/Vo	C	wd	Deep to md	Topsoil stone >35%, FH = tV**	4s1

LUC Unit 3s1

Flat to undulating 'valley infill' basaltic lava flows with arable, stony, well-drained, deep to moderately deep Typic Orthic Allophanic Soils where the topsoil stone content is >5 <35%, (topsoil FH is tS**), and considered to be a moderate limitation to arable use. Profile available water storage limits the range of crops able to be grown without irrigation.

IF Rock = Af/Vo AND Slope = A or B AND Soil = LOT_2, AND Drainage = wd AND Depth = moderately deep or deep AND [topsoil FH is tS**] THEN LUC = 3s1.

LUC Unit 4s1

Rolling to undulating 'valley fill' basaltic lava flows with arable, stony, well-drained, moderately deep to deep Typic Orthic Allophanic Soils where the topsoil stone content is >35 <70%, (topsoil FH is tV**) but lacks significant surface boulders. The high stone content is a severe limitation to arable use. These soils are also prone to severe seasonal soil moisture deficiencies.

IF Rock = Af/Vo AND Slope = C AND Soil = LOT_2, AND Drainage = wd AND Depth = moderately deep or deep AND [topsoil FH is tV**] THEN LUC = 4s1.

Map Unit 11: LOT_3 (700ha)

Typic Orthic Allophanic Soils on very stony / boulder lava flows

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Three LUC units differentiated on slope, stoniness, and depth (and productivity): N5s1, N6s1, N7s1

Rock	Slope	Drainage	Depth	Other	LUC
Vo or Af/Vo or Sc	C, A, B	wd	Deep to moderately deep	Non-arable, topsoil stone >35 <70%, FH=tV**; common surface boulders	5s1
Vo or Af/Vo or Sc	C, A, B	wd	Deep	Non-arable, topsoil stone >35%, FH = tV**; common or greater surface boulders	6s1
Vo or Af/Vo or Sc	C, A, B	wd	Very shallow	Non-arable, topsoil stone >35%, FH = tV**or tX**; common or greater surface boulders	7s1 new

LUC Unit 5s1

Rolling to undulating (C, A, B) basaltic lava flows with non-arable, very stony and boulder, well-drained, deep to very shallow Typic Orthic Allophanic Soils with topsoil stone contents of >35 <70% [topsoil FH is tV**], common surface boulders, but with high dry matter production and negligible to slight limitations or hazards to pastoral, tree crop or forestry use.

IF Rock = Vo or Af/Vo or Sc AND Slope = ≤C AND Soil = LOT_3 AND Drainage = wd AND Depth = deep or very shallow AND topsoil FH is tV** with common surface boulders THEN LUC = 5s1.

LUC Unit 6s1

Rolling to undulating (C, A, B) basaltic lava flows with non-arable, very stony and bouldery well-drained, deep to very shallow Typic Orthic Allophanic Soils with topsoil stone contents of >35 <70% [topsoil FH is tV**], and common or greater surface boulders, which preclude arable use and severely limit production.

IF Rock = Vo or Af/Vo or Sc AND Slope = ≤C AND Soil = LOT_3 AND Drainage = wd AND Depth = deep or very shallow AND topsoil FH is tV** with common or greater surface boulders THEN LUC = 6s1.

LUC Unit 7s1 (new)

Rolling to undulating (C, A, B) basaltic lava flows with non-arable, very stony or extremely stony and bouldery well-drained, very shallow Typic Orthic Allophanic Soils with topsoil stone contents of >70% [topsoil FH is tX**], and common or greater surface boulders which severely limit production and precludes arable use.

IF Rock = Vo or Af/Vo or Sc AND Slope = ≤C AND Soil = LOT_3 AND Drainage = wd AND Depth = very shallow AND topsoil FH is tX** with common or greater surface boulders THEN LUC = 7s1

Map Unit 12: LOT_4 (233ha)

Typic Orthic Allophanic Soils with scoria under tephra on or near scoria cones

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Two LUC units differentiated on slope: N6s1, N6e4

Rock	Slope	Drainage	Depth	Other	LUC
Vo or Sc	C, A, B	wd	Deep	non-arable, stony	6s1
Vo or Sc	F, E, D	wd	Deep	non-arable, steep	6e4

LUC Unit 6s1

Rolling to undulating (C, B, A) tephra mantled scoria slopes with deep, non-arable, stony, well-drained Typic Orthic Allophanic Soils on or near basaltic scoria cones. Stoniness precludes arable use and limits production.

IF Rock = Vo or Sc AND Slope = ≤C AND Soil = LOT_4 AND Drainage = wd AND Depth = deep THEN LUC = 6s1.

LUC Unit LUC 6e4

Steep and moderately steep (F, E, D) tephra mantled scoria slopes with deep, well-drained Typic Orthic Allophanic Soils on or near basaltic scoria cones with a potential for moderate shallow landslide and sheet erosion.

IF Rock = Vo or Sc AND Slope = F or E or D AND Soil = LOT_4 AND Drainage = well drained AND Depth = deep THEN LUC = 6e4.

Map Unit 13: RF_1_2_3 (160ha)

Fluvial Recent Soils

Three (four) LUC units differentiated on drainage: (N2w1)? N3w1a, N4w1a, 6w1a

Rock	Slope	Drainage	Depth	Other	LUC
Af	A, B, C	Imperfectly drained	deep		3w1a
Af	A, B, C	Poorly drained	deep		4w1a
Af	A, B, C	Very poorly drained	deep	Non-arable	6w1a

LUC Unit 3w1a

Flat to gently undulating and rolling (A, B, C) arable floodplains and low terraces with deep, imperfectly drained Fluvial Recent Soils on sedimentary and volcanic alluvium of variable texture and stoniness, with moderately high water tables and prone to occasional flooding and slight streambank erosion.

IF Rock = Af AND Slope = A or B or C AND Soil = RF_1_2_3 AND Drainage = imperfectly drained AND Depth = deep THEN LUC = 3w1a.

LUC Unit 4w1a

Flat to gently undulating and rolling (A, B, C) arable floodplains and low terraces with deep, poorly drained Fluvial Recent Soils on sedimentary and volcanic alluvium of variable texture and stoniness. High water tables and susceptibility to runoff from adjacent hills mean continuing severe wetness and/or flooding limitations to arable use. Potential for moderate streambank erosion and deposition.

IF Rock = Af AND Slope = A or B or C AND Soil = RF_1_2_3 AND Drainage = poorly drained AND Depth = deep THEN LUC = 4w1a.

NB: Unable to distinguish arable from non-arable (4w1 from 6w1) and determine the 'at-site' flood risk remotely.

LUC Unit 6w1a

Flat to gently undulating and rolling (A, B, C) non-arable floodplains and low terraces with deep, poorly drained Fluvial Recent Soils on sedimentary and volcanic alluvium of variable texture and stoniness with continuing severe wetness and/or flooding limitation which precludes arable use, as do the high water tables, the susceptibility to runoff from adjacent hills, and the potential for moderate streambank erosion and deposition.

IF Rock = Af AND Slope = A or B or C AND Soil = RF_1_2_3 AND Drainage = very poorly drained AND Depth = deep, AND the site is non-arable THEN LUC = 6w1a.

Map Unit 14: UDM_1 (152ha)

Densipan Ultic and related soils on terraces.

Two LUC units distinguished on soil depth and depth to pan: N4s4a, N6s5b

Rock	Slope	Drainage	Depth	Other	LUC
Af	≤C	Poorly drained	Deep	Limited rooting depth above pan	4s4a
Af	≤C	Poorly drained	Very shallow	Very limited rooting depth above pan	6s5b

LUC Unit 4s4a

Undulating to flat (B, A, C) alluvial terraces with poorly drained deep Mottled Densipan Ultic Soils with limited rooting depth above the densipan. Soils are of very low fertility, have poor soil structure and severe limitations for arable use.

IF Rock = Af AND Slope = B or C or A AND Soil = UDM_1 AND Drainage = poorly drained (pd) AND Depth = deep THEN LUC = 4s4a.

LUC Unit 6s5b

Undulating to flat (B, A, C) alluvial terraces with poorly drained, very shallow Mottled Densipan Ultic Soils with very limited (<20cm) rooting depth above the densipan. Soils are of very low fertility, have poor soil structure and are unsuitable for arable use.

IF Rock = Af AND Slope = B or C or A AND Soil = UDM_1 AND Drainage = poorly drained (pd) AND Depth = very shallow THEN LUC = 6s5b.

Map Unit 15: UDM_2 (1264ha)

Densipan Ultic and related soils on hills.

Three LUC units differentiated on slope: N4e12, N6e19, N7e8

Rock	Slope	Drainage	Depth	Other	LUC
Ac	B, A	i and pd	Deep		4e12a
Ac	C, D, E	i and pd	Deep or very shallow		6e19a
Ac	F	i and pd	Deep or very shallow		7e8

LUC Unit 4e12a

Undulating hill and downland slopes (B, A) developed on crushed argillite with imperfectly to poorly drained deep Mottled Densipan Ultic Soils of very low natural fertility and a potential for moderate to severe sheet, rill, and gully erosion when cultivated.

IF Rock = Ac AND Slope = B or A AND Soil = UDM_2 AND Drainage = imperfect or poorly drained (I or p) AND Depth = deep THEN LUC = 4e12a.

LUC Unit 6e19a

Strongly rolling to moderately steep hill and downland slopes (C, D, E) developed on crushed argillite with imperfectly to poorly drained deep or very shallow Mottled Densipan Ultic Soils with a potential for severe gully and sheet erosion.

IF Rock = Ac AND Slope = E or D or C AND Soil = UDM_2 AND Drainage = imperfect or poorly drained (I or p) AND Depth = deep or very shallow THEN LUC = 6e19a.

LUC Unit 7e8

Steep hill slopes (F) developed on crushed argillite with imperfectly to poorly drained deep or very shallow Mottled Densipan Ultic Soils with a potential for severe to extreme gully, shallow landslide and sheet erosion.

IF Rock = Ac AND Slope = F AND Soil = UDM_2 AND Drainage = imperfect or poorly drained (I or p) AND Depth = deep or very shallow THEN LUC = 7e8.

Map Unit 16: UYM_1 (2162ha)

Ultic Soils without densipans

Six LUC units determined on rock type (primarily Ac or Sm or Ac+Sm; and wGw) and slope: N3e3, N4e6a, N4e7a, N6e7a, N6e9, N6e17

Rock	Slope	Drainage	Depth	Luc3	Luc4	Luc6
Ac or Sm or Ac+Sm	B, A	i	d	3e3		
	C	i	d		4e6a	
	F, D, E & G	i	d			6e7a
wGw, wGw+Us	C, B, A	i	d		4e7a	
	E, D	i	d			6e9a
	F or G	i	d			6e17a

LUC Unit 3e3

Gently undulating (B, A) downland slopes on crushed argillite and massive sandstone terrain, occasionally partially veneered with ash, with deep imperfectly drained Mottled Yellow Ultic Soils with a potential for moderate sheet, rill, and gully erosion when cultivated.

IF Rock = Ac or Sm or Ac+Sm AND Slope ≤B AND Soil = UYM_1 AND Drainage = imperfectly drained (i) AND Depth = deep (d) THEN LUC = 3e3a.

LUC Unit 4e6a

Rolling (C, B) downland slopes on crushed argillite and massive sandstone terrain with deep, imperfectly drained Mottled Yellow Ultic Soils with a potential for moderate to severe sheet, rill and gully erosion when cultivated.

IF Rock = Ac or Sm or Ac+Sm AND Slope =C AND Soil = UYM_1 AND Drainage = imperfectly drained (i) AND Depth = deep (d) THEN LUC = 4e6a.

LUC Unit 4e7a

Rolling to gently undulating (C, B, A) downland slopes on deeply weathered greywacke terrain with deep, imperfectly drained Mottled Yellow Ultic Soils with a potential, for moderate to severe sheet, rill, and gully erosion when cultivated.

IF Rock = wGw or wGw+Us AND Slope ≤C AND Soil = UYM_1 AND Drainage = imperfectly drained (i) AND Depth = deep (d) THEN LUC = 4e7a.

LUC Unit 6e7a

Steep to strongly rolling (F, D, E and G) hill slopes on crushed argillite and massive sandstone terrain with deep, imperfectly drained Mottled Yellow Ultic Soils with a potential for severe sheet and moderate shallow landslide and gully erosion.

IF Rock = Ac or Sm or Ac+Sm AND Slope ≥ D AND Soil = UYM_1 AND Drainage = imperfectly drained (i) AND Depth = deep (d) THEN LUC = 6e7a.

LUC Unit 6e9a

Moderately steep to strongly rolling (E, D) hill slopes on deeply weathered greywacke terrain with deep, imperfectly drained Mottled Yellow Ultic Soils with a potential for moderate shallow landslide, sheet and earthslip erosion.

IF Rock = wGw or wGw+Us AND Slope = E or D AND Soil = UYM_1 AND Drainage = imperfectly drained (i) AND Depth = deep (d) THEN LUC = 6e9a.

LUC Unit 6e17a

Steep to very steep (F, G) hill slopes on weathered greywacke terrain with deep imperfectly drained Mottled Yellow Ultic Soils with a potential for moderate shallow landslide, sheet and gully erosion (a steeper version of 6e9a).

IF Rock = wGw or wGw+Us AND Slope = F or G AND Soil = UYM_1 AND Drainage = imperfectly drained (i) AND Depth = deep (d) THEN LUC = 6e17a.

