Manaaki Whenua
Landcare Research

Identification of high-risk agricultural activities: national mapping of the location, scale and extent of winter forage cropping and intensive grazing on hill country land

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Identification of high-risk agricultural activities: national mapping of the location, scale and extent of winter forage cropping and intensive grazing on hill country land

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Project and Client

The Ministry for the Environment (MfE) contracted Manaaki Whenua – Landcare Research (MWLR) to map the location, extent and severity of winter forage cropping and intensive grazing on New Zealand agricultural hill country over the 2018 winter season using archival satellite imagery. This information is needed to assist Essential Freshwater policy development processes, especially regarding forage cropping and grazing in the hill country that results in severe de-vegetation and that can have a significant impact on downstream water quality. The results were produced at paddock scale in GIS-polygon format. The work was carried out between January and May 2019.

Objectives

- Assemble a time series of Sentinel-2 satellite imagery covering all regions of mainland New Zealand for autumn to spring 2018. Identify the agricultural land (i.e. exclude forest, rivers, urban areas, etc.) and demarcate those areas having a slope of 7° or more.
- For these hill-country agricultural areas, identify the paddocks considered at risk of soil run-off; i.e. those in which bare soil is observed, or is likely to occur from winter forage grazing practices. Produce the result as a per-paddock GIS polygon layer of the identified high-risk paddocks.
- During the project, provide the interim information required by MfE: a set of early-stage candidate paddocks by 22 February 2019, and a set of provisional regional summary statistics derived from later-stage processing as at 29 March 2019.
- Include attributes required by MfE in the final high-risk paddock map, including identification of region so that per-region metrics can be derived. Based on current/accepted practice, devise a de-vegetation severity index, and include attributes for each paddock, quantifying this through time and in summary form.
- Provide estimates of modelled soil lost in winter from risky agricultural land.
- Assess the validity of the hill country bare ground, winter forage and intensive grazing map, and include this in a report detailing the methodology and results.

Methods

Key data preparation steps were:

- assembling a time series of the most suitable Sentinel-2 satellite imagery covering the New Zealand mainland for the period September 2017 to November 2018 – of this, the imagery from March to September 2018 became the primary data source
- using Manaaki Whenua's processing pipeline to carry out radiometric calibration for all images, and to mask out cloud, shadow and snow
- deriving an agricultural mask using the Land Cover Database and Department of Conservation estate boundaries, and also deriving a mask of steep land (7° or more) based on Manaaki Whenua's 15 m digital elevation model

- selecting the most useful set of images for each region, clipping them to the regional boundaries and applying cloud, shadow, snow and agricultural masks, leaving just valid data for each date
- delineating paddocks in the study site using MWLR's automated paddock boundary mapping method operating on a time series of satellite imagery – this allowed analysis to be performed at the whole-paddock level rather than at the per-pixel level only.

Key steps in the identification and mapping of high-risk paddock polygons were:

- performing per-pixel spectral land-cover classification of all images across all regions – this was calibrated using field data gathered during a separate mapping project carried out for Hawke's Bay Regional Council and used with permission
- summarising per-pixel land cover and the Normalised Digital Vegetation Index (NDVI) into per-paddock polygon (GIS) attributes
- devising a de-vegetation severity index based on the percentage of each paddock polygon observed to be bare soil
- developing multi-temporal rules to identify likely high-risk paddock polygons – these rules take into account their land cover, NDVI and de-vegetation severity during the March to September time series
- estimating soil run-off from each paddock polygon identified as high risk using the universal soil loss equation
- assigning a certainty level to the identification of each high-risk paddock polygon based on the strength of the evidence (spectrally identified as a forage crop and/or positively observed to become bare soil), and also carrying out a limited accuracy assessment using the Hawke's Bay field data (but noting that this data set was not independent of the calibration data).

All processing was carried out on the New Zealand eScience Infrastructure (NeSI) high-performance computing system due to the very large volume of data involved and the substantial computing load.

Results

- A total of 9044 paddock polygons were classified as high risk under the methodology and rules applied in this analysis. These paddock polygons collectively covered 42,082 ha, which is 0.76% of the New Zealand hill country agricultural land (7° slope or more).
- The regions with the most winter forage cropping, as a percentage of the hill country agricultural land, were Southland (2.21%), Otago (1.61%), and Canterbury (1.20%).
- When checked against ground-truth-verified mapping of the Hawke's Bay region, the accuracy of the landcover –pasture or a forage type –was 81.25%.
- Erosion modelling estimates that 689,921 tonnes of sediment may have been lost from the land mapped by these risky paddock polygons.

Conclusions

- Though building on MWLR's existing expertise and processing capability with time-series satellite imagery, this national analysis of high-risk agricultural practices in hill country required significant processing advances, particularly code and work flow development on the NeSI high-performance computing facility, as the data volumes were very large.
- Using medium-resolution Sentinel-2 satellite remote-sensing imagery was the most practical, cost-effective, and timely way to produce the information required by MfE.
- Data processing of each region separately worked well for managing the computing load, with concatenation of results to form national summary statistics at the end of the process.
- The national data on high-risk agricultural practices required by MfE were successfully produced; specifically, mapping of winter forage cropping and intensive grazing in the hill country.
- The results are as accurate as could be achieved under the constraints of the short delivery time frame, the specification of no field data collection, and the high cloud cover prevalent in New Zealand winter months, particularly in the North Island.
- Only limited comparisons with earlier studies can be made due to differences in methodology and the years under investigation. Previous work in Southland, Canterbury and Hawke's Bay, however, indicates similar percentage areas of high-risk hill-country.

Recommendations

For any subsequent work we recommend that ground-truth data be gathered from several locations around New Zealand so that spectral analysis and temporal rule development can be calibrated using data that is relatively local. Sufficient ground-truth data should also be gathered for independent accuracy assessment of the results.

Further recommendations are to:

- complete a study of all agricultural land, rather than restricting the analyses to slopes of 7° or more
- use a minimum mapping unit of 0.2 ha rather than 0.1 ha, to reduce the number of false positive paddock polygons initially flagged (these were removed manually in the current project)
- consider an investigation of the potential reduction in sediment loss if all high-risk hill country was grazed down-slope, rather than up-slope.

1 Introduction

1.1 Project and client

The Ministry for the Environment (MfE) requires data to assist the development of their Essential Freshwater policies. MfE is especially interested in winter forage cropping and grazing practices in the New Zealand hill country that can result in severe de-vegetation and erosion, and thus can have a significant impact on downstream water quality. Information requirements include the spatial extent of hill country forage cropping and intensive grazing, as well as the severity and timing of de-vegetation that results from these practices.

MfE contracted Manaaki Whenua – Landcare Research (MWLR) to produce a national map of these high-risk grazing practices, using time-series satellite imagery spanning autumn to spring 2018. The results were produced at paddock scale in GIS-polygon format so that they can be shared nationally via MfE's online data service. The work was carried out between January and May 2019.

1.2 MfE's specific requirements

For the final product delivery, MfE requires the high-risk paddock polygon map to be supplied as a spatial data layer with specific attributes, including timing information. Per-region statistics are required for the area of agricultural land, and for agricultural land of 7°and steeper. Within this hill country, the spatial data layer outputs comprise:

- paddock polygon boundaries of forage cropping, heavy grazing, and bare ground at the start of winter
- classification of heavily grazed winter pasture, forage cropping, and bare ground still present, with summary statistics of these categories per region
- de-vegetation information for the identified paddock polygons of winter pasture, forage cropping and bare ground areas – this information will be supplied per high risk paddock polygon with the following attributes:
    - a unique paddock polygon ID
    - an overall de-vegetation score
    - an overall de-vegetation threshold
    - the number of cloud-free images in the paddock polygon stack
    - a flag to indicate if the de-vegetation threshold was breached (at any time in the time series)
    - identification of the first image date when the de-vegetation threshold was breached
    - duration: an indication of the length of time (days) de-vegetation thresholds were breached
    - a confidence score for the classification to crop, pasture or bare
    - a confidence score for the overall de-vegetation indicator score reported per paddock polygon

- each polygon date-stamped with a de-vegetation indicator score per date
- the soil erosion rate ($t/km^2/yr$) for each paddock polygon.

Due to urgent requirements within MfE, interim results were to be generated and provided at several points during the project. For the first (February 2019), MWLR was to supply MfE with a GIS layer of candidate paddock polygons. This was at a very early stage of the processing, so it was based on a simple provisional before- and after-winter analysis. It was expected that the layer would be an overestimate of high-risk paddock polygon numbers, to be refined in later stages of processing. The second delivery (by 31 March 2019) was to be per-region summary statistics of high-risk areas, based on processing refinements achieved by this date.

2 Background

2.1 Winter forage

Winter forage can be thought of as any plant-based crop on which livestock animals are grazed over the winter months when pasture growth slows or halts, especially in cooler regions. It is generally restricted to crops that have been sown specifically for consumption during this time. Kale, rape, fodder beet and swedes are common winter forage crops, with smaller areas of other brassicas and cereals, including oats.

These crops are typically strip-grazed, with each daily strip of feed being eaten down to near bare ground and usually not re-growing behind the livestock. Alternatively, animals are sometimes set-stocked (i.e. given access to the whole paddock at once, which they then gradually graze down to near bare soil over a period of weeks or longer).

Bare ground commonly occurs due to animal trampling in wet conditions, especially under intensive block or strip grazing. Pasture (grass) can also be intensively strip-grazed by livestock during winter, and some winter forages are a mix of brassica and grass. In the latter cases, the grass component gets grazed short but is often not removed or killed by the process, so it can grow back after grazing. This would tend not be considered ‘risky’, as there is live vegetation cover throughout, even though it is very short for a period. MfE is specifically interested in bare soil caused by winter forage grazing, not by any other factor (e.g. landslides).

Winter forage grazing by sheep, cattle and deer has a range of impacts on the environment. Impacts include:

- loss of soil through erosion generating sediment and associated nutrients to waterways (McDowell & Houlbrooke 2008; Monaghan et al. 2017)
- greenhouse gas emission (van der Weerden et al. 2017)
- nitrate leaching (see below)
- loss of soil structure due to pugging and soil damage (Drewry & Paton 2005).

Nitrate leaching losses are due to several factors. Under cattle forage grazing, the high stocking rates, low winter temperatures and wetter soil moisture levels contribute to increased density of urine patches and increased drainage of nitrate from the soil root zone. The often-prolonged period of bare ground after grazing and prior to crop or pasture renewal is another factor that contributes to the high risk of nitrate leaching (Shepherd et al. 2012).

Research in New Zealand indicates that winter forage grazing creates a high risk of sediment loss (McDowell et al. 2005; McDowell & Houlbrooke 2008; Monaghan et al. 2017). Sediment and nutrient losses from winter-grazed hill country pasture are greater with increased slope and increased percentage of bare ground associated with soil damage from treading (Nguyen et al. 1998; Sheath & Carlson 1998). Sediment and nutrient loss increases are also directly associated with an increased percentage of bare ground under both winter sheep grazing in pastoral hill country (Elliott & Carlson 2004) and cattle grazing (Russell et al. 2001).

Research in New Zealand has been conducted to design practices to mitigate the impacts of winter forage grazing. These include the use of catch crops (Carey et al. 2016), nitrification inhibitors (Shepherd et al. 2012), reducing grazing duration per day (Drewry & Paton 2005; McDowell et al. 2005), and grazing from the top of the slope by 'strategic grazing' (Monaghan et al. 2017). The use of such practices to reduce impacts on water quality is dependent on new practices, where practical, being adopted by farmers.