Table summarising digital LUC units in terms of key attributes.

LUC Class	Reg. luc unit	Suite	Key characteristics										
			Rock (Pm)	soil (Order)	Slope	soil depth (cm)	TopStones	texture	perm	drainage	erosion	comments	Soil MU
2	2e1	6. young basalt	basaltic, or tephra /X	L, B (N, X)	A, A+B	md >45<100	<5%, 1 or 2	zl, fsl, plus	m, m/r	i to w	0; 1 R,W, Sh	fertile, what are the real diffs bt 2e1 & 2s1? MU LOT_1	MU LOT_1
new	2e1b	6. young basalt	basaltic Vo	BOT	A, A+B	d<100	<5%, 1 or 2	zl, fsl, plus	m, m/r	mw to i	0; 1 R,W, Sh	fertile, what are the real diffs bt 2e1 & 2s1? MU_BOT_1_2	companion LUC 2 for MU_BOT_1_2 Not Used
new	2e1c	6. young basalt? Tephric soils /Ultic paleosol on Gw OR Vu?	tephra /wGw OR Vu	LOM	A, A+B	md >45<100	<5%, 1 or 2	zl, fsl, plus	m, m/r	i to w	0; 1 R,W, Sh	fertile, what are the real diffs bt 2e1 & 2s1? MU LOM_1; MU LOM_2	companion luc 2s for MU LOM_1; MU LOM_2; Not Used
	2s1	6. young basalt	basaltic	L, (N, X)	A, A+B	md >45<100	<5%, 1 or 2	zl, fsl, plus	m, m/r, m/s	i to w	0; 1 R,W, Sh	fertile, MU LOM_1; MU LOM_2	LUC 2 for MU LOM_1; MU LOM_2?
new	2s1b	6. young basalt	basaltic, Vo	BOT	A, A+B	d>100	<5%, 1 or 2	zl, fsl, plus	m, m/r, m/s	mw to i	0; 1 R,W, Sh	fertile, BOT_1_2	BOT_1_2
	2w1	2a. alluvial low terraces	mixed Al, Af	R (B, N)	A, B	d, md, >45	<5%, 1 or 2	zl, fsl, cl?	m, m/s	i to mw	0-1 Sb, D; 1-2 Sb, D	Recent soils. I to MW drained. Flooding risk	companion luc 2 for MU_RT_1_2_3? MU BOM_3_4? Not used
	2w2	2b. alluvial low terraces with gley soils	mixed Al, Af	G	A (B)	d, md, >45	<5%, 1 or 2	zl, fsl, cl?	m, m/s	i	0; 0-1 Sb, D	Gley soils that can be drained. MU GO_al?	companion LUC 2 for MU GO_al? Not used
3	3e1	6. young basalt	basaltic	L, B (N, X)	B+C, C+B	s or d >20<45 (<100)	<35%, 1,2,or 3	zl, fsl, plus	m, m/r, m/s	i to w	0; 1Sh, R	fertile, erosion considered to be the major limitation; MU LOT_1	MU LOT_1
new	3e1b	6. young basalt? Tephric soils /Ultic paleosol on Gw	tephra /wGw	LOM	C	s or d >20<45 (<100)	<35%, 1,2,or 3	zl, fsl, plus	m, m/r, m/s	i to w	0; 1Sh, R	fertile, erosion considered to be the major limitation; MU LOM_1; MU LOM_2	MU LOM_1; MU LOM_2
	3e3	4a. Interbedded & massive sandstone & mudstone	Ac, Sm, Ac+Sm	Ultic	A, B	s >20<45	<5%, 1 or 2	zl, fsl, plus	m, m/r, m/s	i to w	0-1 Sh, R; 1-2 Sh, R	best of the Ultic soils	MU_UYM_1
	3s1	6. young basalt	basaltic	L (N, X)	A, B	s >20<45	<35%, 2,or 3	zl, fsl, cl?	m/r, r	w	0; 1W,Sh,R	fertile, shallow with surface stones, gravels and boulders	MU_LOT_2
new	3s1b	6. young basalt	basaltic, Vo	BOT	A, B	>100	<35%, 2,or 3	zl, fsl, cl?	m/r, r	mw	0; 1W,Sh,R	fertile, shallow with surface stones, gravels and boulders, BOT_1_2 How do you dT stoniness?	BOT_1_2
new	3s3a	3. Quaternary terraces	Gw + Us, Af	BOM	A, B, C	d>100; md >45<100	<5%, 1 or 2	zl, fsl, cl?	m, m/r, m/s	i to w	0; 1W, Sh, R	dissected terraces, foot slopes	MU 2 BOM_3_4
new	3w1a	2a. alluvial low terraces	mixed Al, Af	R (B, N)	A, B	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m, m/s	i to mw	0-1 Sb, D; 1-2 Sb, D	Recent soils. I to MW drained. Flooding risk	MU_RT_1_2_3
new	3w1b	2a. alluvial low terraces	mixed Al, Af	BOM	A, B	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m, m/s	i to mw	0-1 Sb, D; 1-2 Sb, D	BOM soils. I to MW drained. MU BOM_3_4. Flooding risk unable to be assessed, could be 2w.	MU BOM_3_4.
new	3w2	2b. alluvial floodplains & low terraces with gley soils	mixed Al, Af	G	A (B)	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m, m/s	I	0-1 Sb, D; 1 Sb, D	Gley soils that can be drained. MU GO_al?	MU GO_al
new	4e2b	6. young basalt? Tephric soils /Ultic paleosol on Gw	tephra /wGw	LOM	D, E?	s or d >20<45 (<100)	<35%, 1,2,or 3	zl, fsl, plus	m, m/r, m/s	i to w	0; 1Sh, R	fertile, erosion considered to be the major limitation; MU LOM_1; MU LOM_2	MU LOM_1; MU LOM_2
part	4e6a	4b. Sed Rx, older shattered & sheared argillites & sandstone	Ar, Ms, Ss	UYM	C, B, (D)	d >100	<5%, 1 or 2	zl, cl	m/s	I to p	1Sh, G, T, Ss; 2 Sh, G, T, Ss	downlands - whats the diff Bt 4e6, 4e7, 4e8?	MU UYM_1 on Ar, Sm
part	4e6b	4b. Sed Rx, older shattered & sheared argillites & sandstone	Ar, Ms, Ss	Brown	C, B, (D)	d >100	<5%, 1 or 2	zl, cl	m/s	I to p	1Sh, G, T, Ss; 2 Sh, G, T, Ss	downlands - differences bt N4e6, 4e7, 4e8 are not clear	MU_BOM_1_2_5
part	4e7a	5. Greywacke terrain	Gw	UYM, UYT	C, B, (D)	d >100	<5%, 1 or 2	zl, cl	m/s	I to p	0-1ShG, T, Ss; 2 Sh, G, T,	downlands - whats the diff Bt 4e6, 4e7, 4e8?	MU UYM_1 on Gw
part	4e7b	5. Greywacke terrain	wGw, Gw	BOM	C, D, B, (A)	d >100	<5%, 1 or 2	zl, cl	m/s	I to p	0-1ShG, T, Ss; 2 Sh, G, T,	downlands - differences bt N4e6, 4e7, 4e8 are not clear	MU BOM_1_2_5 on Gw
	4e12a	4g. Podzols on sedimentary rocks, UDM on Ac	Ac	UDM	A, B	d>100	<5%, 1 or 2	zl, cl	m/s	I or p	1-2Sh, T; 2Ef, Ss, T	undulating arable component	MU_UDM_2 (A+B slopes)
	4s1	6. young basalt	basaltic	L, B (N, X)	A, B, C	vs, s >10<45	>5>35%, 2, 3, 4	zl, fsl, cl?	m/r, r	w	0-1; 2Sh, 1W,Sh,R	fertile, shallow with surface stones, gravels and boulders	MU_LOT_2
new	4s4_a	4g. Podzols on sedimentary rocks. UDM on terraces	mixed Al, Af	UDM	B, A (C)	d >100	<5%, 1 or 2	zl, cl	m/s	p to i	0--1 Sh; 1-2Sh, G	split into terrace 4s4_a and downland 4s4_b luc units; MU UDM_1	MU UDM_1, deep component
split a	4w1a	2c. poorly drained floodplains and low terraces	mixed Al, Af, Af+Pt	R	A, B, C	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m, m/s	I to p	0-2 Sb, D; 2 Sb, D	mixed soils with wetness limitation, more like original description	MU_RT_1_2_3
split b	4w1b	2b? alluvial floodplains & low terraces with gley soils	mixed Al, Af, Af+Pt	GO?	A, B	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m, m/s	p	0-2 Sb, D; 2 Sb, D	Gley soils that can be drained. GO_al?	GO_al
	New 4w5	Gley soils associated with tephric LOM, BOM soils on hills	Ac+Sm, Gw, Vu	GOT	C, B, A	d>100	<5%, 1 or 3	zl, fsl, cl?	m, m/s	i	0	GOT_1	GOT_1
5	5s1	6. young basalt	basaltic	LOT, X, B	A, B, C	vs, s >10<45	>35%, 4	zl, fsl, cl?	m/r, r	w (i)	0; 1-2Sh	bouldery soils, drainage may be impeded by underlying basalt. HIGHLY PRODUCTIVE???	MU_LOT_3
6	6e4	6. young basalt	basaltic	L, X, B	D, D+E, E, F	vs, s >10<45	>35%, 4	zl, fsl, cl?	m/r, r	w (i)	0-1; 1-2Ss, Sh	bouldery soils, steep slopes	LOT_4
	6e4b	6. young basalt? tephric /Ultic paleosol on Gw	tephra /wGw	LOM	F, E	s or d >20<45 (<100)	<35%, 1,2,or 3	zl, fsl, plus	m, m/r, m/s	i to w	0-1; 1-2Ss, Sh	steep slopes. MU LOM_1	LOM_1
part	6e7a	4b. Sed Rx, older shattered & sheared argillites & sandstone	Ar, Ms, Ss	UXX, UYM	F, D, E	d >100	<5%, 1 or 2	zl, cl	m/s	I to p	1-2Sh, Ss, Ef, T; 2Ef, G, Ss, T, 3 Sh	Hill country - whats the diff Bt 6e7 and 9, 17, 19?	MU UYM_1 on Ar, Sm
part	6e7b	4b. Sed Rx, older shattered & sheared argillites & sandstone	Ar, Ms, Ss	BOM	F, D, E	d >100	<5%, 1 or 2	zl, cl	m/s	I to p	1-2Sh, Ss, Ef, T; 2Ef, G, Ss, T, 3 Sh	Hill country - whats the diff Bt 6e7 and 9, 17, 19?	MU BOM_1_2_5 on Ar, Sm, and ?Vu?
part	6e9a	5. Greywacke terrain	wGw, Gw	UYM, UYT	E, E+D	d>100	<5%, 1 or 2	zl, cl	m/s	i	1-2Ss, Sh, G, Es; 2 Ss, E, Sh, G	not as steep as 6e17, Ultic soils	MU UYM_1 on Gw, easier slopes
part	6e9b	5. Greywacke terrain	wGw, Gw	BOM	E, E+D	d>100	<5%, 1 or 2	zl, cl	m/s	i	1-2Ss, Sh, G, Es; 2 Ss, E, Sh, G	not as steep as 6e17, Brown soils	MU BOM_1_2_5 on Gw, easier slopes
part	6e17a	5. Greywacke terrain	wGw, Gw	UYM, UYT	E+F, F	d>100	<5%, 1 or 2	zl, cl	m/s	i	1-2Ss, Sh, G; 2 Ss, Sh, G	steeper than 6e9	MU UYM_1 on Gw, steeper slopes
part	6e17b	5. Greywacke terrain	wGw, Gw	BOM	F, F+E	d>100	<5%, 1 or 2	zl, cl	m/s	i	1-2Ss, Sh, G; 2 Ss, Sh, G	steeper than 6e9b, MU BOM_1_2_5 steep hill	MU BOM_1_2_5 steep hills on Gw
part	6e19a	4d. Crushed argillite. UDM on Ac	Ac	UDM_2	C, D, E	d or vs	<5%, 1 or 2	zl, cl	m/s	I to p	1-3 G, Sh, Ss; 3G, Sh, Ss	C to E slopes	MU_UDM_2 (>B <F slopes)
new	6e20	4d. Crushed argillite	Ac	BOM	F, G	d or vs	<5%, 1 or 2	zl, cl	m/s	I to p	1-3 G, Sh, Ss; 3G, Sh, Ss	F, G slopes	MU_BOM_1_2_5
	6s1	6. young basalt	basaltic	LOT, X, B	A, B, C, D, E	vs, s >10<45	>35%, 4	zl, fsl, cl?	m/r, r	w (i)	0-1Sh; 1Sh	bouldery soils, drainage may be impeded by underlying basalt	MU_LOT_3; MU_LOT_4
new	6s5_b	4g. Podzols on sedimentary rocks? UDM on terraces	mixed Al, Af	UDM	B, A (C)	vs <20	<5%, 1 or 2	zl, cl	m/s	p	0--1 Sh; 1-2Sh, G	split into terrace 6s5_b and downland 6s5_a luc units; MU_UDM_1	MU_UDM_1 v shallow component
	6w1a	2c. poorly drained floodplains and alluvial low terraces	mixed Al, Af	R, (B),	A	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m/s, s	p	0-2Sb, D; 0-2 Sb, D2-3Sb	frequent flooding OR permaently high WT	LUC 6w for MU_RF_1_2_3
new	6w1b	2b? poorly drained floodplains and alluvial low terraces	mixed Al, Af, Af+Pt	GO?	A, B	d, md, s >20	<5%, 1 or 2	zl, fsl, cl?	m/s, s	p	0-2Sb, D; 0-2 Sb, D2-3Sb	frequent flooding OR permaently high WT. LUC 6 on flood risk	GO_al
new	New 6w4	Acid Gley soils associated with Ultic hill soils	Ar or Ac+Sm	GOA	B, A, C	d >100	<5%, 1 or 2	zl, fsl, cl?	m/s, s	p	0	UYM + GOA_1?	GOA_1
new	New 6w5	Gley soils associated with tephric LOM, BOM soils on hills	Ac+Sm, Gw, Vu	GOT	C, B, A	d >100	<5%, 1 or 2	zl, fsl, cl?	m/s, s	p	0	GOT_1	GOT_1
7	7e8	4d. Crushed argillite. UDM on Ac	Ac	UDM	F	d or vs	<5%, 1 or 2	zl, cl	m/s	I to p	1-3 G, Sh, Ss; 5G, 4Sh, Ss	F slopes	MU_UDM_2 (>E slopes)
new	7s1	6. young basalt	basaltic	LOT	C, A, B	vs, s >10<45	>70%, 4	zl, fsl, cl?	m/r, r	w	0-1; 2Sh, 1W,Sh,R	fertile, shallow with surface stones, gravels and boulders	MU_LOT_3

Appendix 3 – Traditional Mapping LUC Report (LandVision Limited)

Ministry for Primary Industries
Manatū Ahu Matua

Use of modern technology including LiDAR to update the New Zealand Land Resource Inventory

Appendix three

MPI Technical Paper No: 2018/51

Prepared for Craig Trotter

by James Barringer, Ian Lynn, Manaaki Whenua – Landcare Research, Lincoln; Les Basher, Manaaki Whenua – Landcare Research, Nelson; Scott Fraser, Malcolm McLeod, Robbie Price, Manaaki Whenua – Landcare Research, Hamilton; James Shepherd, Raphael Spiekermann, Manaaki Whenua – Landcare Research, Palmerston North; Lachie Grant, LandVision, Nelson.

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Landcare Research Contract Report:	LC 3091

Extended Legend

Northland LUC Mapping Project

For LandCare Research

February 2017

LandVision Ltd

PO Box 7191

WANGANUI

1 TABLE OF CONTENTS

2 BACKGROUND INFORMATION

LandCare Research commissioned LandVision Ltd to undertake paddock scale LUC mapping on approximately 1,000 ha in Northland as part of a wider LUC mapping project.

This report is the extended legend for the associated GIS shape file for the completed mapping work.

3 OBSERVATIONS / COMMENTS

As part of the field mapping process the following observations or comments are made:

1. The main purpose of the mapping was for LUC Units. In determining these all five inventory factors were mapped at the paddock scale. The inventory factors were used to generate the LUC units.
2. The mapping scale occasionally varied according to access and vegetation cover. Generally the mapping scale for pastoral units was around 1:8,000 whilst this stretched out to about 1:12,000 for forested or indigenous bush/scrub with limited access.
3. We tried to name the soils as per the information provided by LandCare Research. Some were of better fit than others. When we are unfamiliar with the local soils and there is inadequate information to properly determine them we would not try to identify the soil name but number them in the legend to represent those shown on the map. The properties should still represent that described in the LUC unit description despite not having a name.
4. The total area mapped was around 1,080 ha. This is about 140 ha more than originally anticipated and the increase more often came about by adjusting to the property boundary. There was at least one lifestyle block that was programmed to be mapped but was not due to inability to make contact with the owner.
5. The aerial photo was of high resolution but considered 'very flat' for field mapping. Further to this the field maps need to extend well beyond the boundary so you can see the bigger landscape features. Many of these blocks were on the edge of the aerial photo and did not provide this.
6. Four additional LUC units were used beyond the Northland LUC suite as it was felt that the detail from paddock scale mapping was not being separated out adequately. These included IIIw5, IIIe6, Ve1 and VIe20 units.
7. We also used an additional erosion type to the LUC handbook – Pugging and treading damage. The severity recorded was based on that for surface erosion types and overall the areas with pugging damage were extensive. It was felt this resulted in significant production loss through reduced soil drainage and soil moisture holding ability. There was also a potential increase in surface wash into waterways. There was very little evidence of any 'avoid, remedy or mitigate' measures for this in the study area.

4 LUC DESCRIPTIONS

The LUC descriptions for the area are shown in the following table.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
IIe1 Fertile free-draining red and brown loam soils developed on gently undulating to undulating slopes on young basalt scoria, basaltic lava flows and occasional ash. Soils are generally deep. 	Volcanic ash. Volcanic ash and lava flows.	YT1	0-7^0	• Contour. • Access. • Deep, fertile soils. • Free-draining.	• Slight surface erosion risk under cultivation. • Seasonal soil moisture deficiency.	Intensive pastoral farming.	• Contour. • Access. • Deep, fertile soils. • Free-draining.
IIIe1 Undulating to rolling slopes on young basaltic lava flows, basaltic scoria and occasional ash with brown and red loam soils. Smaller areas of moderately leached brown granular loam and clay soils on volcanic alluvium may be included on undulating terrace surfaces, often proximal to old andesitic-basaltic volcanics and mountainous terrain.	Volcanic ash and scoria. Volcanic ash and alluvium.	KB+PK KB+PCr PR+PK OW+WK	4-15^0	• Contour. • Access. • Free-draining. • Good natural fertility.	• Moderate surface erosion risk under cultivation. • Seasonal soil moisture deficiency.	Intensive pastoral farming.	• Contour cultivation practices recommended. • Avoid over cultivation and structural degradation of soils. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required in some areas.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
IIIe3 Gently rolling to rolling slopes on deeply weathered interbedded sandstones and mudstones with occasional massive sandstones and mudstones. Sandstones and mudstones sometimes partially veneered by reworked rhyolitic tephra and Quaternary-aged unconsolidated clays and silts. Soils are yellow-brown earths, and weakly podzolised yellow-brown earths. 	Volcanic ash overlying podzolised mudstone and argillite. Volcanic ash overlying mudstone and crushed argillite.	MR MR+WKap RAI H RAI WK+OW	4-15^{0}	• Contour. • Access. • Free-draining. • Good natural fertility.	• Moderate surface erosion risk under cultivation. • Seasonal soil moisture deficiency. • Finer textured soils are prone to pugging and compaction damage from heavy cattle and machinery when wet.	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended. • Control runoff using techniques such as grassed waterways and diversion banks. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Avoid over cultivation and structural degradation of soils. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required in some areas. •

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
IIIe6 Undulating to rolling slopes within subdued rolling landscape on greywacke. Soils are yellow-brown earths. 	Greywacke (Gw)	MR WF+MR	4-15^0	• Contour. • Access. • Good natural fertility.	• Slight to moderate to severe surface erosion risk under cultivation. • Seasonal soil moisture deficiency. • Finer textured and impeded drainage soils are prone to pugging and compaction damage from heavy cattle and machinery when wet.	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended. • Control runoff using techniques such as grassed waterways and diversion banks. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Avoid over cultivation and structural degradation of soils. • Maintain pasture cover through fertility and stock management. • Consider and review stocking rate to minimise overstocking and concentrated stock movements.
IIIw1 Flat to undulating floodplains, valley plains and low to intermediate terraces with recent soils, and occasional yellow-brown earths and brown granular loams and clays, on sedimentary and volcanic alluvium. Runoff from surrounding hills and moderately high water table increase the wetness limitation.	Alluvium.	YA WF	0-7^0	• Contour. • Access. • Good natural fertility. • Reasonable natural drainage.	• Potential for slight to moderate streambank erosion and deposition. • Finer textured soils are prone to pugging and compaction damage from heavy cattle and machinery when wet. • Potential for occasional	Intensive pastoral farming.	• Care with heavy cattle and machinery to minimise risk of pugging and compaction damage.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
					flooding.		
IIIw2 Poorly drained flat areas within floodplains, valley plains and on low terraces with gley fertile soils developed on sedimentary and volcanic alluvium. 	Alluvium. Alluvium and volcanic ash.	PCr WFm KR1 KR1+KR2	$0-3^{0}$	• Contour. • Access. • Good natural fertility.	• Potential for slight to moderate streambank erosion and deposition. • Finer textured, poorly drained soils are highly prone to pugging and compaction damage from heavy cattle and machinery when wet. • Potential for occasional flooding.	Intensive pastoral farming with drainage.	• May require flood protection with streambank protection and stopbanks. • Drainage required to improve potential productive capacity and cropping versatility. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Maintain vegetation clearance within stream and river channels. • Shelterbelts.
IIIw5 Flat to undulating areas with imperfectly to poorly drained soils developed on volcanic ash.	Volcanic ash and alluvium.	YTw	$0-3^{0}$	• Contour. • Access. • Reasonable natural fertility.	• Potential for slight wind and sheet erosion if cultivated. • Impeded soil drainage makes it prone to pugging and compaction damage from heavy cattle and	Intensive pastoral farming with drainage.	• Drainage required to improve potential productive capacity. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
					machinery. • Potential for occasional surface ponding.		
IIIs1 Flat to rolling slopes on relatively young basalt rocks with numerous stones, gravels and boulders scattered over surface and throughout soil profile. Soils are usually free-draining, light textured and often range from 30-90cm deep over hard weathered basalt rock. Gravels and boulders typically comprise 10-35% by volume of soil profile. 	Volcanic ash and scoria.	PCr WFm PK+PR	0-7^0	• Contour. • Access. • Good natural drainage. • Good cattle winter country.	• Stoniness and shallow soil depth are moderate limitations to arable use. • Potential for slight wind, sheet and rill erosion under cultivation. • Seasonal soil moisture deficiency. • May require irrigation to maintain crops during dry periods.	Intensive pastoral farming.	• May require irrigation to maintain crops during dry periods. • Stone picking may be required to enable cultivation for crop establishment and/or pasture renewal. • Minimum tillage practices recommended. • Avoid over cultivation and structural degradation of soils. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required in some areas.
IIIs2 Flat to undulating slopes on deeply weathered basalt rocks and	Unconsolidated sandstones and fractured greywacke.	KE+MR KE+YA WK+KE	0-7^0	• Contour. • Access.	• Potential for slight sheet and rill erosion under cultivation.	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
occasional ash. Soils moderately to strongly leached brown loams. Soils of lower fertility than those of Class II units, have poorer drainage characteristics and are subject to seasonal soil moisture deficiencies, giving moderate limitations for arable use. 					• Seasonal soil moisture deficiencies. • Low natural fertility. • High phosphate retention soil. • Potential for pugging and compaction damage from heavy cattle and machinery.		• Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Avoid over cultivation and structural degradation of soils. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements.
IIIs3 Flat to gently rolling slopes on intermediate to moderately high Quaternary terraces and plains on alluvium associated with other sedimentary lithologies, such as limestone, sandstone and mudstone. Surficial deposits include water sorted tephras. Soils spatially complex, and include yellow-brown loams, yellow-brown earths, brown granular loams and redzinas.	Loess and old alluvium.	KR MR+KR RAI	0-7^{0}	• Contour. • Access. • Some areas of high fertility. • Some areas of good natural drainage.	• Potential for slight rill and sheet erosion under cultivation. • Variability of soil drainage and fertility. • The poorer drained soils are prone to pugging and compaction damage from heavy cattle and machinery.	Intensive pastoral farming with some drainage.	•

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
IVe2 Rolling to strongly rolling slopes on young basaltic rock and ash. Soils strongly leached brown and red loams which may be affected by moisture deficiencies, particularly during summer months. 	Volcanic ash and scoria. Volcanic ash overlying crushed argillite.	PK+KB H+AP1 PK+PR	8-20^0	• Contour. • Access. • Free-draining. • Good natural fertility.	• Moderate to severe surface erosion risk under cultivation. • Potential for slight to moderate sheet, soil slip, rill, gully and wind erosion. • Seasonal soil moisture deficiency.	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended. • Control runoff using techniques such as grassed waterways and diversion banks and plan for runoff interception zones. • Avoid over cultivation and structural degradation of soils. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Maintain pasture cover through fertility and stock management. • Seasonal irrigation may be required in some areas.
IVe5 Rolling to strongly rolling slopes	Loess over massive silty sandstone and	MR MR+WKap	8-20^0	• Contour. • Access.	• Moderate to severe surface erosion risk	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
with subdued rolling to hilly landscape (e.g. lower hillslopes), downlands on strongly weathered interbedded and occasionally massive sandstones and mudstones. Soils typically weakly to moderately podzolised yellow-brown earths. 	mudstone.	MR+RAI H RAI WK+OW		• Free-draining. • Good natural fertility.	under cultivation. • Potential for slight to moderate sheet, soil slip, tunnel gully earthflow and rill erosion. • Seasonal soil moisture deficiency. • Finer textured soils are prone to pugging and compaction damage from heavy cattle and machinery when wet.		recommended. • Control runoff using techniques such as grassed waterways and diversion banks. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Avoid over cultivation and structural degradation of soils. • Maintain pasture cover through fertility and stock management. • Space plant trees in erosion-prone areas and pair plant trees in gullies. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required in some areas.
IVe6 Gently rolling to strongly rolling slopes within a subdued rolling to hilly landscape on fractured and sheared argillites, sandstones and mudstones. Occasionally complexed with shattered and	Crushed argillite.	AP1+H WK+OW	8-20^0	• Contour. • Access. • Good natural fertility.	• Moderate to severe surface erosion risk under cultivation. • Potential for moderate sheet, gully, soil slip,	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended. • Control runoff using techniques such as grassed waterways and