This project is primarily concerned with mapping high-risk paddock polygons and includes modelled estimates of sediment loss.

2.2 Previous bare-ground and winter-forage mapping

MWLR has a long history of mapping vegetation cover and bare soil for a range of purposes in environmental modelling and primary production. This work has involved a number of remote sensing satellite services, with applications including rangelands vegetation cover (Dymond et al. 1992) , nitrate leaching modelling (Lilburne & North 2010), sediment discharge over a range of land uses (Dymond et al. 2010, 2018), agricultural land uses and crop types and timings (North et al. 2019), and winter forage mapping (North et al. 2015, 2016, 2017).

Most of this land cover and land use work was carried out at a regional level and has resulted in robust methodologies that we have now applied to this national mapping of high-risk hill country. Key factors of the methodology are:

- using time series of analysis-ready satellite imagery
- semi-automated data processing on national high-speed computing facilities
- mapping on a per-paddock basis
- combining spectral analysis with a series of rule sets.

For more detail about this previous work, please refer to Appendix 1.

2.3 Sentinel-2 satellite imagery

MWLR use temporal sequences of Sentinel-2 imagery for their remote sensing mapping projects. Details of this satellite service are summarised in Appendix 2.

3 Objectives

- Assemble a time series of satellite imagery covering all regions of New Zealand for the period autumn to spring 2018. Identify the agricultural land (i.e. exclude forest, rivers, urban areas, etc.) and demarcate those areas having a slope of 7° or more.
- For these hill-country agricultural areas, map the land cover, separating winter forage crops, bare ground and pasture. Identify the paddock polygons considered at risk of soil run-off; i.e. those in which bare soil is observed or likely during the winter period. Report the mapping results as a GIS layer of the identified high-risk paddock polygons, together with their metrics.
- During the project, provide interim information as required by MfE: a set of early-stage candidate paddock polygons by 22 February 2019, and a set of provisional regional summary statistics derived from later-stage processing as at 29 March 2019.
- Include attributes required by MfE in the final high-risk paddock polygon map, including identification of region so that per-region metrics can be derived. Based on current/accepted practice, devise a bare ground severity index, and include attributes for each paddock polygon quantifying this through time and in summary form.
- Assess the validity of the hill-country winter forage and intensive grazing map and include this in a report detailing the methodology and results.

4 Methods and process

Numerous image-processing steps were taken to derive the locations of high-risk grazing on hill country from Sentinel-2 imagery. These processes, listed below, are detailed sequentially in this section:

1. image selection, assembly, calibration, and masking
2. paddock boundary mapping
3. NDVI analysis for early delivery of candidate paddock polygons
4. spectral, per-pixel classification of March to September imagery
5. implementation of the per-pixel and per-paddock polygon multi-temporal rules
6. manual checking of the riskiness veracity of the paddock polygons

4.1 Assemble, calibrate and mask satellite imagery

The key image preparation steps are as follows (they are explained in more detail below).

- For each image, carry out radiometric calibration and topographic flattening.
- For each image, create a cloud mask and mask out snow and deep shadow.
- Assemble a time series of the most suitable cloud-free satellite imagery covering the North and South Islands of New Zealand for the period September 2017 to November 2018.
- Select the required study site (i.e. agricultural land of 7° slope or more).

4.1.1 Data selection

The full archive of Sentinel-2 imagery from 1 September 2017 to 30 November 2018 was examined, and images with the best coverage (least cloud) for each region were listed. A decision was made to work at the regional level for ease of processing. That is, although some of the basic workflow to create analysis-ready imagery was carried out per orbit track, later processing ran region by region. We used the 2018 Statistics NZ regional boundaries (StatsNZ 2017).

A core set of the most cloud-free and most suitably timed imagery for paddock boundary mapping was identified. These data lists are shown in Appendix 3, with the images selected for paddock boundary mapping highlighted. Table 1 summarises the image counts, per region, for the prime identification and classification interval.

Table 1. Counts of imagery per region, per month, for March to September 2018

Region	Mar	Apr	May	Jun	Jul	Aug	Sep
Northland		1	1	3	2		
Auckland			2	2	2		3
Bay of Plenty	1	3	1	1	1	1	2
Waikato	1	1	1	1	2		2
Gisborne	1	3		1	1	1	1
Taranaki	2	2	2	2		2	2
Manawatū	3	3	2		1		1
Hawke's Bay	1	4		2	3	3	2
Wellington	1				1	1	2
Nelson		2	2	2			1
Tasman		1	1	2			1
Marlborough	1			2	1		1
West Coast	2			3			2
Canterbury	2		2	2	2	2	2
Otago	2	2		2	5	2	2
Southland	1	1	1	2	5	2	3

Notes: (1) pink rectangles indicate no data for that month; (2) not all images cover the entire region.

4.1.2 Calibration

Our processing pipeline takes the Sentinel data from the European Space Agency (ESA) hub and runs them through a series of automated correction and calibration procedures, including conversion to the New Zealand Transverse Mercator (NZTM) map grid.

The end-product of our processing pipeline is a topographically 'flattened' product to minimise brightness variations in hilly areas (Shepherd & Dymond 2003). This flattening uses an atmospheric model together with a digital elevation model (DEM) to calculate vegetation canopy reflectance on flat land. This produces clean spectral signatures, thus improving the capacity for automated classification.

The methodology is based on imagery with sun elevation angles of 40 degrees and upwards. However, in New Zealand, with our high latitude position and the 10:00–10:30 a.m. orbit crossing times, the flattened product is primarily fit for purpose for higher sun elevation parts of the year, with some residual topographic effect during the winter. For example, at the end of summer in Southland, the sun elevation angles dip below 40 degrees by the beginning of March; in the Bay of Plenty, the elevation angle remains at 40 degrees and above until, roughly, 20 March.

4.1.3 Masking

Cloud, cloud shadow and haze strongly affect our ability to see and recognise land covers and must be removed to reduce this source of error. There are cloud masks as part of the bundle of raw satellite imagery that we download, but these are not fit for purpose. Until recently our cloud cleaning has been carried out manually. However, time and resource constraints on this project precluded this: the image data set is much too large for manual cloud-cleaning to be practical. Fortuitously, our in-house-developed cloud, shadow and haze removal systems have recently improved to the point where we are able to apply them directly. There may be some edge effects still present in the cleaned data sets, and fine haze is always extremely difficult to detect, but the overall result is now fit for purpose.

The recent improvements to our cloud-masking procedure include taking our time-series-controlled layer (TMASK) and then running an algorithm that also looks at the approximate likely cloud–shadow distances (based on sun azimuths). Where no matches of cloud and cloud shadow are seen, we conclude that the flagged segment is a false positive and can be removed.

This process has greatly reduced the incidence of targets such as gravel in river courses, and some bare ground areas, being detected as cloud or cloud shadow. The TMASK clean-up algorithm contains several other routines that make similar minor but significant improvements. In addition, the Sentinel-2 cirrus band is used to mask out very thin, faint, cirrus clouds, which may have an impact on NDVI calculation. The masked regions (cloud and cloud shadow) are then smoothed and filled using a generalisation algorithm. Figure 1 shows an example of the cloud and cloud shadow detection improvements.

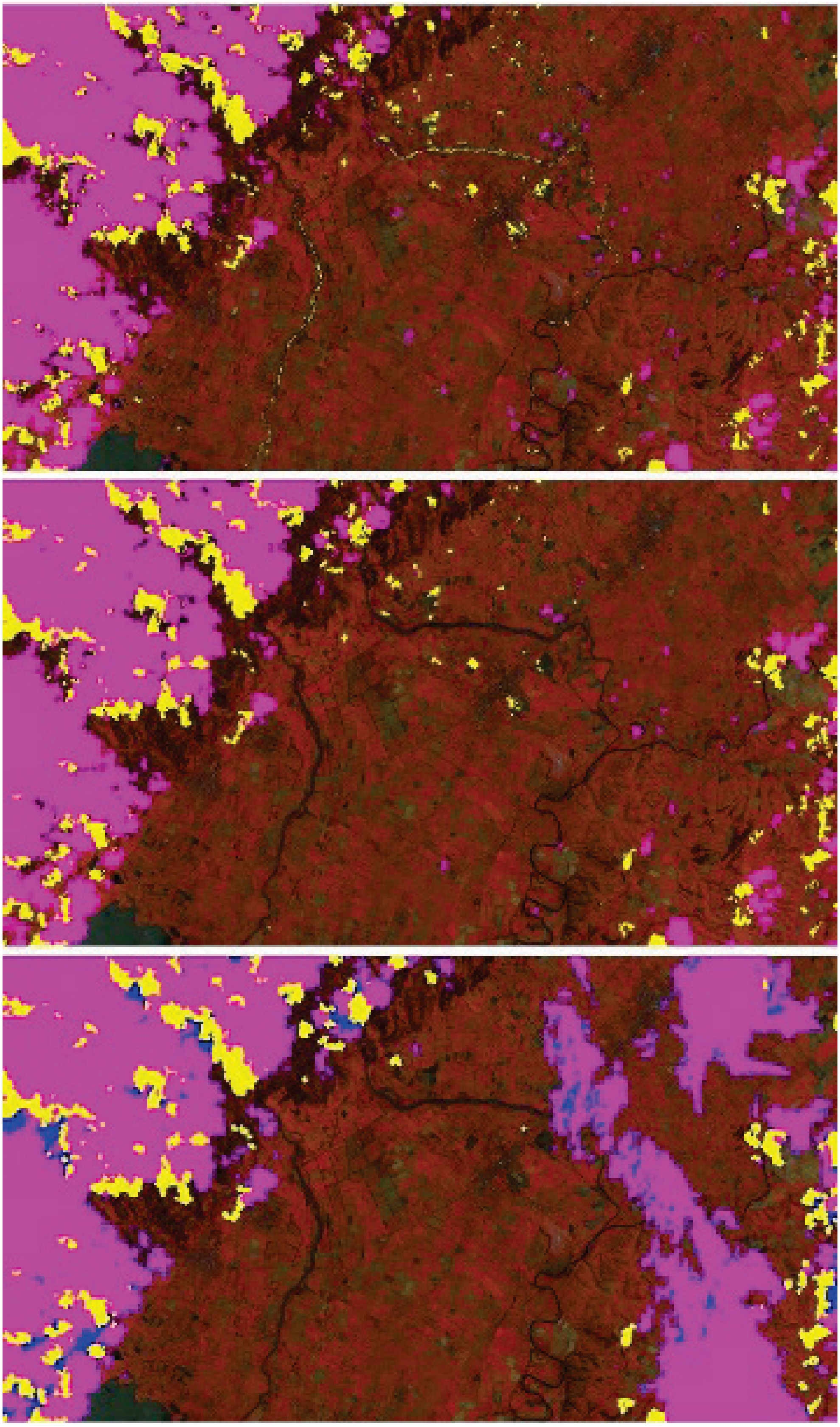

Figure 1. An example of the improvements recently made to our cloud masking procedures. The three panels show the original TMASK product (top panel), intermediate clean-up step (centre panel) and the full clean-up step (bottom panel), together with the cirrus mask and generalisation step (blue). Along with other improvements, most of the false positives, especially along river channels, are now no longer detected as clouds (pink) or cloud shadows (yellow).