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
sheared volcanic deposits. Soils yellow-brown earths and occasionally associated with brown granular loams and clays or brown loams. 					earthflow and earthslip erosion. • Soils generally imperfectly to poorly drained. • Finer textured and poorly drained soils are prone to pugging and compaction damage from heavy cattle and machinery when wet.		diversion banks. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Avoid over cultivation and structural degradation of soils. • Maintain pasture cover through fertility and stock management. • Space plant trees in erosion-prone areas and pair plant trees in gullies. • Shelterbelts. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required in some areas.
IVe7 Gently to strongly rolling slopes within subdued rolling to hilly landscape on greywacke. Soils are yellow-brown earths.	Greywacke (Gw)	MR+RA	8-20^{0}	• Contour. • Access. • Good natural fertility.	• Moderate to severe surface erosion risk under cultivation. • Potential for slight to moderate sheet, soil slip, tunnel gully earthflow and rill erosion.	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended. • Control runoff using techniques such as grassed waterways and diversion banks. • Care with heavy cattle and machinery to minimise risk of

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
					• Seasonal soil moisture deficiency. • Finer textured and impeded drainage soils are prone to pugging and compaction damage from heavy cattle and machinery when wet.		pugging and compaction damage. • Avoid over cultivation and structural degradation of soils. • Maintain pasture cover through fertility and stock management. • Space plant trees in erosion-prone areas and pair plant trees in gullies. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization.
IVe8 Gently rolling to rolling slopes within subdued rolling landscape on relatively unstable fractured and sheared mixed sedimentary lithologies, with high proportion of mudstone. Land surface is typically hummocky and irregular with broken terrain caused by mass movement. Typical soils are yellow-brown earths and podzolised yellow-brown earths.	Sheared mixed lithologies.	AP	8-20^0	• Contour. • Access. • Good natural fertility.	• Moderate to severe surface erosion risk under cultivation. • Potential for slight to moderate sheet, soil slip, tunnel gully earthflow and rill erosion. • Seasonal soil moisture deficiency. • Finer textured and impeded drainage soils	Intensive pastoral farming.	• Minimum tillage and contour cultivation practices recommended. • Control runoff using techniques such as grassed waterways and diversion banks. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Avoid over cultivation and structural degradation of soils.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
					are prone to pugging and compaction damage from heavy cattle and machinery when wet. • Soils have poor internal drainage.		• Maintain pasture cover through fertility and stock management. • Space plant trees in erosion-prone areas and pair plant trees in gullies. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization.
IVw1 Flat to gently undulating areas on floodplains, valley plains and low terraces on alluvium, with continuing severe wetness or flooding limitation to arable use. Severe limitations to cropping because of runoff from adjacent hills, flooding of streams and high water tables. Potential for moderate streambank erosion and deposition. Recent soils on alluvium characteristic of this unit.	Alluvium and colluvium.	YU YU+YUy PCm WU KR2	0-7^{0}	• Contour. • Access. • Reasonable natural fertility. • Holds on longer during dry periods.	• Potential for slight to moderate streambank erosion and deposition. • Soils are generally poorly drained. • Soils are highly prone to pugging and compaction damage from heavy cattle and machinery when wet. • Potential for occasional flooding.	Intensive pastoral farming with drainage.	• May require flood protection with streambank protection and stopbanks. • Drainage and drain maintenance required however high water tables, periodic flooding and runoff from surrounding hills can make this difficult. • Care with heavy cattle and machinery to minimise risk of pugging and compaction damage. • Maintain vegetation clearance within stream and river channels.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
IVw3 Flat to gently undulating slopes with organic soils on peat and alluvium. Typically narrow peat-filled valleys with continuing severe wetness limitation subject to occasional flooding. 	Alluvium and peat.	YUy	0-7^0	• Contour. • Access. • Reasonable natural fertility. • Holds on longer during dry periods.	Potential for slight streambank erosion and deposition. High water table. Soils are generally poorly to very poorly drained. Soils are highly prone to pugging and compaction damage from heavy cattle and machinery when wet. • Potential for occasional flooding.	Intensive pastoral farming with drainage.	• Care with heavy cattle.
IVs1 Flat to rolling slopes on young basalt rock with numerous stones, gravels and boulders scattered over land surface and throughout the soil profile. Soil depths often range from 15 to 60cm over hard weathered basalt rock. Surface characterized	Volcanic ash and scoria.	PK+KB PR+PK	0-15^0	• Contour. • Access. • Good natural drainage. • Good cattle winter country.	• Stoniness and shallow soil depth are severe limitations to arable use. • Potential for moderate sheet and slight wind erosion.	Intensive pastoral farming.	• Contour. • Access. • Good natural drainage. • Good cattle winter country.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
by outcrops of basalt boulders often forming hummocky mounds. Gravel/ boulder content in some areas can be greater than 35% by volume of soil profile. 					• Potential for slight wind, sheet and rill erosion under cultivation. • Seasonal soil moisture deficiency. • May require irrigation to maintain pasture and crops during dry periods.		
Ve1 Strongly to moderately steep rolling slopes forming subdued hilly terrain on interbedded and occasionally massive sedimentary lithologies excluding greywacke and limestone. Rock types include sandstones, mudstones and conglomerate. Soils are yellow-brown earths. Minor argillite or jointed mudstone may be included where rock types are complexed or closely associated with interbedded sandstone and mudstone or massive sandstone.	Patchy volcanic ash overlying mudstone and crushed argillite. Mudstone and crushed argillite.	MR+MRH AP1 AP+H RAI	16-25^{0}	• Contour. • Reasonable natural drainage. • Reasonable natural fertility.	• Potential for slight to moderate mass movement and gully erosion. • Finer textured soils are prone to pugging damage from heavy cattle when wet.	Pastoral farming with soil conservation.	• Control runoff using techniques such as grassed waterways and diversion banks. • Space plant trees in erosion-prone areas and pair plant trees in gullies. • Care with heavy cattle to minimise risk of pugging damage. • Maintain pasture cover through fertility and stock management. • Consider and review stocking rate to minimise overstocking and concentrated stock movements.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
Vs1 Undulating to gently rolling slopes on relatively young basalt rock with numerous stones, gravels and boulders scattered over land surface and throughout the soil profile. Soil depths may be less than 20-30cm in some areas, and gravels and boulders often comprise greater than 35% of the soil profile. 	Scoria and lava flows.	PK+Br PK PK+OWb	0-15^0	• Contour. • Responds well to fertilisers. • Generally good natural drainage.	• Potential for slight to moderate sheet erosion. • High stone content and shallow soils limit cultivation and crop production. • Seasonal soil moisture deficiency. • Drainage can be impeded by underlying basalt.	Intensive pastoral farming.	• Control runoff using techniques such as grassed waterways and diversion banks. • Maintain pasture cover through fertility and stock management. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required.
Vle4 Strongly rolling to steep slopes on basalt flows and basaltic scoria. Includes scoria cones, mounds,	Scoria cones and lava domes.	PK+OWb OWb+PK	16-25^0 Some 26-35^0	• Stable hill country • Good natural fertility. • Good natural	• Potential for slight to moderate soil slip and sheet erosion and slight gully erosion.	Pastoral farming with soil conservation.	• Control runoff using techniques such as grassed waterways and diversion banks. • Maintain pasture cover through

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
lava domes, and escarpments bordering terraces and plains. 				drainage.	• Seasonal soil moisture deficiency.		fertility and stock management. • Space plant trees in erosion-prone areas and pair plant trees in gullies. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization.
VIe7 Strongly rolling to moderately steep slopes forming hilly terrain. Shattered and sheared argillite complexed with sandstone and bedded mudstone. Minor constituents of crushed argillite (siliceous claystone) and/or jointed mudstone also recorded. Sandstones and mudstones often deformed showing evidence of shearing and shattering. Faulting or folding often proximal to land on sheared lithologies. Soils are yellow brown earths.	Crushed argillite and mudstone. Patchy ash over crushed argillite and mudstone.	YCH+WK	16-25^0	• Reasonable natural fertility. • Reasonable drainage.	• Potential for moderate earthflow, gully, soil slip, tunnel gully and earthslip erosion and severe sheet erosion. • Seasonal soil moisture deficiency. • Finer textured soils are prone to pugging damage from heavy cattle when wet. • Bare ground can be difficult to re-vegetate.	Pastoral farming with soil conservation.	• Care with heavy cattle to minimise risk of pugging damage. • Space or block plant trees in erosion-prone areas and pair plant trees in gullies.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
VIe8 Moderate to steep slopes forming hilly to steepland terrain where interbedded sandstones and mudstones are dominant lithologies with less extensive areas on massive sandstones, mudstones and conglomerate. Rock types, often of Miocene age, may be associated with minor constituents of argillite and jointed mudstone. 	Silty sandstone and mudstone.	MRH MRH+OG	21-35^0	• Reasonable natural fertility. • Reasonable drainage.	• Potential for moderate earthflow, gully, soil slip, tunnel gully and earthslip erosion and severe sheet erosion. • Finer textured soils are prone to pugging damage from heavy cattle when wet. • Bare ground can be difficult to re-vegetate.	Pastoral farming with soil conservation.	• Control runoff using techniques such as grassed waterways and diversion banks. • Maintain pasture cover through fertility and stock management. • Space or block plant trees in erosion-prone areas and pair plant trees in gullies. • Care with heavy cattle to minimise risk of pugging damage. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization. Avoid undercutting slopes.
VIe9 Strongly rolling to moderately steep slopes forming hilly terrain on	Greywacke (Gw)	RA+MR	16-25^0	• Low natural fertility. • Reasonable	• Potential for moderate soil slip, earthslip, sheet, earthflow and	Pastoral farming with soil	• Control runoff using techniques such as grassed waterways and

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
deeply weathered greywacke and greywacke. Soils are yellow-brown earths. 				drainage.	gully erosion. • Seasonal soil moisture deficiency. • Bare ground can be difficult to re-vegetate.	conservation.	diversion banks. • Maintain pasture cover through fertility and stock management. • Space or block plant trees in erosion-prone areas and pair plant trees in gullies. • Oversow and fertilise slip scars. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization. Avoid undercutting slopes.
VIe12 Gently rolling to moderately steep slopes form rolling to moderately steep (hilly) terrain on fractured and sheared mixed lithologies, often a complex of multi-coloured sedimentary rock types (e.g. argillite, sandstone, mudstone) and minor volcanic rock (e.g. ancient volcanics). Rock types often allochthonous, with relatively high proportion of mudstone. Terrains are characteristically unstable showing hummocky slope profiles	Sheared mixed lithologies.	AP	$8\text{-}25^0$	• Reasonable natural fertility. • Contour albeit broken.	• Potential for moderate to severe earthflow and gully erosion and moderate tunnel gully, sheet, soil slip and earthslip erosion. • Poor drainage due to broken slopes causing disrupted drainage. • Prone to pugging and treading damage from heavy cattle.	Pastoral farming with soil conservation.	• Control runoff using techniques such as diversion channels, grassed waterways and graded banks. • Maintain pasture cover through fertility and stock management. • Space or block plant trees in erosion-prone areas and pair plant trees in gullies and tunnel gullies. • Subsurface drainage on easier slopes. • Care with heavy cattle to

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
with earthflow, gully, soil creep and soil slip erosion forms.							minimise risk of pugging and treading damage. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization. Avoid undercutting slopes.
VIe17 Moderate to steep slopes forming steep hilly terrain on greywacke rock, and occasional deeply weathered greywacke. Soils are yellow-brown earths and related steepland soils. A steeper version of VIe9. 	Greywacke (Gw)	RAH	21-35^0	• Low natural fertility. • Reasonable drainage.	• Potential for moderate soil slip, sheet and gully erosion and slight earthslip erosion. • Seasonal soil moisture deficiency. • Bare ground can be difficult to re-vegetate.	Pastoral farming with soil conservation.	• Control runoff using techniques such as grassed waterways and diversion banks. • Maintain pasture cover through fertility and stock management. • Space or block plant trees in erosion-prone areas and pair plant trees in gullies. • Oversow and fertilise slip scars. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization. Avoid undercutting slopes.
VIe19 Rolling to moderately steep slopes	Crushed argillite.	APH+PPH PPH+AP	16-25^0	• Moderate natural fertility.	• Potential for severe gully, sheet, soil slip	Pastoral farming with soil	• Control runoff using techniques such as grassed waterways and

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
forming steep hilly terrain on fractured and sheared - 'crushed' - argillites, commonly referred to as siliceous shale or siliceous claystone. Soils are podzolised yellow-brown earths and also podzols on dacite-rhyolite rock. 		PPH+WKH			and earthslip erosion. • Soils are strongly leached and podzolised. • Finer textured and poorer drained soils are prone to pugging damage from heavy cattle when wet.	conservation. Erosion control forestry.	diversion banks. • Deep ripping may be required to break up hard layers at depth. • Maintain pasture cover through fertility and stock management. • Space or block plant trees in erosion-prone areas. • Retirement and block planting of gullies. • Oversow and fertilise slip scars. • Care with heavy cattle to minimise risk of pugging damage. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Careful planning of earthworks to avoid soil destabilization. Avoid undercutting slopes.
VIe20 Strongly rolling to steep banks on elevated river terraces. Found adjacent to rivers and streams.	Alluvium over gravels.	YA+Br (bare rock) PCm+PCr YCH+KR2	16-35^0	• Potential biodiversity values. • Gravel resource.	• Potential for severe streambank erosion and moderate deposition. • Friable recent soils prone to disturbance and damage from heavy cattle.	Riparian retirement.	• Fence to exclude stock from streambanks. • Willow plantings on the pressure points of the streambank. • Enhance streambank with planting of riparian species.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
Vlw1 Low lying flat to gently undulating land within floodplains, valley plains, low terraces, and narrow valleys on alluvium with a continuing severe wetness limitation. Subject to frequent flooding or a permanently high water table. Typical soils, often mottled, are recent soils and yellow-brown earths. 	Colluvium. Alluvium and colluvium.	OG YUy KR+YUy	0-3^{0}	• Contour. • Potential biodiversity values. • Natural filter for sediment and nutrients.	• Potential for moderate to severe streambank erosion and deposition. • Permanently high water table. • Friable recent soils prone to disturbance and damage from heavy cattle. • Extreme pugging risk from cattle. Potential stock trap.	Riparian / wetland retirement.	• Fence to exclude stock from streambanks. • Willow plantings on the pressure points of the streambank. • Enhance with planting of wetland and riparian species.
Vlw3 Flat to gently undulating with organic soils on peat and alluvium. Includes low lying flats, narrow valleys, plains, inter-dune swamps,	Peat and colluvium.	OG	0-3^{0}	• Contour. • Potential biodiversity values. • Natural filter for	• Potential for slight to moderate streambank erosion and deposition. • Friable recent soils	Riparian / wetland retirement.	• Fence to exclude stock from streambanks. • Willow plantings on the pressure points of the streambank.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
etc. areas on peat often drained and reclaimed but have continuing or prolonged wetness limitation due to flooding or permanently high water table. 				sediment and nutrients.	prone to disturbance and damage from heavy cattle. • Permanently high water table. • Extreme pugging risk from cattle. Potential stock trap.		• Enhance with planting of wetland and riparian species.
VIs1 Flat to rolling with some strongly rolling to moderately steep slopes on relatively young basalt flow terrains with numerous stones, gravels and boulders scattered over land surface and throughout soil profile. Soil depths commonly less than 30cm over hard weathered basalt rock, and gravels and boulders typically comprise greater than 35% by volume of soil profile.	Volcanic ash and scoria.	PK+KB PK+OWb OWb+Br (bare rock) OWb+PK+Br (bare rock)	0-25^0	• Contour. • Relatively stable land. • Good natural drainage. • Good cattle winter country.	• Potential for slight sheet and gully erosion. • Unsuited to cultivation due to presence of stones and boulders. • High stone content and shallow soils limit cultivation and crop production. • Seasonal soil moisture deficiency. • Low natural fertility.	Pastoral farming.	• Control runoff using techniques such as grassed waterways and diversion banks. • Maintain pasture cover through fertility and stock management. • Consider and review stocking rate to minimise overstocking and concentrated stock movements. • Seasonal irrigation may be required.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
							
VIIe8 Moderately steep to steep slopes, often with repeated pattern of incision, forming steep hilly and mountainous terrain on fractured and sheared-crushed argillites. Typically has acute narrow ridges and abrupt, steep hill slopes prone to sheet and gully erosion. Hillslopes are often scarred by slips, and stream heads have masses of slumped debris. Typical soils are podzolised yellow-brown earths. Represents steeper or more erodible parts of VIe19. 	Crushed argillite.	H+PPH+WKH	21-35^{0}	• Generally sheltered country.	• Potential for extreme gully erosion, very severe sheet and soil slip erosion, moderate earthslip and rill erosion and slight earthflow erosion. • Bare ground difficult to revegetate. • Prone to weed infestation (e.g. gorse).	Erosion control forestry.	• Long term erosion control from erosion control forestry. • Control runoff and employ caution with tree planting, road construction and scrub clearance. • Install adequate drains and culverts to minimise soil erosion and maintain water quality. • Retirement and block planting of gullies. • Careful planning of earthworks to avoid soil destabilization. Avoid undercutting slopes.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
VIIw1 Low-lying, flat areas on floodplains and low terraces (river flats) with water tables at or near surface. Includes many alluvial river flats and swamps with continuing severe wetness limitation and subject to frequent flooding or permanently high water table. Recent soils, often mottled, on alluvium or alluvium and peat. Represents areas difficult to drain, land used for flood retention, and areas generally of high flood risk. 	Fine sedimentary and volcanic alluvium.	OG OG+Owb	0-3^{0}	• Contour. • Access.	• Potential for slight to severe streambank erosion and deposition. • Subject to frequent flooding or has a permanently high water tables. • Soils generally poorly drained. • Prone to severe pugging from stock.	Extensive pastoral farming. Retirement and flood retention area.	• Management should be considered on a long-term basis and planning should take whole catchment into account. • If pastoral farming continues, take extreme care to minimise pugging damage from stock. • Careful management for flood detention
VIIw2 Peat-filled valleys, plains, and coastal swamps with water tables at or near the surface, areas frequently flooded, have continuing wetness limitation. Peat is strongly acid and very poorly drained.	Peat and colluvium.	OGd	0-3^{0}	• Contour. • Potential biodiversity values. • Natural filter for sediment and nutrients.	• Potential for slight to moderate wind and sheet erosion and deposition and slight gully erosion. • Friable recent soils prone to disturbance and damage from	Wetland retirement.	• Fence to exclude stock. • Enhance with planting of wetland species.

Description	Parent material	Dominant soil	Slope (degrees)	Strengths	Weaknesses	Land use suitability	Conditions of use
					heavy cattle. • Permanently high water table. • Extreme pugging risk from cattle. • Potential stock trap.		

5 LAND RESOURCE INVENTORY DESCRIPTIONS

The land resource inventory factors (rock type, soil type, and slope) are described in the following sections.

5.1 Geology descriptions

The main rock types found on the area are shown in the following table

Rock types found on the property	
	**Crushed Argillite association of rocks (Ac):** Loose or soft clayey, extremely closely ("crushed") material, with various angular indurated rock fragments (cm-sized). This is an association of originally strong bedded or interbedded mudstone (argillite) and associated rocks that have undergone a high degree of deformation. The intense fracturing, shearing and brecciation has reduced the rock mass strength. The high degree of deformation of these rocks and resulting reduction in strength makes crushed argillite susceptible to severe gully and earthflow erosion.
	**Lavas and welded ignimbrites (Vo):** weak to extremely strong, typically fine to medium grained basaltic to rhyolitic volcanic rocks; lavas, welded ignimbrite, shallow intrusives and minor inter-layered pyroclastics. Tertiary age or younger volcanics whose topographic expression (constructional cones, flows, plateaus, domes and sheets) are largely determined by primary layering and jointing. This rock is typically stable and often forms steep bluffy slopes. Rockfall and scree are common where the rock is relatively fresh. With deep weathered mantle, soil slip and sheet erosion are common.
	**Colluvium (Co):** rock fragments and soil material which have accumulated at the base of steep slopes as a result of gravity.
	**Scoria (Sc):** Rough, crusty, solidified lava containing numerous cavities that originated as gas bubbles in the lava while it was still molten.
	**Massive mudstone (Mm):** very weak to weak mudstone, typically massive but sometimes with rare or indistinct bedding, of variable composition. Soil slip erosion is common, with shallow earthflow on the colluvial footslopes.

	**Peat (Pt):** Extremely weak, dark brown or black organic residue mixed with various amounts of mineral matter. Surface or near surface deposits thicker than 50 cm. A widespread Quaternary deposit produced by the partial decomposition and disintegration of vegetation.
	**Ashes older than Taupo ash (Mo):** (pictured) is found on the flat to easy hill country slopes. It is described as compact to very compact, moderately to completely weathered clay-rich, surface or near surface, bedded or massive, ash and some lapilli. Grassed and forested slopes formed on tephra are generally stable where less than 20 degrees. Slopes steeper than 20 degrees are subject to sheet erosion while soil slip or slump erosion may occur with slip planes on weathered layers or tephra interfaces. The soils formed from this ash are typically yellow-brown loams.

5.2 Soils Descriptions

The dominant soil types recorded on the area are described in the following table.

	**Name**: Aponga clay **Soil map symbol**: AP **Grid Reference:** 1681495.74 : 6077879.76 **Photo ID:** 150966 (Dodd) **Vegetation:** Semi improved pasture. **Slope:** Rolling to strongly rolling. **Landscape position:** Rolling to strongly rolling crushed argillite slopes. **LUC Unit:** IIIe3, IVe6,IVe8, Ve1, VIe12 **Parent material:** Crushed argillite. **Drainage status:** Imperfectly to poorly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development:** Weakly to moderately developed. **Pugging susceptibility**: High. **Profile description**: Ah – 21 cm weakly to moderately developed fine nutty blocky light grey (7.5YR 7/1)silty clay loam; on Eg – 20 cm very weakly developed, hard, fine to very fine blocks, comes to powder very easily, white (7.5YR 8/1) sandy clay; on Bt – 30 cm very weakly developed coarse blocky pinkish white (7.5YR 8/2) fine sandy clay with many reddish yellow (10YR 6/6) mottles; on C – Crushed argillite. **Comments**: Yellow brown earth strongly leached to weakly podzolised.

	**Name**: Aponga silty clay loam **Soil map symbol**: AP1 **Grid Reference:** 1689831.02 : 6086006.61 **Photo ID:** 237 (McCulloch) **Vegetation:** Semi-improved pasture**.** **Slope:** Strongly rolling to moderately steep. **Landscape position:** Rolling downlands and easy hill slopes. **LUC Unit**: IVe6, Ve1 **Parent material**: Crushed argillite. **Drainage status:** Imperfectly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: High. **Profile description**: Ah – 20 cm moderately developed, medium nut and crumb, friable when moist, plastic when wet, dark grey 10YR 4/1 silty clay loam; on Bt – moderately developed, medium nut and block, friable when moist, very plastic when wet, yellowish brown 10YR 5/4 silty clay loam with many orange and few gley mottles. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.
	**Name**: Aponga hill soil. **Soil map symbol**: APH **Grid Reference:** 1681428.75 : 6077817.15 **Photo ID:** 150964 (Dodd) **Vegetation:** Forestry and low quality pasture. **Slope:** Moderately steep to steep hill. **Landscape position**: Hill slope **LUC Unit**: VIe19 **Parent material:** Crushed argillite **Drainage status:** Moderately well drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: Low. **Profile description**: Ah – 17 cm weakly developed fine to very fine crumby nut light brownish grey (10YR

	6/2) sandy loam with few 4-6 mm sharp angular argillite chips; on Bh – 14 cm weakly developed fine to very fine crumby nut yellowish brown (10YR 5/6) sandy loam with few 4-6 mm sharp angular chips; on Bw - 33 cm very weakly developed fine to very fine crumby granular brownish yellow (10YR 6/8) loamy sand with many argillite chips; on C – pale yellow (2.5Y 7/4) crushed argillite **Comments**: Moderately to strongly leached.
	**Name**: Hukerenui sandy silt loam **Soil map symbol**: H **Grid Reference:** 1689491.49 : 6085460.50 **Photo ID:** 222 (McCulloch) **Vegetation:** Improved pasture with some kikuyu and paspalum. **Slope:** Undulating to rolling. **Landscape position**: Downlands. **LUC Unit**: IIIe3, IVe2, IVe5 **Parent material:** Volcanic ash overlying crushed argillite. **Drainage status:** Imperfectly to moderately well drained. **Soil consistence:** Friable when moist, slightly plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: Moderate to high. **Profile description**: Ap – 20-25 cm moderately developed, fine to medium nut and crumb, friable when moist, slightly plastic when wet, dark brown 10YR 3/3 fine sandy silt loam; on Bw – 15-20 cm moderately developed, fine to medium nut and crumb, friable when moist, slightly plastic when wet, dark yellowish brown 10YR 4/4 fine sandy silt loam; on C – moderately developed, fine to medium nut and crumb, friable when moist, slightly plastic when wet, yellowish brown 10YR 5/6 fine sandy silt loam. **Comments**: Variant of Soil 1a but with shallower topsoil. High phosphate retention soil. Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

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Name: Kara silt loam

Soil map symbol: KR

Grid Reference: 1692139.44 : 6090580.59

Photo ID: 051 (Simpson)

Vegetation: Improved pasture, kikuyu and some rushes.

Slope: Flat to undulating.

Landscape position: Low old alluvial terrace.

LUC Unit: IIIs3, IVw1, VIw1

Parent material: Loess and old alluvium.

Drainage status: Poorly drained.

Soil consistence: Friable when moist, very plastic when wet.

Degree of topsoil development: Moderately to weakly developed.

Pugging susceptibility: High.

Profile description:

Ap – 25-30 cm moderately to weakly developed, medium to coarse nut and crumb, friable when moist, very plastic when wet, dark grey 10YR 4/1 silty clay loam with few brown mottles; on

Bg – moderately to weakly developed, medium to coarse nut and block, friable when moist, sticky when wet, very pale brown 10YR 8/3 clay loam with many gley and few orange mottles.

Comments: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet.

Management considerations: Extreme care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.
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Name: Kara silty clay loam

Soil map symbol: KR1

Grid Reference: 1683189.14 : 6083772.07

Photo ID: 303 (Ngawhitu)

Vegetation: Improved pasture and some scattered rushes.