4.1.4 Study site selection

MfE's area of interest was agricultural land with a slope of 7° or greater. We therefore constructed a mask to screen out non-agricultural land such as urban areas, rivers and forests, as well as all land in the Department of Conservation (DOC) estate (the 2016 version of the DOC estate boundaries was used for the latter). The prime input for this step was the current version (4.1) of the New Zealand Land Cover Database (LCDB 2015). We considered the following LCDB classes to be 'agricultural' for our purposes:

- short-rotation cropland
- orchard, vineyard or other perennial crop
- high-producing grassland
- low-producing grassland
- tall tussock grassland
- depleted grassland
- landslide.

The only exception is if the LCDB class is not one of the high-producing types (the first three on the list above), and the NZ Land Resource Inventory (NZLRI 2010) has a value of 'rive' in the SLOPE field: we mask out these areas to assist in removing stony, scrubby riverbank vegetation from consideration. Figures 2 and 3 show examples of this masking for two regions. Figures 4 and 5 show examples of the imagery from selected dates with both the cloud- and non-agricultural-land-masking applied.

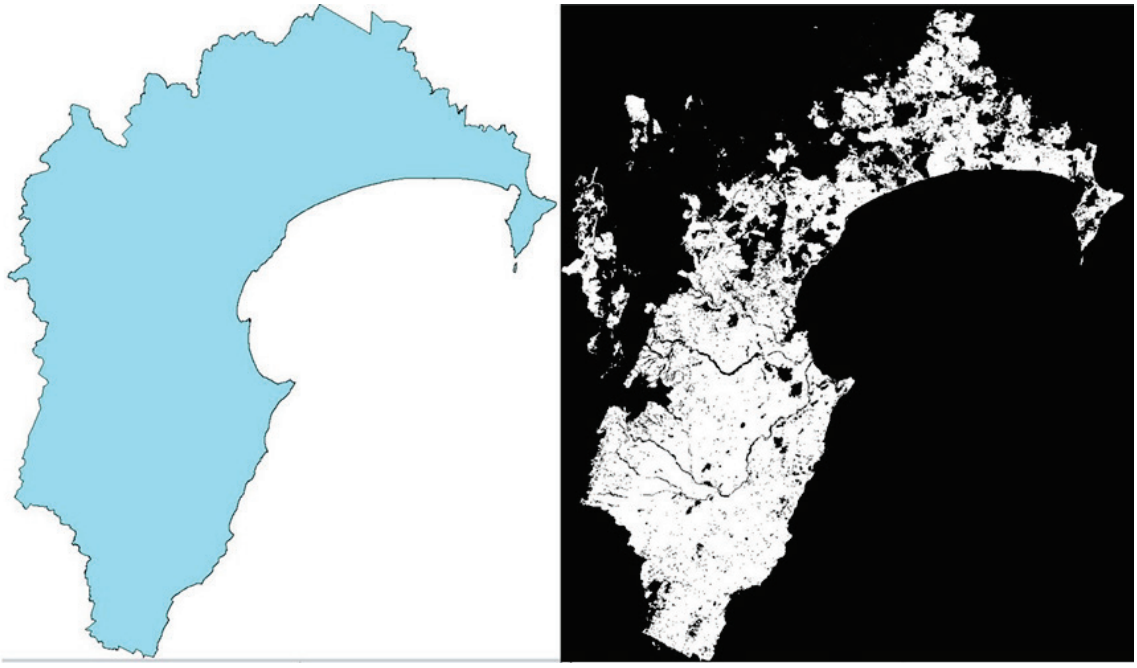

Figure 2. The boundary of the Hawke's Bay region (left) compared with the region once all the non-agricultural land has been masked out.

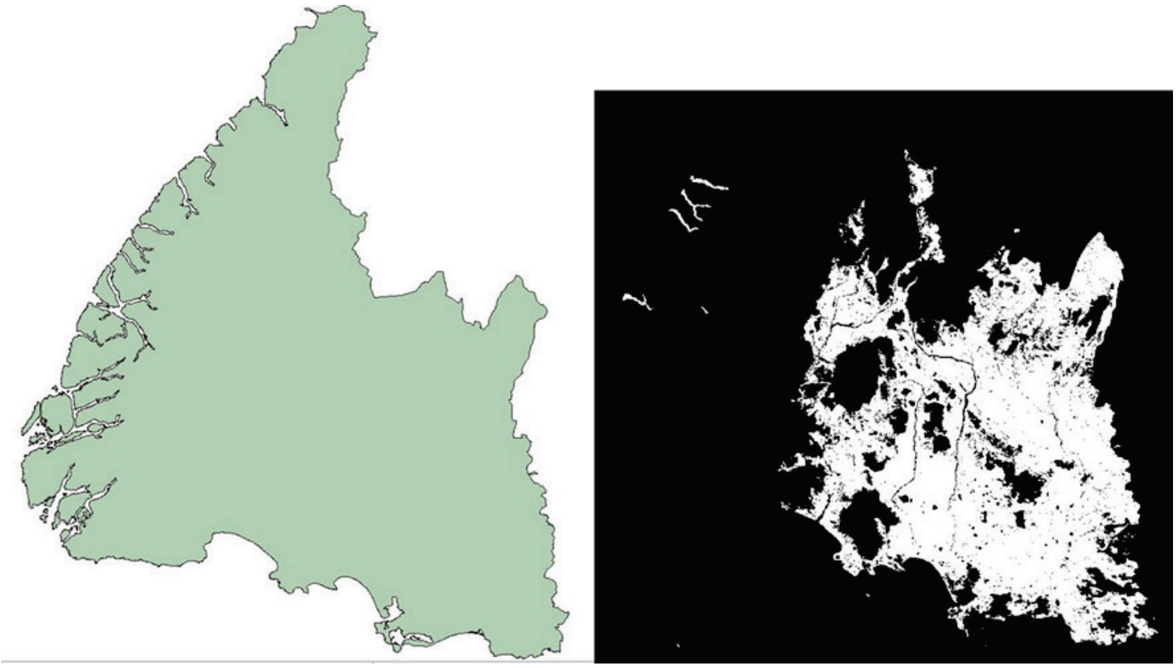

Figure 3. The boundary of the Southland region (left) compared with the region once all the non-agricultural land has been masked out. Much of the region, especially on the western side, is removed by the mask.
Note: there is an error in the masking, which has included four fjords and a small lake in the agricultural area, but these do not affect subsequent calculations.

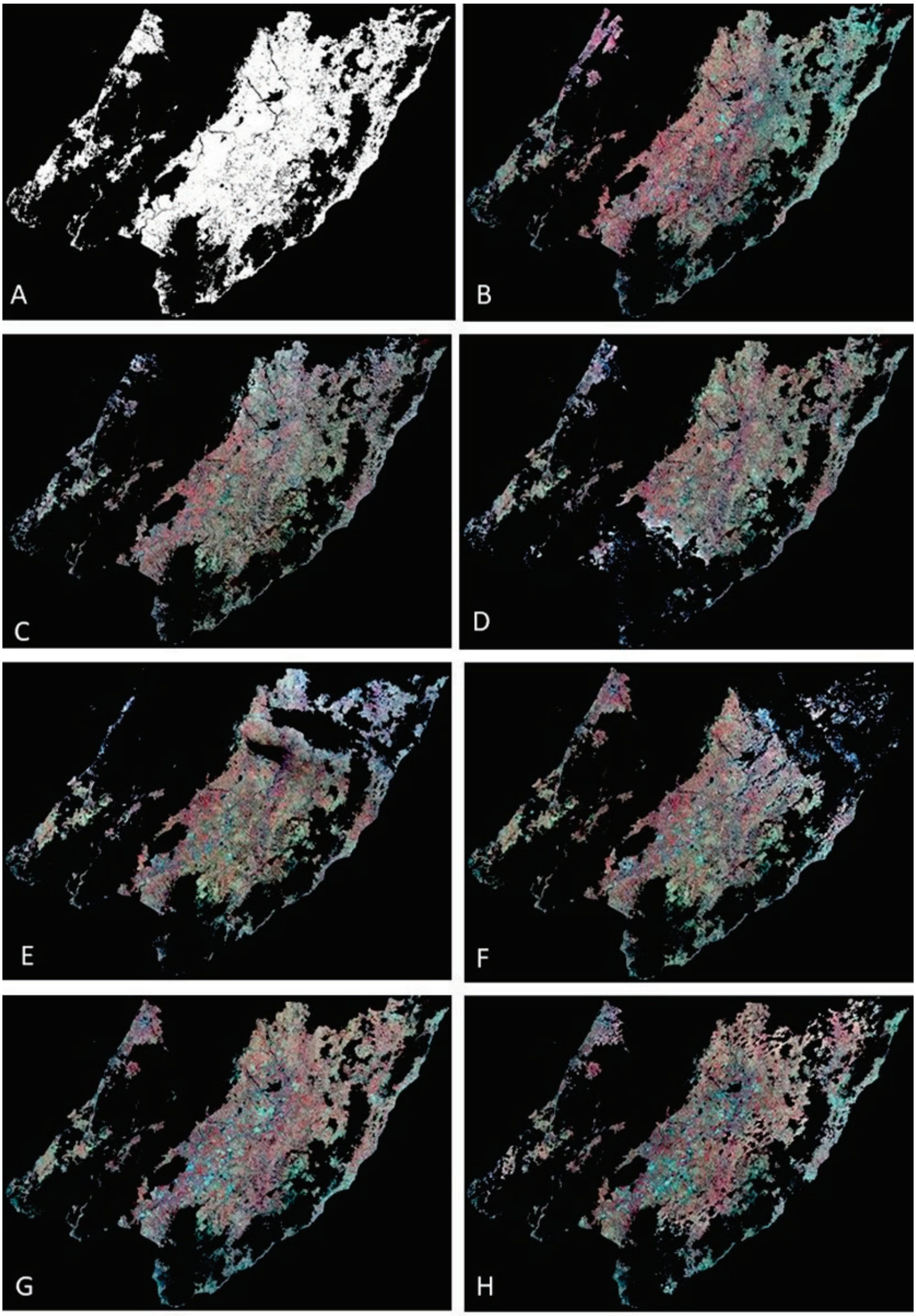

Figure 4. The full set of images for the Wellington region, with the non-agricultural land and cloud masked out.
This depicts *all* the agricultural land: the 7° slope constraint has yet to be applied. Note: some remnant cloud is still present in some of the masked images. A. the regional agricultural mask; B. 12 March 2018; C. 10 July 2018; D. 24 August 2018; E. 13 September 2018; F. 18 September 2018; G. 18 October 2018; H. 12 November 2018. (All dates are in universal time.)

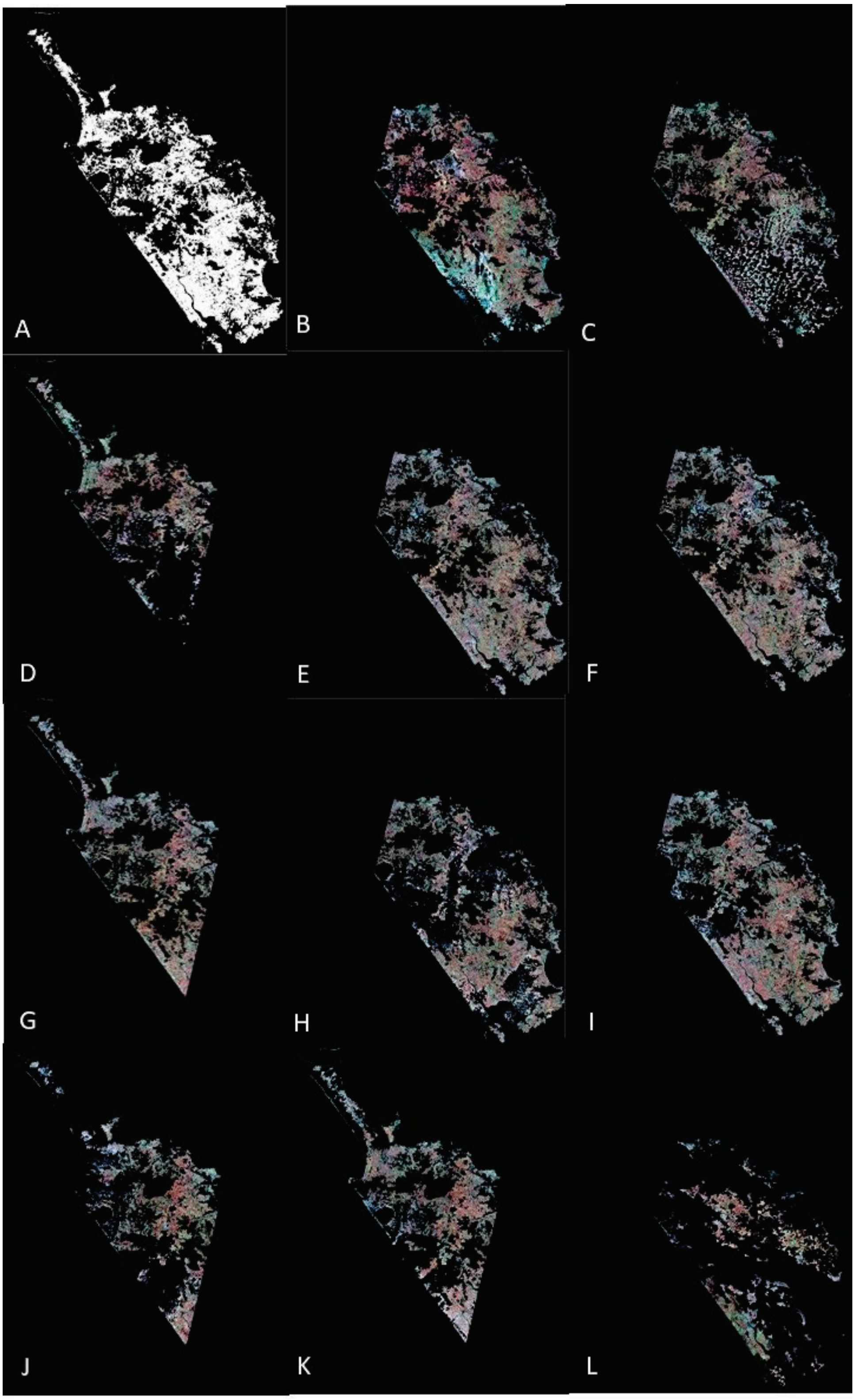

Figure 5. The full set of images for the Northland region, with non-agricultural land and cloud masked out.
This depicts *all* the agricultural land: the 7° slope constraint has yet to be applied This is an example of a region that straddles two satellite orbit tracks: the eastern and western edges are covered by a single orbit track, but the centre falls into an overlap zone. Note: some remnant cloud is present in some of the masked images. A. the regional agricultural mask; B. 9 January 2018; C. 24 January 2018; D. 12 April 2018; E. 29 May 2018; F. 8 June 2018; G. 21 June 2018; H. 28 June 2018; I. 3 July 2018; J. 11 July 2018; K. 4 October 2018; L. 25 November 2018. (All dates are in universal time.)

Finally, to separate hill country from plains, the 7° slope 'contour' is imposed. This is calculated on a paddock-by-paddock basis using slope maps that were generated from MWLR's 15 m raster DEM (which was derived from LINZ 20 m contours) and uses the average per-pixel slope within the paddock polygon boundary. Figure 6 shows a tile of the raster slope layer used in the project.

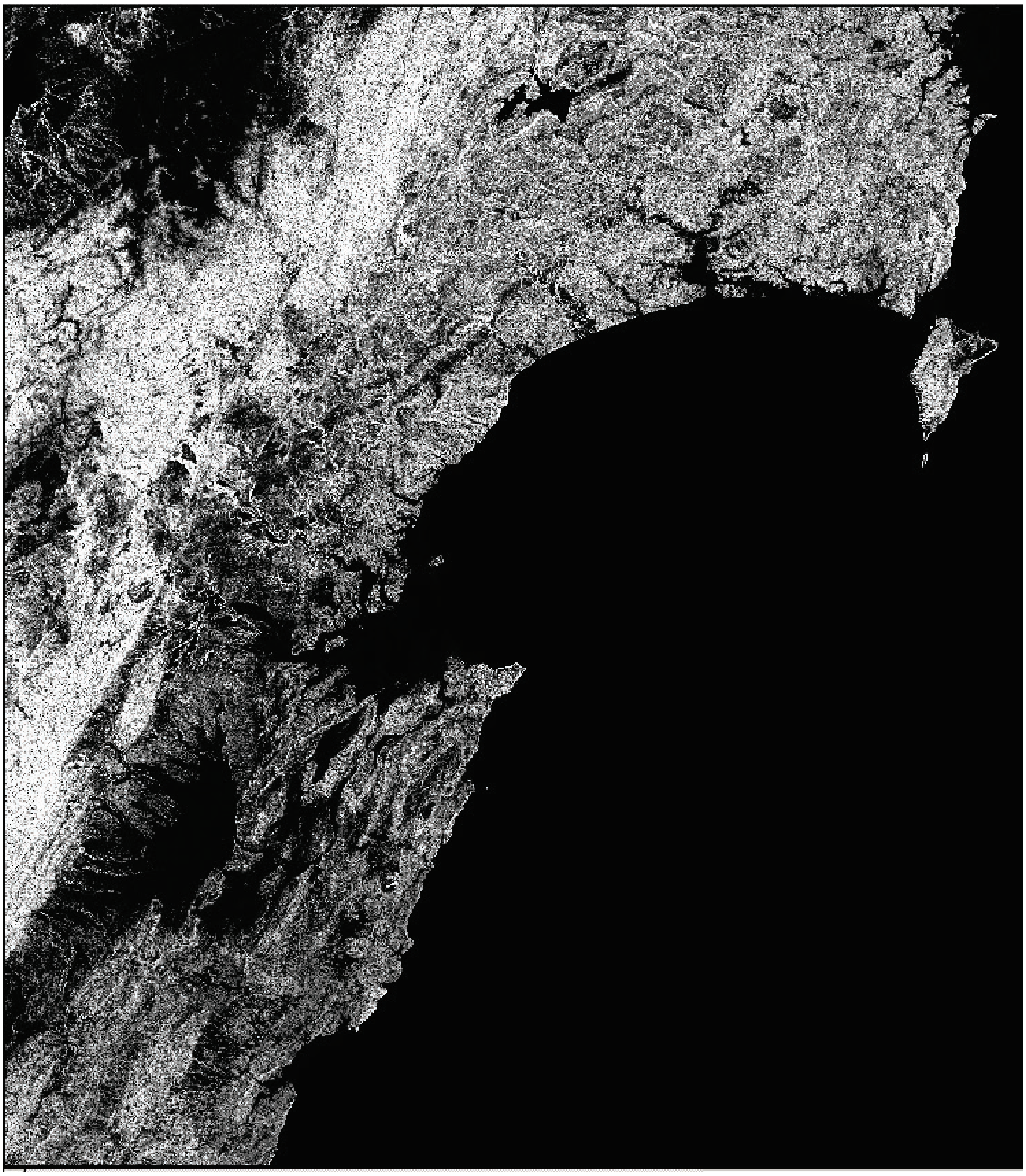

Figure 6. An example of the slope information later used to separate paddock polygons defined as hill country from the rest of the agricultural land. Slopes in this tile vary from 0° to around 50°. Pure black = 0°; pure white = 90°.

4.2 Paddock boundary mapping

A vector layer of paddock boundaries is created using an algorithm (North, Pairman et al. 2019) implemented to run on the NeSI (New Zealand eScience Infrastructure) high-performance computing system. This is a very important step for the later land-use classification because it enables paddocks to be analysed and classified as whole objects. This is more robust than considering only the classification of individual pixels (Ullman 1996).

The algorithm works by finding boundaries between different crops and land covers. Use of a time sequence of images, typically over a year, enables paddock boundaries not visible in one image to show up at another time. Generally, these will be demarcated by fence-lines, but sometimes there will be parts of paddocks planted out with different crops, or the same crop managed differently, and our algorithm will define these as separate paddocks. An example of the resulting polygons is shown in Figure 7.

The steps in paddock boundary mapping are as follows.

- Select a suitable time series of satellite images that cover a year, or at least a full sequence of a crop life cycle, and that are as cloud free as achievable.
- Identify areas of high standard deviation in the spectral values (which can be expected across linear features such as shelterbelts and farm tracks, as well as between different land covers) using a series of directional filters that emphasise the detection of long, linear features.
- Convert the raster linework created by the previous process to vector linework. During this phase, this linework is tidied up; small breaks are closed by extending existing line ends, and smoothing removes pixel stair-casing. In addition, the road network is burned into the linework. Then, the linework is converted to polygons, with any very small ones (less than 0.1 ha) removed since they are more likely to be houses, other buildings, trees etc. rather than paddocks.
- Buffer the insides of the paddock polygons by 14 m to obtain a polygon that excludes pixels near boundaries, which may be mixtures of paddock and edges. The pixels within this buffered polygon can be used for spectral analysis of the paddock, though the final classification is applied to the original (unbuffered) paddock polygon.

Our methodology was developed on flat land and tends to over-divide the hilly areas, where slope, aspect and shadowing can add false boundaries. We applied the paddock boundary mapping to band-ratio images (rather than to the original spectral data) to minimise these variations of light and shade, but some residual effects remain. However, the effect of this on the results should be minimal since the false boundaries tend to be within paddocks. That is, the paddock may be subdivided but the high-risk areas contained within the paddocks are still identified.