Slope: Flat to undulating.

Landscape position: Low, old alluvial terrace.

LUC Unit: IIIw2

Parent material: Old alluvium.

Drainage status: Imperfectly to poorly drained.

Soil consistence: Friable when moist, very plastic when wet.

Degree of topsoil development: Moderately to weakly developed.

Pugging susceptibility: High.
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Profile description:

Ap – 25-30 cm moderately to weakly developed, medium nut and crumb, friable when moist, very plastic when wet, dark grey 10YR 4/1 silty clay loam with few indistinct low chroma mottles; on

Bw – 30-35 cm moderately to weakly developed, medium nut and block, friable when moist, sticky when wet, yellow 10YR 7/6 clay loam with few orange mottles; on

Cg – moderately to weakly developed, medium nut and block, friable when moist, sticky when wet, yellow 10YR 8/6 clay loam with few to many gley and orange mottles.

Comments: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet.

Management considerations: Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

Name: Kara clay loam

Soil map symbol: KR2

Grid Reference: 1682973.26 : 6083750.48

Photo ID: 306 (Ngawhitu)

Vegetation: Semi-improved pasture with numerous rushes and buttercup.

Slope: Flat to undulating.

Landscape position: Low, wet points in old alluvial terrace.

LUC Unit: IIIw2, IVw1

Parent material: Old alluvium and colluvium.

Drainage status: Poorly to very poorly drained.

Soil consistence: Friable when moist, very plastic when wet.

Degree of topsoil development: Weakly developed.

Pugging susceptibility: High to extreme.

Profile description:

Ahg – 20 cm weakly developed, medium nut and crumb, friable when moist, very plastic when wet, greyish brown 10YR 5/2 silty clay loam with few brown mottles; on

Br – 10 cm weakly developed, medium nut and block, friable when moist, sticky when wet, very pale brown 10YR 8/2 clay loam with many gley mottles; on

Cr – weakly developed, medium nut and block, friable when moist, sticky when wet, white 10YR 8/1 clay loam with many gley and orange mottles.

Comments: Fine soil texture and poor drainage makes it very vulnerable to pugging and compaction damage when wet.

Management considerations: Extreme care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

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Name: Kiripaka silt loam.

Soil map symbol: KB

Photo ID: 140864 (Shand)

Vegetation: Semi improved pasture.

Slope: Undulating to Gently rolling.

Landscape position: Flat to gently rolling surfaces on basalt lava terraces.

LUC Unit: IIIe1

Parent material: Volcanic ash.

Drainage status: Imperfectly drained.

Soil consistence: Very friable when moist, plastic when wet.

Degree of topsoil development: Weakly developed.

Pugging susceptibility: High.

Profile description:

Ap – 14 cm weakly developed fine nutty crumb brown (7.5YR 4/3)silt loam with many live roots, evidence of pugging, very friable when moist, plastic when wet, wavy boundary; on

Bh – 21 cm weakly developed fine crumby nut dark yellowish brown (10YR 4/6) sandy loam; on

Bg – 18 cm weakly developed fine to very fine blocky crumby yellow (10YR 8/6) silty clay with few to many mottles; on

C – gleyed clay formed from well weathered and strongly leached volcanics.

Comments: Clay pan at about 40 cm affects drainage. Fine soil texture and impeded drainage make this soil prone to pugging and compaction damage from cattle and machinery.

Management considerations: Care with cattle and machinery to minimise the risk of pugging and compaction damage.

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Name: Kiripaka sandy clay loam

Soil map symbol: KB1

Photo ID:140868 (Shand)

Vegetation: Semi improved pasture.

Slope: Undulating to gently rolling (B+C)

Landscape position: Flat to gently rolling surfaces on basalt lava terraces.

LUC Unit: IIIe1

Parent material: Basaltic lavas, scoria, and older ash or tephra.

Drainage status: Imperfectly to poorly drained.

Soil consistence: Friable when moist, plastic when wet.

Degree of topsoil development:

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	Pugging susceptibility: High. **Profile description:** Ap – 19 cm weakly developed fine nutty crumb brown (7.5 YR 4/2) sandy loam with few low chroma mottles all the way to the surface; on Bh – 25 cm weakly developed fie nutty crumb very dark brown (7.5YR 2.5/3) sandy silt loam with 20% mottling and few iron concretions; on Cg – gleyed silty clay to clay with 70% mottling and iron and manganese concretions. **Comments**: Subsoil like potters clay. Very plastic. Fine soil texture and impeded drainage make this soil prone to pugging and compaction damage from cattle and machinery. **Management considerations:** Care with cattle and machinery to minimise the risk of pugging and compaction damage.
	**Name**: Kiripaka sandy loam **Soil map symbol**: KB2 **Grid Reference:** 1688517.71 : 6085675.95 **Photo ID:** 203 (McCulloch) **Vegetation:** Improved pasture with some kikuyu and paspalum. **Slope:** Flat to undulating. **Landscape position:** Low ash terrace and slightly raised knobs around woolshed. **LUC Unit:** 3e1,3s1, IVe2, IVs1 **Parent material:** Volcanic ash over scoria flows. **Drainage status:** Moderately well to well drained. **Soil consistence:** Friable when moist, slightly plastic when wet. **Degree of topsoil development:** Weakly to moderately developed. **Pugging susceptibility**: Moderate. **Profile description**: Ap – 20 cm weakly to moderately developed, fine to very fine crumb and nut, friable when moist, slightly plastic when wet, dark brown 10YR 3/3 fine sandy loam; on Bw – 25-35 cm weakly to moderately developed, fine to very fine crumb and nut, friable when moist, slightly plastic when wet, dark yellowish brown 10YR 4/4 sandy loam.; on C – weakly to moderately developed, fine to medium granular crumb, friable when moist, slightly plastic when wet, strong brown 7.5YR 4/6 sandy loam. **Comments**: High phosphate retention soil. Fine soil texture makes it vulnerable to slight pugging and compaction damage when wet. Reworked and rounded boulders appear in profile. **Management considerations:** Care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.

	**Name**: Marua deep phase **Soil map symbol**: MR **Grid Reference:**1692073.05 : 6091068.17 **Photo ID:** 080 (Halliday) **Vegetation:** Improved pasture, kikuyu and some paspalum. **Slope:** Undulating to rolling. **Landscape position:** Rolling downlands. **LUC Unit**: IIIs3, IVe5 **Parent material:** Loess over silty sandstone and mudstone. **Drainage status:** Moderately well drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: Moderate. **Profile description:** Ap – 30 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, brown 10YR 4/3 fine sandy silt loam; on Bh – 30-35 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, yellowish brown 10YR 5/6 fine sandy silt loam; on BC – moderately developed, fine to medium crumb and nut, friable when moist, slightly plastic when wet, yellow 10YR 7/8 sandy silt loam. **Comments**: Fine soil texture makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.
	**Name**: Marua hill soil **Soil map symbol**: MRH **Grid Reference:** 1691838.73 : 6089085.49 **Photo ID:** 028 (Simpson) **Vegetation:** Low quality pasture, low fertility species including paspalum, Yorkshire fog and crested dogs tail. **Slope:** Easy to steep hill and sidings. **Landscape position**: Gully heads. **LUC Unit**: VIe8, Ve1 **Parent material:** Patchy loess over silty sandstone and mudstone. **Drainage status:** Moderately well to imperfectly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Moderately developed.

	Pugging susceptibility: Moderate. **Profile description:** Ah – 20-22 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, brown 10YR 4/3 fine sandy silt loam; on Bh – 30-35 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, yellowish brown 10YR 5/6 fine sandy silt loam with few indistinct low chroma mottles; on BC – moderately developed, fine to medium crumb and nut, friable when moist, slightly plastic when wet, yellow 10YR 7/6 sandy silt loam with few orange mottles. **Comments**: Fine soil texture makes it vulnerable to pugging and compaction damage when wet. Potential for slight to moderate soil slip erosion. **Management considerations:** Care with heavy cattle during extended wet periods to minimise risk of pugging damage. Consider planting of poplar or willow poles over the erosion-prone parts of the hill slope, but can be difficult to achieve with cattle regularly in the paddock.
	**Name**: Ohaeawai sandy silt loam **Soil map symbol:** OW **Grid Reference:** 1682784.95 : 6083661.88 **Photo ID:** 308 (Ngawhitu) **Vegetation:** Improved pasture, kikuyu and paspalum. **Slope:** Undulating to rolling. **Landscape position**: Downlands. **LUC Unit:** IIIe1 **Parent material:** Volcanic ash over crushed argillite. **Drainage status:** Moderately well drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development:** Moderately developed. **Pugging susceptibility:** Moderate. **Profile description:** Ap – 30 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark greyish brown 10YR 4/2 fine sandy silt loam; on Bw – 35 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, yellowish brown 10YR 5/6 silt loam; on BC – moderately developed, medium to fine nut and crumb, friable when moist, very plastic when wet, yellow 10YR 8/6 silty clay loam with few orange and gley mottles. **Comments**: High phosphate retention soil. Fine soil texture makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

	**Name**: Ohaeawai bouldery sandy loam **Soil map symbol**: OWb **Grid Reference:** 1683619.90 : 6084195.53 **Photo ID:** 276 (Ngawhitu) **Vegetation:** Low quality pasture, low fertility species including paspalum, Yorkshire fog and crested dogs tail. **Slope:** Strongly rolling to moderately steep. **Landscape position:** Steeper contoured parts of scoria fan and lava flow. **LUC Unit:** VIs1 **Parent material:** Scoria and lava flows. **Drainage status:** Excessively well drained. **Soil consistence:** Friable when moist, non-plastic when wet. **Degree of topsoil development:** Weakly to moderately developed. **Pugging susceptibility**: Low. **Profile description** Ah – 5-12 cm weakly to moderately developed, fine to coarse nut and crumb, friable when moist, non-plastic when wet, dark reddish brown 5YR 2.5/2 sandy loam with many small to large scoria fragments. R – weakly developed to structureless, coarse crumb, very friable when moist, non-plastic when wet, pinkish white 7.5YR 8/2 coarse sandy loam with profuse small to medium scoria fragments. **Comments:** Good winter cattle country. Dries out early in the summer. Low natural fertility. Profuse scoria boulders over the soil surface and throughout the soil profile. **Management considerations:** Maintain vegetative cover through soil fertility and stock management.
	**Name**: Otonga peaty clay **Soil map symbol**: OG **Grid Reference:** 1692008.45: 6089497.83 **Photo ID:** 114 (Owhareiti) **Vegetation:** Wetland species, rushes, water pepper, willow weed, buttercup and some unimproved pasture. **Slope:** Flat to undulating. **Landscape position:** Wet guts and swampy areas. **LUC Unit:** VIw1, VIw3 **Parent material:** Peat and colluvium. **Drainage status:** Very poorly drained. **Soil consistence:** Friable when moist, plastic when wet.

	Degree of topsoil development: Weakly developed. **Pugging susceptibility**: Extreme. **Profile description:** Om – 12-15 cm weakly developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark greyish brown 10YR 4/2 peaty silt loam with many brown mottles.; on Br – 18-20 cm weakly developed, medium nut and crumb, friable when moist, very plastic when wet, dark grey 10YR 4/1 silty clay loam with many gley mottles; on Cr – weakly developed, blocky, friable when moist, sticky when wet, very pale brown 10YR 8/3 clay with profuse gley and many orange mottles. **Comments**: Permanently high water table makes this soil extremely prone to pugging damage. Good natural filter for sediment and nutrients. Found mostly in wet swampy guts. **Management considerations:** Consider fencing off these soils and planting up with wetland and riparian species. Much of this has already been achieved.
	**Name**: Otonga loamy peat **Soil map symbol**: OGd **Grid Reference:** 1683876.77 : 6083657.74 **Photo ID:** 264 (Ngawhitu) **Vegetation:** Low quality pasture, rushes and wetland species. **Slope:** Flat to undulating. **Landscape position:** Wet guts and swampy areas. **LUC Unit**: VIIw2 **Parent material:** Peat and colluvium. **Drainage status:** Very poorly drained. **Soil consistence:** Very friable when moist, plastic when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: Extreme. **Profile description:** Ag – 15-20 cm weakly developed, fine to medium crumb and nut, very friable when moist, plastic when wet, 10YR 2/2 peaty silt loam with profuse brown and few gley mottles; on Br – weakly developed, fine to medium nut and block, friable when moist, sticky when wet, 10YR 7/1 silty clay loam with profuse gley and brown mottles. **Comments**: Permanently high water table makes this soil extremely prone to pugging damage. Good natural filter for sediment and nutrients. **Management considerations:** Consider fencing off these soils and planting up with wetland and riparian species.

	**Name**: Pakotai brown clay **Soil map symbol**: PCr **Grid Reference:** 1689155.49 : 6085627.72 **Photo ID:** 218 (McCulloch) **Vegetation:** Improved pasture with some scattered rushes and buttercup. **Slope**: Flat. **Landscape position:** Low old alluvial terrace. **LUC Unit:** 3w2 **Parent material:** Alluvium over lava flows. **Drainage status:** Poorly drained. **Soil consistence:** Friable to firm when moist, sticky when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: High. **Profile description**: Ap – 15-20 cm weakly developed, medium to coarse nut and block, friable to firm when moist, sticky when wet, dark greyish brown 10YR 4/2 clay loam with few brown mottles; on Bg – 10-15 cm weakly developed, medium to coarse nut and block, friable to firm when moist, sticky when wet, light yellowish brown 10YR 6/4 clay loam with many orange and gley mottles and few small lava stones; on Cg – weakly developed, medium to coarse nut and block, friable to firm when moist, sticky when wet, very pale brown 10YR 7/4 clay loam with many orange and gley mottles and few to many small to large lava stones **Comments:** Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.
	**Name**: Pakotai dark grey clay **Soil map symbol**: PCm **Grid Reference:** 1688949.38 : 6085863.39 **Photo ID:** 211 (McCulloch) **Vegetation:** Semi-improved pasture and rushes. **Slope:** Flat to undulating. **Landscape position:** Low spot in the old alluvial terrace. **LUC Unit:** 4w1, 6e20 **Parent material:** Alluvium and lava flows overlying basalt. **Drainage status:** Poorly to very poorly drained. Heavily pugged.