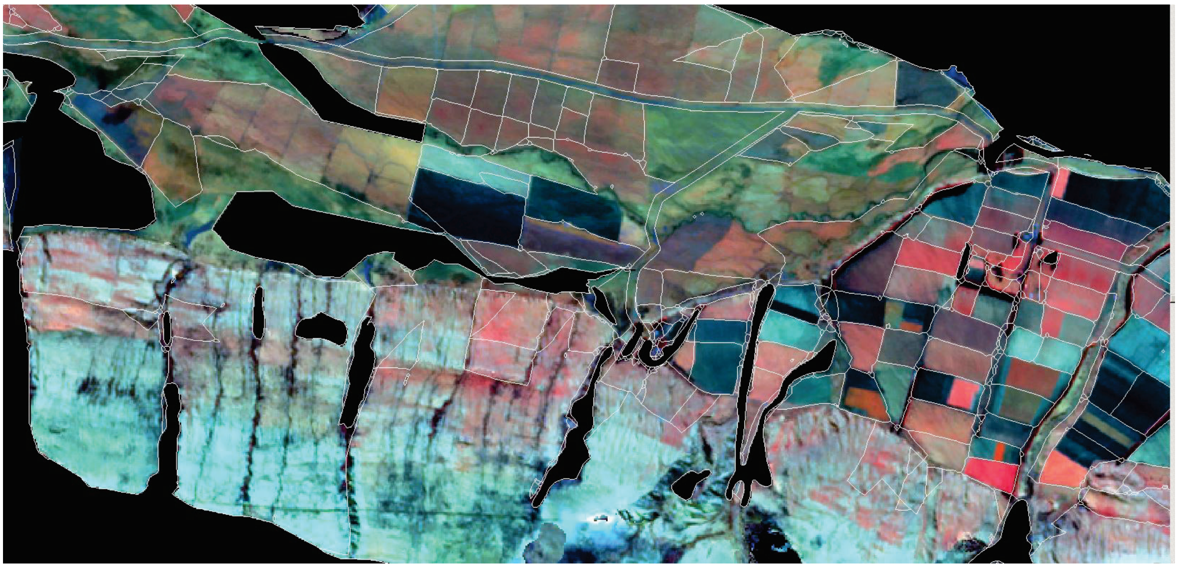

Figure 7. An example of the paddock boundary layer (in white) overlain onto a Sentinel-2 satellite image taken on 3 August 2018 NZST. This area is a mix of hill country and flat land.

4.3 Early supply of candidate paddock polygons

Due to urgency at MfE, a provisional layer of candidate paddock polygons was required at an early stage of the processing (by 22 February 2019). For this, we used only the Normalised Difference Vegetation Index (NDVI) and some simple rules to detect candidate paddock polygons. It was expected to overestimate the number of high-risk paddock polygons, with subsequent processing required to refine this.

Brief notes on the method used to generate this initial layer are contained in Appendix 4.

4.4 Spectral/temporal land-cover classification (per pixel)

Use of complete spectral information was required to better separate bare ground from other low-NDVI ground covers. The identification of bare ground paddock polygons is carried out at the pixel level, and the processing operates on a multi-temporal stack of image classifications in which the classified land-cover classes are:

1 bare soil

2 stubble/dead vegetation

3 winter forage brassica

4 winter forage fodder beet

5 winter forage cereal

6 pasture

7 pasture (poor/rough)

8 partial cover brassica

9 partial cover fodder beet

10 partial cover cereal

11 partial cover pasture

12 non-agricultural tussock/herbfield

13 trees/scrub.

Pixel-by-pixel spectral classification is carried out using a maximum likelihood (ML) classifier. The training data for this classifier were spectral signatures derived from previous analysis of Hawke's Bay winter forage cropping (North, Belliss et al. 2019). Mean spectral responses and spectral covariance matrices for ML classification of new imagery were developed for several subclasses that have been grouped together into the previous list of distinct classes. Each pixel of each image in the March to September set of imagery was assigned the ML class output by the classifier for the determination of dominant land cover in autumn and winter. The spectral classification methodologies have been programmed to run in a parallel manner on the NeSI high-performance computing system.

The dominant land cover in autumn/winter was identified for each pixel. For pixels that did not become vegetated until after 30 June, this class could be either bare soil or dead vegetation; the images showing bare soil and dead vegetation for a pixel were counted, and the dominant class was assigned to that pixel's classification. Analysis of all other pixels used the temporal range of image classifications in which that pixel was vegetated. Pixels with a majority of valid images corresponding to a particular type of full-cover winter forage or bare ground were assigned to that winter land-cover class. The list of winter land-cover classes is as follows (WF = winter forage):

WLC1. bare soil

WLC2. dead vegetation

WLC3. trees/scrub

WLC4. tussock/herbfield

WLC5. low cover pasture

WLC6. Pasture

WLC7. WF fodder beet

WLC8. WF cereal

WLC9. WF brassica

WLC10. WF unknown

Vegetated pixels that were not distinctly identified as belonging to classes WLC3, WLC4, WLC6, WLC7, WLC8, or WLC9 were assigned to WLC5 or WLC10.

Figure 8 is an example of a typical winter forage crop gradually being strip-grazed over a winter. We would expect the dominant autumn/winter land cover within this paddock to be classified as one of the winter forage types, where this type is identified using images from the relevant date range during which the pixels were vegetated.

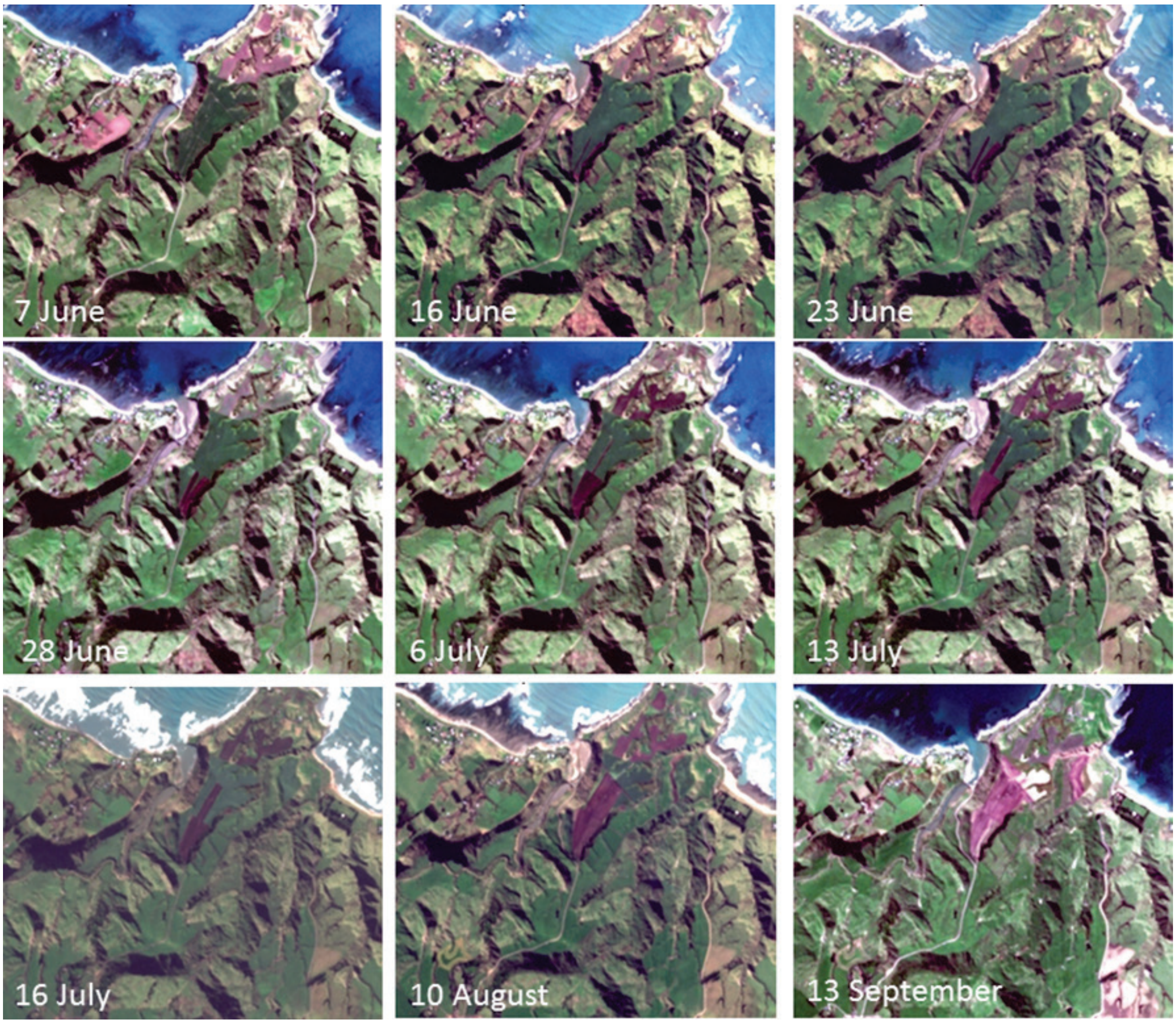

Figure 8. A typical example of the temporal pattern that indicates a winter forage crop. The large paddock in the upper centre of this subscene is fully vegetated (green) in early June and then, from mid-June, the vegetation cover is gradually reduced by strip-grazing until the ground is completely bare (pink/brown) by mid-September. To the left of the winter forage paddock (on the other side of the river) is a paddock that is bare in early June and then greens up, remaining green right through to September. This could be an example of a summer crop that has been replaced by an intercrop pasture. Source: 2018 imagery of an area in northern Hawke's Bay.

4.5 Per-paddock statistics, bare ground severity indices, and the identification of high-risk winter grazing

The results of the classification steps outlined above are used to derive the per paddock statistics of the final vector product:

1. **image dates on which transitions between vegetated and bare states occur**
2. **dominant land cover in autumn/winter (WLC class).**

Then we derive the following statistics.

3 Per-paddock polygon percentage of bare soil pixels, calculated for each image date

The bare soil area percentage is our 'de-vegetation severity index'. This is calculated from the percentage of bare soil pixels (not dead vegetation) in the *buffered* paddock polygon area. If there are no data (or too few pixels) in the paddock polygon, then a no-data value is assigned.

4 The 'starting classification' of forage crop, pasture and bare ground, as required by MfE

This is based on imagery from March through to May, and is derived by calculating the number of valid pixels within the buffered area of the paddock polygon summed across all image dates in the 1 March to 30 May period, and then calculating the fraction of them in each of the following class definitions: bare soil, dead vegetation, pasture, forage crop. The assigned class is that with the maximum fraction over 0.5. If the maximum fraction is less than 0.5, then the paddock polygon is flagged as unknown.

MfE initially suggested that this classification be based on imagery from March–April only, but the extension to May improves the chance of image coverage in autumn. In addition, much of the grazing – though not all – begins after the end of May. We note that some forage crops, particularly oats and leafy turnip, tend to be planted late and would usually not be visible in March or even April. With these crops the paddock would often still be bare soil or dead vegetation during the autumn. For this reason, we use our dominant winter land-cover classification (described below) in subsequent analysis steps, rather than using this autumn 'starting classification'.

5 The dominant winter land cover

This is based on the per-pixel dominant land-cover classification, as described in section 4.4 (listed as 2. above). Within each paddock polygon the classes of the pixels are gathered together to derive an overall classification for the paddock. We want to know whether there is a spectrally identifiable winter forage crop in the paddock polygon, or pasture, or whether the paddock polygon is bare soil throughout the autumn/early winter period.

The starting classification (4. above) goes some way towards providing this, but with the variation in planting and grazing dates for winter forage this flag will allow a more robust identification.

The dominant winter land cover is calculated from the fraction of valid pixels within the buffered area of the paddock polygon that are in each of the land-cover classes. The class with the highest fraction of pixels is assigned to the LandCover attribute (if two classes have the same fraction, then the order of classes determines the precedence).

6 Intensive winter grazing

These statistics are derived for the paddocks identified as winter forage or pasture, but not for areas classified as non-agricultural or extended-period (autumn/winter) bare soil/dead vegetation, or as low-cover/undeveloped pasture. The following statistics are required by MfE, and we use them for the final identification of high-risk paddocks:

- first bare date
- last bare date
- length of time the paddock polygon is bare – bare period
- overall de-vegetation severity score – based on the average bare soil percentages between May and September, inclusive.