Soil consistence: Friable to firm when moist, sticky when wet.

Degree of topsoil development: Weakly developed.

Pugging susceptibility: High to extreme.

Profile description:

Ah - 8 cm weakly developed, fine to medium nutty crumb, friable to firm when moist, sticky when wet, very dark brown 10YR 2/2 clay loam with many brown and few gley mottles; on

Bg – 10-12 cm weakly developed, medium to coarse nut and block, friable to firm when moist, sticky when wet, light yellowish brown 10YR 6/4 clay loam with many gley and brown mottles and few to many small lava stones; on

Cr - weakly developed, medium to coarse nut and block, friable to firm when moist, sticky when wet, brown 7.5YR 5/4 clay with profuse gley and brown mottles and many small to large lava stones.

Comments: Variant of Soil 2a but with more lava stones in the profile and across the soil surface and poorer drainage. Fine soil texture and poor drainage makes it extremely vulnerable to pugging and compaction damage when wet.

Management considerations: Extreme care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage. Requires drainage to improve pasture productivity.

Name: Papakauri sandy loam

Soil map symbol: PK

Grid Reference: 1683590.79 : 6083985.87

Photo ID: 271 (Ngawhitu)

Vegetation: Low quality pasture, low fertility species including paspalum, Yorkshire fog and crested dogs tail.

Slope: Undulating to strongly rolling.

Landscape position: Easier contoured parts of scoria fan overlaid with ash.

LUC Unit: VIs1

Parent material: Scoria and volcanic ash.

Drainage status: Well to excessively well drained.

Soil consistence: Friable when moist, non-plastic when wet.

Degree of topsoil development: Weakly to moderately developed

Pugging susceptibility: Low.

Profile description

Ah – 10-15 cm weakly to moderately developed, fine to coarse nut and crumb, friable when moist, non-plastic when wet, dark reddish brown 5YR 2.5/2 sandy loam with few small to medium scoria fragments; on

Bw – weakly developed, fine to coarse crumb, very friable when moist, non-plastic when wet, dark reddish brown 5YR 3/4 sandy loam with many small to large scoria fragments.

Comments: Good winter cattle country. Dries out early in the summer. Low natural

	fertility. Profuse scoria boulders on the soil surface preclude this soil from cultivation – even on the rolling country. **Management considerations:** Maintain vegetative cover through soil fertility and stock management.
	**Name**: Parahaki fine sandy loam **Soil map** symbol: PR **Grid Reference:** 1688085.17 : 6084604.58 **Photo ID:** 177 (Owhareiti) **Vegetation:** Improved pasture with some kikuyu and paspalum. **Slope:** Undulating to rolling. **Landscape position**: High ash terrace. **LUC Unit**: IIIe1, IVe2, IVs1 **Parent material:** Volcanic ash and scoria. **Drainage status**: Well drained. **Soil consistence:** Friable to loose when moist, non-plastic when wet. **Degree of topsoil development:** Weakly to moderately developed. Pugging susceptibility: Low. **Profile description**: Ap – 20-25 cm weakly to moderately developed, fine crumb and nut, friable to loose when moist, non-plastic when wet, dark reddish brown 5YR 2.5/2 sandy loam; on Bw – weakly developed, fine crumb, friable to loose when moist, non-plastic when wet, yellowish red 5YR 4/6 sandy loam with few fine to small scoria fragments. **Comments:** High phosphate retention soil. Fine soil texture makes it prone to surface erosion if vegetative cover is removed. **Management considerations:** Good cattle winter country. Care with cultivation to minimise risk of surface erosion. Consider minimum tillage and direct drill techniques for pasture renewal.
	**Name**: Pokapu hill soil **Soil map symbol**: PPH **Grid Reference:** 1682249.91 : 6078531.54 **Photo ID:** 151012 (Dodd) **Vegetation:** Semi-improved pasture, forestry, indigenous bush. **Slope:** Moderately steep to steep hill. **Landscape position:** Argillite hills and sidings. **LUC Unit:** VIe19 **Parent material:** Crushed argillite. **Drainage status:** Imperfectly drained.

	Soil consistence: Friable when moist, sticky when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: Moderate to high. **Profile description**: Ah – 20 cm weakly developed, fine nutty crumb, friable when moist, sticky when wet, light grey 10YR 7/1 sandy clay loam; on AB –12 cm weakly developed, fine nutty crumb, friable when moist, sticky when wet, very pale brown 10YR 7/4 sandy clay loam with few to many small to large argillite fragments; on B –weakly developed, fine to very fine crumby nut, friable when moist, sticky when wet, very pale brown 10YR 8/4 fine sandy clay loam; on Cg – structureless, very fine crumb, friable when moist, very sticky when wet, very pale brown 10YR 8/3 fine sandy clay loam with few gley mottles. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging damage when wet. Prone to moderate soil slip, debris avalanche and gully erosion. **Management considerations:** Care with heavy cattle during wet periods to minimise risk of pugging damage. Space plant poplars and willows over the erosion-prone parts of the slope and gully system.
	**Name**: Rangiora silty clay loam. **Soil map symbol:** RA **Grid Reference:**1691898.507-6093735.259 **Photo ID:** 130774 (Andrews) **Vegetation:** Low quality pasture, low fertility species including paspalum, Yorkshire fog and crested dogs tail. **Slope:** Flat, flat to undulating. **Landscape position:** Lower flats. **LUC Unit:** IIIs2 **Parent material**: unconsolidated sands and weathered greywacke. **Drainage status:** Moderately well drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility:** Medium to high, high when wet. Profile description: Ap – 14 cm weakly developed fine nutty crumb brown (10YR 4/3) silty clay loam, friable when moist, plastic when wet; on Bh – 30 cm weakly developed fine to very fine nutty crumb light yellowish brown (10YR 6/4) silt loam with many roots all the way down; on C – Massive dark yellowish brown (10YR 4/6) silty clay with few lightish red (5YR 6/4) mottles.

	Comments: Evidence of pugging on the surface due to the weak nature of the topsoil. **Management considerations:** Care with heavy cattle when wet.
	**Name**: Rangiora clay loam, hill soil **Soil map s**ymbol: RaH **Photo ID:** 130819 (Andrews) **Vegetation:** Semi-improved pasture & native vegetation. **Slope:** Easy to moderate hill country. **Landscape position**: Hill country. **LUC Unit:** VIe9, VIe17. **Parent material**: Deeply weathered greywacke. **Drainage status**: Imperfectly drained **Soil consistence**: Friable when moist plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: Moderate to high under pasture. **Profile description**: Ah – 15 cm weakly to moderately developed fine nutty silty clay, dark grey brown (10YR 4/1), B1 – 18 cm weakly to moderately developed yellowish brown (10YR 5/6) heavier clay, slightly sticky when wet, medium to fine nutty blocky structure B2 – 16 cm moderately developed fine nutty block brownish yellow (10YR 6/8) clay, slightly sticky when wet, on C – Reddish yellow (7.5YR 6/8) clay.
	**Name**: Rangiora clay loam and silty clay loam **Soil map symbol**: RAI **Grid Reference:** 1692172.77 : 6091023.17 **Photo ID:** 098 (Halliday) **Vegetation:** Improved pasture, kikuyu and some paspalum. **Slope:** Undulating to rolling. **Landscape position:** Rolling downlands. Heavily pugged. **LUC Unit**: IIIe3, IIIs3 **Parent material:** Loess over silty sandstone and mudstone. **Drainage status:** Imperfectly to poorly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: Moderate to high. **Profile description**:

	Ap – 20-25 cm moderately developed, medium nut and crumb, friable when moist, plastic when wet, dark grey 10YR 4/1 silty clay loam; on B – 25-30 cm moderately developed, medium nut and block, friable when moist, very plastic when wet, dark greyish brown 10YR 4/2 silty clay loam with few orange mottles; on Bg – moderately developed, medium nut and block, friable when moist, sticky when wet, very pale brown 10YR 7/4 clay loam with few to many orange and gley mottles. On C – Loess over silty sandstone and mudstone. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.
	**Name**: Waiotira clay loam, hill soil **Soil map symbol**: YCH **Grid Reference:** 1683690.55 : 6083568.95 **Photo ID:** 333 (Ngawhitu) **Vegetation:** Low quality pasture, low fertility species including paspalum, Yorkshire fog and crested dogs tail. **Slope:** Moderately steep. **Landscape position:** Easy to steep hillsides, sidings and stream margins. **LUC Unit:** VIe7, VIe20 **Parent material:** Crushed argillite and mudstone. **Drainage status:** Imperfectly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: High. **Profile description**: Ah – 15-20 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark greyish brown 10YR 4/2 silty clay loam; on Bh – 20-25 cm moderately developed, medium to fine nut and block, friable when moist, very plastic when wet, very pale brown 10YR 7/4 clay loam with few indistinct low chroma mottles; on C – moderately developed, medium to fine nut and block, friable when moist, very plastic when wet, very pale brown 10YR 8/4 clay loam with few to many orange mottles. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

	**Name**: Waipapa silt loam. **Soil map symbol**: KO **Grid Reference:**1686161.405-6087745.54 **Photo ID:**140871 (Shand) **Vegetation:** Semi improved pasture. **Slope:** Flat to undulating. **Landscape position**: Alluvial terrace. **LUC Unit:** IIIw2, IVw1 **Parent material**: Alluvium. **Drainage status:** Imperfectly to poorly drained due to Iron pan. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: Moderate to high. **Profile description**: Ap – 15 cm very weakly developed fine to very fine nutty crumb, very friable when moist, plastic when wet, very dark brown (7.5YR 2.5/3) silt loam, many roots; on Bh - 12 cm weakly to very weakly developed, fine nutty crumb brown (7.5YR 4/4) silt loam, many roots; on Bfm – 3 cm yellowish red (5YR 4/6) iron pan, very consolidated; on Bg – 15 cm + pinkish grey (7.5YR 6/2) sandy clay with few to many iron concretions. On fine alluvium. **Comments**: Iron pan at about 28 cm restricts drainage. Fine soil texture and impeded drainage make this soil prone to pugging and compaction damage from cattle and machinery. **Management considerations:** Care with cattle and machinery to minimise the risk of pugging and compaction damage.
	**Name**: Waipu clay **Soil map symbol**: YU **Grid Reference:** 1692292.21 : 6090529.67 **Photo ID:** 043 (Simpson) **Vegetation:** Improved pasture, buttercup and some rushes, **Slope:** Flat to undulating. **Landscape position:** Narrow alluvial valley. Heavily pugged. **LUC Unit:** IVw1 **Parent material**: Alluvium. **Drainage status:** Poorly drained. **Soil consistence:** Friable when moist, sticky when wet.

	Degree of topsoil development: Moderately to weakly developed. **Pugging susceptibility**: High. **Profile description**: Ap – 30-35 cm moderately to weakly developed, medium to fine nut and block, friable when moist, sticky when wet, dark greyish brown 10YR 4/2 silty clay loam with many brown and few gley mottles.; on Bg – moderately to weakly developed, medium to coarse nut and block, friable to firm when moist, sticky when wet, light yellowish brown 10YR 6/4 clay loam with many gley and orange mottles. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Extreme care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.
	**Name**: Waipuna clay loam **Soil map symbol**: WU **Grid Reference:** 1683880.50 : 6083522.61 **Photo ID:** 261 (Ngawhitu) **Vegetation:** Semi-improved pasture, rushes and buttercup. **Slope**: Flat to undulating. **Landscape position:** Colluvial fans. Heavily pugged in places. **LUC Unit:** IVw1 **Parent material:** Colluvium derived from crushed argillite. **Drainage status:** Poorly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development:** Moderately to weakly developed. **Pugging susceptibility**: High. **Profile description**: Ah – 20 cm moderately to weakly developed, medium nut and crumb, friable when moist, plastic when wet, dark grey 10YR 4/1 silt loam with few brown and gley mottles.; on Bg – moderately to weakly developed, medium nut and block, friable when moist, sticky when wet, light brownish grey 10YR 6/2 silty clay loam with many gley and brown mottles and few fine iron concretions. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

Name: Wairua silt loam

Soil map symbol: YA

Grid Reference: 1692378.02 : 6090683.17

Photo ID: 065 (Simpson)

Vegetation: Semi-improved pasture, kikuyu and paspalum.

Slope: Flat to undulating.

Landscape position: Alluvial flats and streambanks.

LUC Unit: VIe20

Parent material: Alluvium over gravels.

Drainage status: Moderately well to well drained.

Soil consistence: Friable when moist, slightly plastic when wet.

Degree of topsoil development: Weakly developed.

Pugging susceptibility: Moderate to low.