7 High-risk paddock polygons

High-risk paddock polygons are identified using the following rules (summarised in Table 2), which assign a certainty of 3 (good), 2 (medium) or 1 (low) to this assessment:

RiskCert 3: identified as specific winter forage type and observed to become bare soil.

RiskCert 2: cases (1) identified as specific winter forage type and not observed to become bare soil, but there are no late winter/early spring images available in which to observe it; (2) identified as unknown winter forage and observed to become bare soil; or (3) identified as pasture and observed to become bare prior to the end of August.

RiskCert 1: cases (1) identified as fodder beet or cereal winter forage type and not observed to become bare soil, even though there are late winter/early spring images available; (2) identified as brassica winter forage type and not observed to become bare soil, even though there are late winter/early spring images available, and there is an NDVI drop between autumn and winter greater than 0.3; or (3) identified as unknown winter forage and not observed to become bare soil.

Table 2. Summary of certainty levels for high-risk paddocks

	Dominant winter land cover	Paddock observed to become bare soil (>20%) in winter/early spring	Valid image data exists in period mid-August to end-September	Significant NDVI drop from autumn to winter
RiskCert 3 (good)	Brassica or fodder beet or cereal	Yes	N/A	N/A
RiskCert 2 (medium) – case 1	Brassica or fodder beet or cereal	No	No	No
RiskCert 2 (medium) – case 2	Unknown winter forage	Yes	N/A	N/A
RiskCert 2(medium) – case 3	Pasture	Yes (before end-August)	N/A	N/A
RiskCert 1 (low) – case 1	Fodder beet or cereal	No	Yes	N/A
RiskCert 1 (low) – case 2	Brassica	No	Yes	Yes
RiskCert 1 (low) – case 3	Unknown winter forage	No	N/A	N/A

4.6 Derivation and application of bareness severity indices

Twenty percent bare ground is a key threshold when sediment load is over an order of magnitude greater than normal pasture grazing (Dymond & Herzig 2015). This is also the figure referred to in the original request for work as the definition for 'starting bare ground'. In general, the literature shows that sediment loads increase markedly after a 20% bare ground threshold (e.g. Nguyen et al. 1998). Other studies have also shown increased sediment loss as the percentage of bare ground increases (Elliott & Carlson 2004; Russell et al. 2001). In the model of Dymond & Herzig (2015), soil erosion on bare ground is 100 times greater than that on pasture, so when the percentage of bare ground in a paddock is 20% the average soil erosion is 20 times that of a pasture paddock.

In the study of Nguyen et al. (1998), for example, the quantity of suspended solids in runoff generally increased with the extent of soil damage and runoff volume. The study reported soil damage (various indicators) above 40% on steep slopes had considerably greater suspended sediment runoff than for easy-contoured slopes. Russell et al. (2001) reported a relationship of sediment loss from percentage bare ground and average slope, while Elliott & Carlson 2004 reported suspended sediment yield increased with the percentage bare ground.

For winter forage grazing (such as on brassicas) in New Zealand, the data on percentage of bare ground from field experiments is scarce in the published literature. Common observation indicates that once the forage crops have been grazed and pugged, bare ground remains until a new crop or pasture is sown. Some literature also reports that winter grazed/pugged forage crop bare ground remains until subsequent re-sowing (Monaghan et al. 2017).

Sediment and nutrient losses from sheep and cattle winter-grazed hill country pasture are greater with increased percentage of bare ground and soil damage from treading (Nguyen et al. 1998; Sheath & Carlson 1998; Russell et al. 2001; Elliott & Carlson 2004). Sediment loss in hill country pasture is directly related to the percentage of bare ground (Russell et al. 2001; Elliott & Carlson 2004). Particulate nutrient (total phosphorus and total Kjeldahl nitrogen) loss in hill country pasture is also directly related to the percentage of bare ground (Elliott & Carlson 2004).

Bare ground is the main driver for risk of soil loss, but it is exacerbated by high rainfall, steep and long slopes, and poorly drained soils. The soil erosion model of Dymond and Herzig (2015) takes into account these risk factors. The rainfall factor is proportional to the square of rainfall. The slope steepness factor is proportional to the square of slope. The slope length factor is proportional to the square root of slope length. We have applied this model to every paddock, found at risk in this study, to estimate the total soil loss from each paddock over winter resulting from the risk factors. To give an indication of risk to receiving waters we have compared the total soil lost from risky paddocks with total sediment loads in rivers for each region.

The winter sediment load in rivers is the sediment delivered to all the REC segments (streams that are defined in NIWA's River Environment Classification database of all New Zealand, where all first-order sub-catchments and associated streams are defined) in the region during winter. This is a New Zealand Empirical Erosion Model (NZeem®)

calculation (Dymond et al. 2010) that takes 5/12ths of the annual average sediment load as the load delivered during a 5-month period over winter (May–September in this report). The soil lost in (this extended) winter from risky hill country agricultural land (last column of Table 5) is the soil lost from the paddocks as estimated using the New Zealand Universal Soil Loss Equation (New Zealand Universal Soil Loss Equation) (Dymond & Herzig 2015). Approximately half this lost soil, as modelled, is likely to end up in streams, with the remaining half being deposited on flat land before reaching streams.

4.6.1 Definition of de-vegetation indicator

Table 3 gives the definition of de-vegetation and other indicators as required by MfE in contract section 'Summary and time series statistics of spatial data output 4'. Indicators required by MfE are in the left column and resulting definitions are in the right-hand column. This includes bare soil percentages for each high-risk paddock at every date in the time series. We have defined the risky de-vegetation threshold to be the point where 20% or more of the paddock's area is bare soil.

Table 3. Paddock-level summary data required by contract in left column, with resulting definition in right column

A. Unique polygon ID for paddock	Unique polygon ID for paddock
B. An *overall* de-vegetation indicator score	Average % bare ground in winter.
C. An *overall* de-vegetation threshold	Average of % bare ground in winter >20%
D. No. of cloud-free images in polygon's image stack	No. of cloud-free images in polygon's image stack
E. Flag to indicate if the de-vegetation threshold has been breached at any time in time series	Define a threshold of bare ground >20% (the `de-vegetation threshold').
F. Identification of when de-vegetation threshold was breached (first image date showing breach).	Identification of when de-vegetation threshold was breached (first image date showing breach).
G. Indication of length of time a particular threshold –20%– is breached (days); for bare ground polygons, this will show recovery (if any) over the winter season.	Indication of length of time the particular threshold (20%) is breached (days); for bare ground polygons, this will show recovery (if any) over the winter season.
H. confidence score for the classification as crop, pasture, or bare ground	Overall classification accuracy **(**LCConf – the proportion of pixels in the paddock that matched its predominant classification)
I. Confidence score for the overall de-vegetation indicator score reported as a summary statistic per polygon	Incorporated into RiskCert A three-level indicator of risky practice based on observed land-cover and de-vegetation threshold breach dates

Originally, MfE was also interested in forage crops that are planted but do not establish properly. If a forage crop was slow to establish but grew on into the winter and was then eaten down, it will have been picked up in our classification methodology. However, if it never established, then it is difficult to distinguish these paddocks from areas of spring pasture renewal, which could still have relatively low cover in November. In the case of a forage crop that did not establish, it is likely that some type of vegetation would have grown in the paddock by the following autumn. After discussions with MfE at the meeting in late February, we understood that areas that become bare during the winter are their prime focus; areas that remained bare or semi-bare right throughout were less important, and both parties agreed that this metric was not required.

4.7 Manual checking of paddock polygons

The paddock polygons flagged as high risk by the rules in section 4.5 could still contain false positives due to remnant cloud or shadow, or to remaining shrubland etc. not masked out by LCDB.

Manual checking of these candidate paddock polygons flagged as high risk by the rules in section 4.5 was carried out using the Landcare Research Map Accuracy dashboard. This tool facilitates simultaneous viewing of multiple data sets so that rapid decisions can be reached, in this case, on the veracity of a series of target paddock polygons.

For this specific task the dashboard was set up with eight viewers and populated with a sequence of images. Table 4 shows the layout of the dashboard and Figure 9 shows an example of it populated with imagery. Viewer 5, at the bottom left, is always the date at which the paddock polygon is first identified as being bare; the other viewers contain the best distribution of image dates on either side of the viewer 5 date, in chronological order. If there are no data, then the screen is blank. The target polygons always appear centred in the imagery, and the magnification can be varied to suit the size of the target polygon under consideration.

Table 4. Layout of the dashboard for checking the paddock polygons

Viewer 1 A date before viewer 2 OR no data	Viewer 2 A date before viewer 3 OR no data	Viewer 3 A date before viewer 4 OR no data	Viewer 4 A date before viewer 5 OR no data
Viewer 5 Image recording the first time the paddock was identified as bare	Viewer 6 A date after viewer 5 OR no data	Viewer 7 A date after viewer 6 OR no data	Viewer 8 A date after viewer 7 OR no data

To make a decision, the operator views the imagery in the various screens and is able to quickly determine whether the paddock polygon is correctly identified as a forage crop that has become or will become bare, or if it has been flagged incorrectly. The dashboard has been set up so that simple keystrokes record the decision to either retain or remove the polygon, then move the view to the next candidate paddock polygon.

If additional information is required, then more viewers can be added to work alongside the core eight, displaying data such as the latest LCDB, or SPOTMaps.

The manual checking was run region by region.

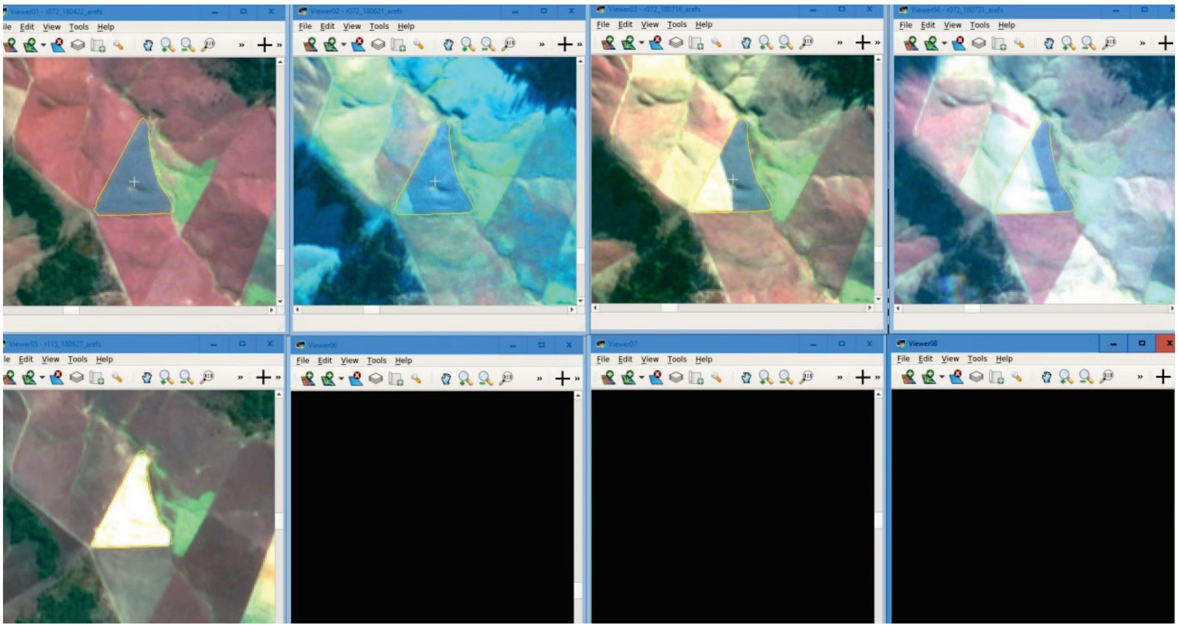

Figure 9. Map accuracy dashboard set up for the Southland region.
Here there are no image data to populate viewers 6–8; viewer 1 contains an image from 22 April, viewer 2 from 21 June, viewer 3 from 16 July, viewer 4 from 31 July, and, finally, viewer 5 from 27 September. The images show a clear succession from a paddock polygon fully covered in brassicas, through gradual amounts of break feeding, and a completely bare paddock polygon at the end of the image series.