Profile description:

A – 20-25 cm weakly developed, fine crumb and nut, friable when moist, slightly plastic when wet, brown 10YR 4/3 sandy silt loam; on

Bh – weakly developed, fine crumb and nut, friable to loose when moist, slightly plastic when wet, light yellowish brown 10YR 6/4 silty sand; on

C - weakly consolidated to structureless seam of small to large alluvial gravels.

Comments: Fine soil texture makes it prone to slight pugging and compaction damage when wet. Prone to frequent surface flooding from the adjacent Manaia Stream.

Management considerations: Care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage. Consider retiring stream margins from stock and enhancing with riparian and native species – but main difficulty is flooding damage to riparian fences.

Name: Waitakere sandy loam

Soil map symbol: YT1

Grid Reference: 1687162.79 : 6084288.93

Photo ID: 111 (Owhareiti)

Vegetation: Improved pasture with some kikuyu and paspalum.

Slope: Flat to undulating.

Landscape position: Low ash terrace.

LUC Unit: IIe1

Parent material: Volcanic ash.

Drainage status: Moderately well drained.

Soil consistence: Friable when moist, slightly plastic when wet.

Degree of topsoil development: Moderately developed.

	Pugging susceptibility: Moderate. **Profile description**: Ap – 40-45 cm moderately developed, fine to medium nut and crumb, friable when moist, slightly plastic when wet, dark brown 10YR 3/3 fine sandy loam; on Bw – moderately developed, fine to medium nut and crumb, friable when moist, slightly plastic when wet, very dark brown 10YR 2/2 fine sandy loam. **Comments**: High phosphate retention soil. Fine soil texture makes it vulnerable to slight pugging and compaction damage when wet **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.
	**Name**: Waitakere sandy loam, wet phase **Soil map symbol**: YTw **Grid Reference:** 1687176.64 : 6084366.17 **Photo ID:** 116 (Owhareiti) **Vegetation:** Improved pasture with some rushes. **Slope**: Flat. **Landscape position**: Low ash terrace. **LUC Unit:** IIIw5 **Parent material**: Volcanic ash. **Drainage status:** Imperfectly drained. **Soil consistence:** Friable when moist, slightly plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: Moderate to high. **Profile description**: Ap – 20 cm moderately developed, medium to fine nut and crumb, friable when moist, slightly plastic when wet, very dark brown 10YR 2/2 fine sandy loam; on Bw – 35 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark yellowish brown 10YR 4/6 silt loam; on Bg – moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark yellowish brown 10YR 3/6 silt loam with few orange mottles and iron concretions. **Comments**: High phosphate retention soil. Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.

Name: Waipu silt loam

Soil map symbol: YUy1

Grid Reference: 1689611.50 : 6086342.16

Photo ID: 082 (Halliday)

Vegetation: Unimproved pasture, rushes and buttercup.

Slope: Flat to undulating.

Landscape position: Wet guts and swampy areas.

LUC Unit: VIw1

Parent material: Colluvium.

Drainage status: Very poorly drained.

Soil consistence: Friable when moist, plastic when wet.

Degree of topsoil development: Weakly developed.

Pugging susceptibility: Extreme.

Profile description:

Ahg – 5 cm weakly developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark grey 10YR 4/1 silt loam with many gley mottles; on

Eg – 20 cm weakly developed, medium to fine nut and crumb, friable when moist, plastic when wet, grey 10YR 5/1 silt loam with many gley mottles; on

Bg – weakly developed, medium to coarse nut and block, friable when moist, sticky when wet, very pale brown 10YR 7/3 silty clay loam with many gley and orange mottles.

Comments: Fine soil texture and poor drainage makes it very vulnerable to pugging and compaction damage when wet. Found mostly in wet guts and drains.

Management considerations: Consider retiring from stock and enhancing with riparian and native species.

Name: Whakapara silt loam

Soil map symbol: WF

Grid Reference: 1692392.21 : 6090813.92

Photo ID: 092 (Halliday)

Vegetation: Improved pasture.

Slope: Flat to undulating.

Landscape position: Alluvial flats.

LUC Unit: IIIw1

Parent material: Alluvium.

Drainage status: Moderately well drained.

Soil consistence: Friable when moist, plastic when wet.

Degree of topsoil development: Weakly to moderately developed.

Pugging susceptibility: Moderate.

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Profile description:

Ap – 20-25 cm weakly to moderately developed, fine to medium crumb and nut, friable when moist, plastic when wet, dark greyish brown 10YR 4/2 silt loam; on

Bw – 25-30 cm weakly to moderately developed, fine to medium crumb and nut, friable when moist, slightly plastic when wet, dark yellowish brown 10YR 4/4 fine sandy silt loam; on

BC – weakly to moderately developed, fine to medium nut and crumb, friable when moist, slightly plastic when wet, light yellowish brown 10YR 6/4 fine sandy silt loam with few indistinct low chroma mottles.

Comments: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet.

Management considerations: Care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.
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Name: Whakapara mottled silt loam

Soil map symbol: WFm

Grid Reference: 1689611.50 : 6086352.15

Photo ID: 242 (McCulloch)

Vegetation: Improved pasture and scattered rushes.

Slope: Flat.

Landscape position: Low terrace formed from recent alluvium.

LUC Unit: 3w2

Parent material: Alluvium.

Drainage status: Imperfectly drained.

Soil consistence: Friable when moist, plastic when wet.

Degree of topsoil development: Weakly developed.

Pugging susceptibility: High.

Profile description:

Ap – 20-25 cm weakly developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark greyish brown 10YR 4/2 silt loam; on

BC – 10-15 cm weakly developed, medium to fine crumb and nut, friable when moist, plastic when wet, very pale brown 10YR 7/4 silt loam with few orange and brown mottles; on

C – weakly developed, medium to fine crumb and nut, friable when moist, plastic when wet, very pale brown 10YR 7/3 sandy silt loam with few orange and brown mottles and few iron concretions.

Comments: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet.

Management considerations: Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.
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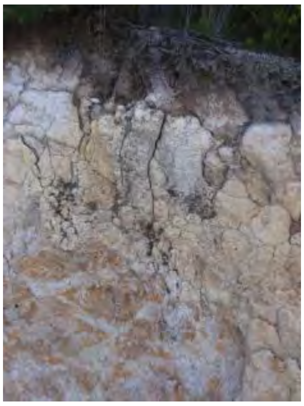
	**Name**: Whakapara silt loam & clay loam. **Soil map symbol**: WF **Grid Reference:** 1691362.35-6093748.09 **Photo ID:** 130839 (Andrews) **Vegetation:** Low quality pasture, wetland association species**.** **Slope:** Flat to undulating. **Landscape position:** swamps in gully systems. **LUC Unit**: IVw1 **Parent material:** Fine alluvium formed and weathered greywacke. **Drainage status:** Poorly drained. **Soil consistence:** Plastic when moist. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: High. **Profile description**: Ap – 20 cm Weakly developed fine nutty blocky black (10YR 2/1) silty clay loam with few brown mottles; on Bw – weakly developed fine nutty crumb and blocky very pale brown (10YR 8/2) silty clay; on C – fine alluvium formed from greywacke.
	**Name**: Wharekohe silty clay loam **Soil map symbol:** WK **Grid Reference:** 1683383.43 : 6083570.58 **Photo ID:** 286 (Ngawhitu) **Vegetation:** Improved pasture, kikuyu and some paspalum. **Slope:** Undulating to rolling. **Landscape position:** Downlands. **LUC Unit:** IIIe3, IVe5, IVe6 **Parent material:** Patchy volcanic ash overlying crushed argillite and mudstone. **Drainage status:** Imperfectly to moderately well drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Moderately developed. **Pugging susceptibility**: Moderate to high. **Profile description**: Ap - 20-25 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark greyish brown 10YR 4/2 silty clay loam; on Bh – 25-30 cm moderately developed, medium to fine nut and block, friable when moist, very plastic when wet, very pale brown 10YR 7/4 clay loam with few indistinct low

	chroma mottles; on BC - moderately developed, medium to fine nut and block, friable when moist, very plastic when wet, very pale brown 10YR 8/4 clay loam with few to many orange mottles. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. **Management considerations:** Care with heavy cattle and machinery during wet periods to minimise risk of pugging and compaction damage.
	**Name**: Wharekohe silt loam. **Soil map symbol**: WK **Grid Reference:**1691687.898-6093690.015 **Photo ID:** 130783 (Andrews) **Vegetation:** Low fertility pasture. **Slope:** Flat to undulating. **Landscape position:** Low spot in the alluvial terrace by the creek **LUC Unit:** IIIs2 **Parent material:** strongly weathered greywacke. **Drainage status:** Poorly drained. **Soil consistence:** Friable when moist, plastic when wet. **Degree of topsoil development**: Weakly developed. **Pugging susceptibility**: High. **Profile description**: Ap - 27 cm weakly developed fine nutty crumb grey (10YR 5/1)sandy silt loam with few mottles up to the surface (<5%), friable when moist, plastic when wet; on Bw – 22 cm weakly developed fine to medium firm blocky light yellowish brown (10YR6/4) sandy clay loam; on C - Olive yellow (2.5Y 6/6) silty clay loam.
	**Name**: Wharekohe sandy loam, with pan **Soil map symbol**: WKap **Grid Reference:** 1691073.81 : 6089562.30 **Photo ID:** 017 (Simpson) **Vegetation:** Improved pasture, kikuyu and some paspalum. **Slope:** Undulating to rolling. **Landscape position:** Rolling downlands. **LUC Unit**: IIIe3 **Parent material:** Loess over silty sandstone and mudstone. **Drainage status:** Imperfectly to poorly drained. **Soil consistence:** Friable when moist, plastic when wet.

	Degree of topsoil development: Moderately developed. **Pugging susceptibility**: Moderate to high. **Profile description**: Ap – 15-20 cm moderately developed, medium to fine nut and crumb, friable when moist, plastic when wet, dark grey 10YR 4/1 silt loam; on Bh – 10-15 cm moderately developed, medium to fine nut and crumb, friable when moist, very plastic when wet, pale brown 10YR 6/3 silty clay loam with few low chroma mottles; on Bg – moderately developed, medium to fine nut and block, friable when moist, sticky when wet, yellow 10YR 7/6 sandy clay loam with few to many orange and gley mottles and iron concretions. **Comments**: Fine soil texture and impeded drainage makes it vulnerable to pugging and compaction damage when wet. Iron stone pan at approximately 30-40 cm depth. **Management considerations:** Care with heavy cattle and machinery during extended wet periods to minimise risk of pugging and compaction damage.
	**Name**: Wharekohe silt loam, hill soil **Soil map symbol:** WKH **Photo ID**: 150944 (Dodd)

5.3 Slope

The definitions of the slope classes mapped on the Land Resources Map are shown in the table below.

Slope class	Degrees	Slope description	Access suitability
A	0-3°	Flat to gentle undulating	Tractor
B	4-7 °	Undulating	Tractor
C	8-15 °	Rolling	Tractor
D	16-20 °	Strongly rolling	Some tractor, four-wheel bike
E	21-25 °	Moderately steep	Two-wheel bike
F	26-35 °	Steep	Walking and some two-wheel bike
G	>35	Very steep	Walking
+	Indicates a compound slope		
/	Indicates average slope is borderline between two slope classes		
‘	Indicates a dissected slope		

5.4 Extended Erosion Legend

The definitions of the erosion types mapped on the Land Resources Map are shown in the table below.

Soil slip erosion (Ss): Slip erosion is a shallow and rapid sliding or flowing movement of soil and subsoil, exposing a slip surface which is approximately parallel to the slope. Debris comes to rest in the area from the base of the exposed slip to the toe of the slope. There can be some rotational movement, leaving a concave slip plane. The slip plane is usually less than 1 m (but sometimes up to 2m) below the original surface. Soil slip erosion is most evident during or immediately after heavy rain. This is due to saturation of the soil, which increases the soil mass, lubricates the slip plane, and turns pore water pressure positive. The resisting forces are shear strength of the soil, cohesion of the material, and tensile strength of the plant roots in the soil. The severity of the potential for slip erosion dictates effective control measures. Space planted trees will effectively control slip erosion where the potential is only slight to moderate. Higher potential requires closed canopy plantings such as afforestation or retirement.
Gully erosion (G): Gully erosion is the removal of soil or soft rock material by water, forming distinct narrow channels which usually carry water during and immediately after rains. The main control of gully erosion is by controlling storm water run-off over the gully head and through the gully floor. The control techniques include drop structures over the gully head, plantings (space plantings of critical points or retirement), and reducing peak runoff rates with coffer dams.
Debris Avalanche (Da): Debris avalanche occurs when there is a sudden massive avalanche of material from above and it scours out a trail over which it crosses to the regolith.
Pugging (P): the damage or destruction of soil structure of wet soils from stock. Drainage is further inhibited and runoff of surface water increased. Productivity can be significantly limited.

5.5 Erosion Severity Rankings

The table below outlines the classification for severity.

Erosion severity	LRI symbol

Slight	1
Moderate	2
Severe	3
Very severe	4
Extreme	5

5.6 Vegetation Cover

The table below outlines the vegetation codes used for the area.

Vegetation	LRI symbol
Improved pasture	gI
Semi-improved pasture (effective)	gS
Unimproved / retired pasture	gU
Exotic conifer species	fF
Exotic broadleaf species	fR
Indigenous bush	fO
Manuka, Kanuka scrub	sM
Fern	sF
Gorse	sG
Rushes	hR
Wetland association species	hW
Un-vegetated	uV
Vegetation is scattered	*
Cutover vegetation	c