5 Results

5.1 Provisional early results

Provisional results – see Appendix 4 for details – were supplied during the project work in order to meet MfE reporting deadlines.

5.2 High-risk paddock results after manual verification of candidate polygons

There were 11,505 paddock polygons identified in the RiskCert categories defined in section 4.5. Figure 10 shows a subscene of these candidate paddock polygons.

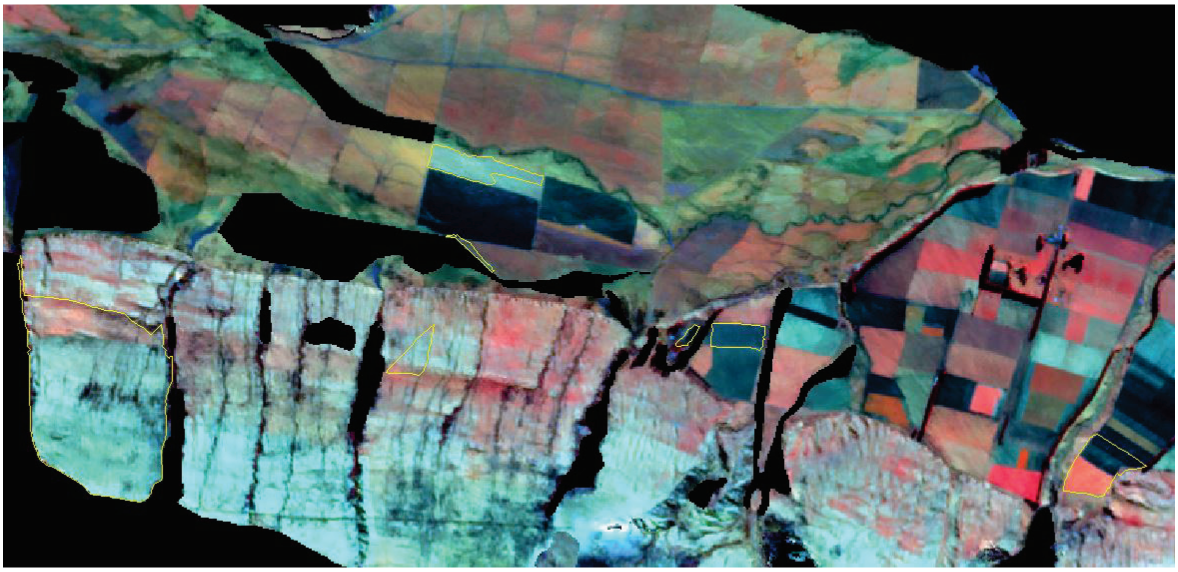

Figure 10. Seven candidate paddock polygons (outlined in yellow) on a Sentinel-2 image subscene of inland Canterbury taken 3 August 2019 NZST.

All 11,505 candidate high risk paddock polygons were manually checked for veracity. In general, we found that the algorithm selecting the high-risk paddock polygons was working well, although the paddock numbers rejected during the manual checking process varied enormously from region to region. For example, the large South Island regions of Otago (12%), Canterbury (18%) and Southland (9%) had low rejection rates; Auckland (83%) and Northland (79%) had the highest. The paddock polygons identified as false positives and thus rejected tended to be very small and in areas of shady gullies, often admixed with some shrubland. For example, in Tasman, where there were only 89 candidate paddocks, 50 of these (56%) were rejected and comprised small areas, often slivers, of mostly shrubland (28% of the total polygons), or mostly shadow (18% of the total polygons), and usually a combination of both. Many of these errors are likely to reflect masking errors. That is, they are revealing minor mapping errors in the national land-cover database that was used to create the non-agricultural land mask.

In our paddock boundary mapping methodology, which creates the paddock polygons, we use a threshold of 0.1 ha, discarding all polygons below this size as they are unlikely to be actual paddocks. For future work we could consider raising the threshold to, perhaps, 0.2 ha. This should reduce the number of false positives in the paddock polygons without affecting the results.

A series of accepted and rejected polygons are shown in Appendix 5. These include examples of masking errors; that is, areas that should not have been part of the agricultural land including examples of water and shrubland.

The number of candidate paddock polygons to be checked varied from region to region, with none in Nelson and over 4000 in Otago. The numbers checked and the numbers included/rejected are shown in Table 5.

Table 5. Candidate paddock polygon numbers before and after manual checking

Region	Number of paddock polygons to be checked	Number of rejected polygons	Number of risky paddock polygons	Area of risky paddock polygons (ha)	Percentage of hill country defined as risky	Soil lost in winter from risky agricultural land >7° (t) *
Northland	140	111	29	416	0.15%	76,538
Auckland	48	40	8	34	0.04%	171
Waikato	988	302	686	2337	0.43%	40,641
Bay of Plenty	296	154	142	563	0.59%	7476
Gisborne	146	108	38	254	0.08%	6327
Hawke's Bay	629	184	445	1794	0.37%	34,260
Taranaki	139	72	67	182	0.12%	2002
Manawatū	480	297	183	684	0.08%	10,966
Wellington	49	13	36	161	0.07%	4005
Nelson	0	0	0	0	-	0
Tasman	89	50	39	245	0.45%	4029
Marlborough	177	91	86	363	0.19%	4247
Westland	16	3	13	35	0.45%	1610
Canterbury	2333	435	1898	10,844	1.20%	150,070
Otago	4715	489	4226	16,232	1.61%	193,595
Southland	1260	112	1148	7938	2.21%	153,983
Total	**11,505**	**2461**	**9044**	**42,082**	**0.76%**	**689,921**

*see section 4.6 for information on the significance of these metrics

After this manual checking to remove unauthentic paddock polygons, the final number of risky paddock polygons was 9044.

5.3 Final high-risk paddock polygon results

The final classification of the risky paddock polygons is shown in Table 6 and is further broken down to specific classes in Table 7.

Table 6. Regional classification counts and areas of high-risk hill country polygons

Region	Number of high-risk paddock polygons classified as forage	Area of high-risk polygons classified as forage (ha)	Number of high-risk paddock polygons classified as pasture	Area of high-risk polygons classified as pasture (ha)
Northland	24	395	5	21
Auckland	1	0	7	34
Waikato	431	1536	255	801
Bay of Plenty	71	334	71	229
Gisborne	26	206	12	48
Hawke’s Bay	356	1411	89	383
Taranaki	43	100	24	81
Manawatū	149	584	34	100
Wellington	36	161	0	0
Nelson	0	0	0	0
Tasman	29	174	10	71
Marlborough	45	202	41	161
Westland	11	33	2	2
Canterbury	1272	7086	626	3758
Otago	3391	13,056	835	3176
Southland	1025	7104	123	834
Total	**6910**	**32,383**	**2134**	**9698**

Table 7. Detailed classification counts of the high-risk paddocks for the regions

Region	WLC6 Pasture		WLC7 WF-fodder beet		WLC8 WF-cereal		WLC9 WF-brassica		WLC10 WF-unknown	
	No.	Area (ha)	No.	Area (ha)	No.	Area (ha)	No.	Area (ha)	No.	Area (ha)
Northland	5	21	0	0	0	0	24	395	0	0
Auckland	7	34	0	0	0	0	1	0	0	0
Waikato	255	801	5	18	16	54	410	1,464	0	0
Bay of Plenty	71	229	0	0	2	3	61	318	8	12
Gisborne	12	48	0	0	0	0	24	204	2	3
Hawke's Bay	89	383	2	7	24	73	320	1,313	10	18
Taranaki	24	81	1	3	3	3	35	85	4	10
Manawatū	34	100	0	0	2	3	142	575	5	6
Wellington	0	0	0	0	0	0	35	159	1	2
Nelson	0	0	0	0	0	0	0	0	0	0
Tasman	10	71	1	1	1	3	27	170	0	0
Marlborough	41	161	0	0	3	9	40	190	2	2
Westland	2	2	0	0	0	0	10	33	1	1
Canterbury	626	3,758	4	7	4	13	1,258	7,054	6	11
Otago	835	3,176	4	6	20	38	3,320	12,896	47	117
Southland	123	834	2	2	5	20	997	6,996	21	86
Total	**2,134**	**9,698**	**19**	**44**	**80**	**219**	**6,704**	**31,852**	**107**	**269**

Note: WLC1 (bare soil), WLC2 (dead vegetation), WLC3 (trees/scrub), WLC4 (tussock/herbfield), and WLC5 (low cover pasture) are not risky paddock polygons under the rules as defined for this project. Thus the numbers and areas of these are all zero.

From our previous regional winter forage mapping experience, we suspect that fodder beet is underestimated, i.e. that some fodder beet paddocks have been classified as brassica. This is likely due to the lack of fodder beet ground-truth from the 2018 Hawke's Bay data. However, we had no fodder beet paddocks in the crop-type accuracy assessment (section 6.2) so are unable to quantify this.

Once all the checking was completed, a layer of the final risky paddock polygons was created. This was calculated for each region and then concatenated to a national layer. Figure 11 shows a subscene of the final paddock polygons.

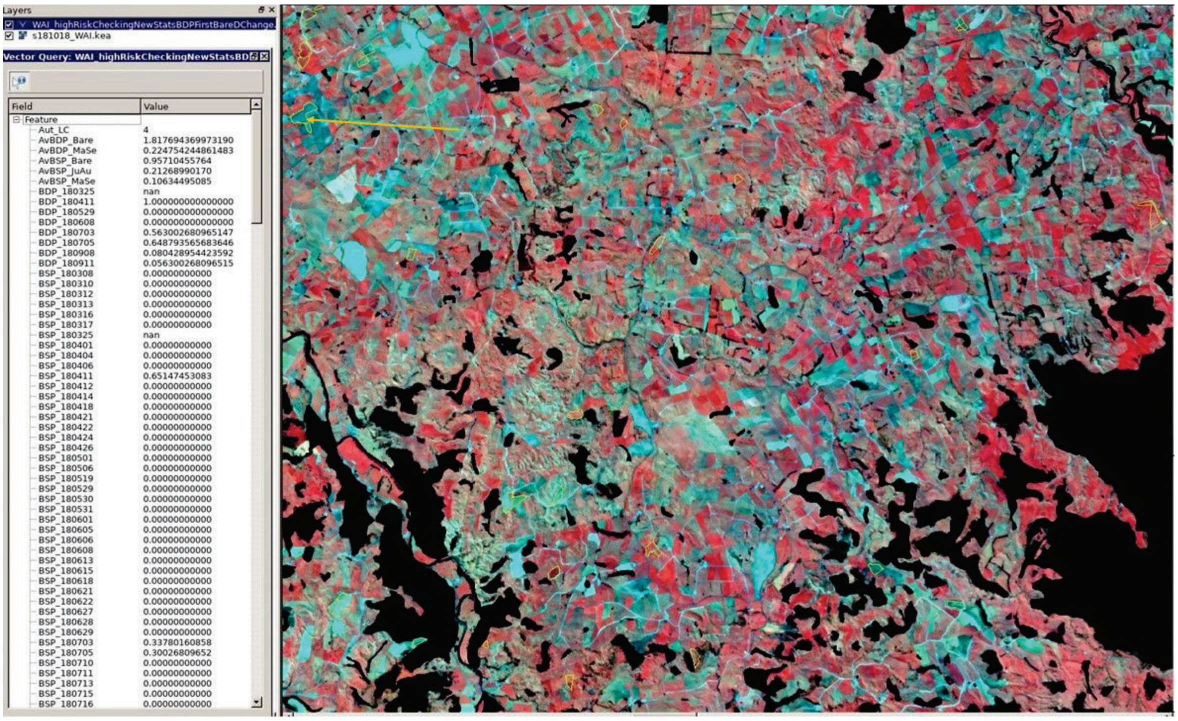

Figure 11. Part of the final GIS layer of high-risk paddock polygons, with the start of the long list of polygon attributes arrayed on the left of the image.
These metrics refer to the paddock indicated by the yellow arrow. This is a subscene of the data in the Waikato region, overlain on an image from mid-October.

Figure 12 shows the national distribution of risky hill country paddocks (over 7° slope).

Figure 12. National distribution of risky hill country paddocks.

9044 paddock polygons were classified as high risk under the methodology and rules applied in this analysis.

These 9044 paddock polygons collectively covered 42,082 ha, which is 0.76% of the New Zealand hill country agricultural land.

Identified risky hill country paddocks as a percentage of New Zealand agricultural land (all slopes) = 0.3%

The regions with the most winter forage cropping, as a percentage of the hill country agricultural land, were Southland, Otago and Canterbury.

Soil estimated to be lost from erosion of these high-risk paddock polygons over the extended winter = 689,921 tonnes

6 Accuracy assessment

Factors affecting the accuracy of the high-risk paddock assessment are discussed below.

6.1 Cloud cover

Due to the typical New Zealand winter weather patterns, some regions had sub-optimal imagery coverage. Manawatū was the most affected. Although our risky paddock polygon mapping methodology is robust and works well in the areas where we have adequate imagery covering the time sequence required, we do not have a precise measurement of how much we have missed. Several regions had no cloud-free data for long time intervals. For example, there was no imagery for the Wellington region for the 3 months from April to June. However, Manawatū was the only region where the visual checkers reported difficulties, so we can assume that all the other regions had adequate coverage.

6.2 Lack of ground truth

We understand that the urgency with which these results were required by MfE precluded the forward scheduling of this work and the concomitant collection of ground-truth data. However, this meant that we were not able to follow our established practice of tuning the spectral analyses for each region. Instead, we just used field data collected for a separate winter 2018 mapping project carried out in Hawke’s Bay (North, Belliss, et al. 2019), along with our general knowledge from previous projects in Southland and Canterbury. The field data available may not have been ideally suited to all the other regions.

With no field investigation to provide ground truthing, making a useful accuracy assessment of these results is difficult. However, we can look at proxy metrics.

6.3 Land cover accuracy

Courtesy of Hawke's Bay Regional Council we are permitted to use the ground truth data we gathered for their 2018 winter forage map. For that project we spent a week in the field, visiting farmers to access paddock histories and travelling the length of the region, collecting 'over-the-fence' observations of land covers as at early June 2018. These observations covered the gamut of agricultural land covers – not just winter forage crops – and were predominantly collected from the alluvial plains and rolling countryside. Thus, when it came to a comparison of this ground truth to the current hill country mapping, the coincident paddock polygons (slope of 7° or more) were few and far between.

However, this has provided an opportunity to compare the classification accuracy of the MfE high-risk hill country mapping with the classification accuracy of the more detailed and quantified Hawke's Bay 2018 winter forage mapping. This comparison checked the land cover classification of pasture, brassica and cereal. The results of the 48 coincident paddock polygons are presented in Table 8. Note that there were some differences in paddock boundaries between the two data sets, and there were also some differences in the average slope metrics of the paddock polygons. As a result, and to increase the size of this sparse data set, some paddock polygons were accepted into the sample with somewhat lower average slope calculations for one or both data sets.

Table 8. A comparison of paddock polygon classifications between the MfE risky paddock polygon data set and paddocks ground-truthed in June 2018 for a separate project

Paddock polygons	Number	Percentage	Comments
Correct land cover classification match (brassica or pasture or cereal)	39	81	
Incorrect land cover match	9	19	Four (8% of the total) of these were confusions between young (emerging) cereal crops and pasture. These two can be confused in the field.
Total	**48**	**100**	

6.4 Comparisons with earlier regional winter forage mapping

We were able to directly compare some of the hill country winter forage paddocks between the HBRC (North, Belliss, et al. 2019) and MfE projects, because both were for winter 2018. However, the Environment Canterbury mapping project was for winter 2016 (North et al. 2017) and the Environment Southland project for winter 2017 (North et al. 2018), so the locations of winter forage paddocks would be expected to be different than those in the MfE (winter 2018) project. This means that a direct comparison of paddock locations for accuracy assessment is not possible. In addition, these datasets have been prepared in somewhat different ways for similar, but not the same, purpose. Direct comparisons between this project's national high-risk paddock polygons layer and these earlier maps are therefore limited.

We did, however, overlay the MfE study area (agricultural land of slope 7 degrees or more) on the maps produced in these previous studies. For each previous study we calculated the percentage area mapped into winter forage classes within a zone demarcated by the 2018 MfE study site. For the Canterbury region in 2016 the area mapped as winter forage was 1.43% of the study site zone, compared to 1.20% judged to be high-risk in the 2018 MfE study. For the Southland region in 2017, the winter forage area was 2.49% of the study site zone, compared to 2.21% high-risk in the 2018 MfE study. For Hawke's Bay, these figures are 0.36% and 0.37%, with both mapping projects undertaken for winter 2018.

7 Data delivery to MfE

The national high-risk hill country paddock polygons were delivered to MfE in a geodatabase file. Table 9 lists the labels on the required summary time-series statistics.

Prior to this MfE were supplied with provisional, work-in-progress statistics on 22 February and again on 22 March. Details of these are provided in Appendix 4.

Table 9. Check sheet of attribute labels in the geodatabase listed in order as per the contract requirements

Required summary data	Label in the geodatabase	Units	Valid values
A. Unique polygon ID	UniqueID		REG_########
B. Landcover assessed for the whole period (Autumn and Winter)	LandCover		{1: WLC1 (Bare soil), 2: WLC2 (Dead vegetation), 3: WLC3 (Trees/scrub), 4: WLC4 (Tussock/herbfield), 5: WLC5 (Low cover pasture), 6: WLC6 (Pasture), 7: WLC7 (WF fodder beet), 8: WLC8 (WF cereal), 9: WLC9 (WF brassica), 10: WLC10 (WF unknown)}
C. An overall de-vegetation indicator score	AvBSP_MaSe	proportion of bare pixels	[0 – 1]
D. Number of cloud free images in the paddock polygon's image stack	ImageCount	number of entirely cloud-free images	[0 – 32]
E. Flag to indicate if the de-vegetation threshold has been breached at any time in the time series	AnyBare		{0: No images with 20% bare pixels, 1: At least one image with 20% bare pixels}
F. Flag to indicate if the de-vegetation threshold was breached (first image showing breach)	FirstBareD	date or 0 if N/A	YYMMDD or 0

Required summary data	Label in the geodatabase	Units	Valid values
G. Indication of the length of time particular de-vegetation thresholds are breached (days); for bare ground paddock polygons, this will show recovery (if any) over the winter season	BarePeriod	days between first and last continuous bare observations (inclusive)	[0 – 134] (0 if the paddock is never observed to be bare, 1 if there is only a single image showing bare soil)
H. Confidence score for the classification as crop, pasture, or bare ground	LCConf	Proportion of pixels classified as LandCover	[0 – 1]
I. Confidence score for the overall de-vegetation indicator score reported as a summary statistic per polygon	RiskCert		{1: Low certainty, 2: Medium certainty, 3: Good certainty}
J. Annual soil loss from paddock polygon in tonnes	SoilLoss	tonnes	[0 – 60592]
K. Average slope of the paddock polygon	slope_avg	degrees	[7 – 53]
L. Area of paddock polygon in square meters	area_m2	square metres	[1,000 – 1,000,000]
Spatial data layer of spatial data output 3 (A-I above) including summary and time series de-vegetation statistics for the identified winter pasture, forage cropping, and bare ground areas per paddock polygon	BSP per date	Proportion of bare pixels	[0 – 1]

8 Discussion

Our past winter forage mapping projects in Southland, Canterbury and the Hawke's Bay were predicated on the collection and provision of contemporaneous field data, employed to both develop the methodology (train the classifications) and to assess the accuracy of the resulting maps. For this national risky hill country mapping, no field data was specifically gathered, and we were reliant upon ground truth from a separate study conducted for Hawke's Bay Regional Council. Our methodology development has been iterating towards minimising the amount of field data required but, in our opinion, some should always be collected to fine tune the methodology to each region/season/country under investigation and for checking the accuracy of results.

Nonetheless, we have produced an information layer that, although it could be improved upon with additional time, money and effort, is fit for purpose.

It is difficult to make direct comparisons with our previous winter forage mapping projects, or to identify trends, due to the short time interval involved (2013-2018), variations in methodologies, and the uneven distribution of our previous studies. However a limited comparison within the boundary of the MfE study site (agricultural land of 7 degrees slope or more) showed that the percentage area of winter forage mapped in Canterbury (2016), Southland (2017) and Hawke's Bay (2018) is similar in magnitude to the percentage area of high-risk paddocks mapped for MfE (2018).

Strategic grazing of winter forage crops is a recent best management practice that implements break-feeding from the top of the slope to the bottom, instead of the traditional bottom-up method (Monaghan et al. 2017). This method enables a much shorter time available for sediment loss near critical source areas, such as near streams. A recent study reported this strategic grazing method can reduce sediment and phosphorus losses by 94% and 84%, respectively (Monaghan et al. 2017). That study also reported an 83% reduction in total nitrogen loads, and a reduction of compaction and pugging damage when strategic grazing was implemented, with a subsequent delay in soil physical damage, and therefore reduced overland flow/runoff.

Our current risk assessment looks at whether 20% or more of the paddock's area becomes bare soil during the course of the winter but does not take account of which part of the paddock (up- or down-slope) becomes bare first. Future work that could be undertaken using methods developed in this report, if sensitive enough, could be to investigate the extent to which this new top-to-bottom grazing practice is being adopted by farmers throughout the country, if at all. Determining the extent of practice adoption through time provides information on rate of farmer behaviour change and would also be of value to regional authorities for environmental regulation and freshwater management. If some regions have better uptake of this practice, this could help determine what industry or regional communication tools were most effective.

9 Conclusions

MWLR successfully produced the national data on high-risk agricultural practices required by MfE, focused on mapping winter forage cropping and intensive grazing in the hill country. The results are as accurate as we could achieve under the circumstances of the short delivery time frame and the specification of no field data collection. The typical winter conditions – specifically cloud and low sun elevations – challenged our ability to assemble ideal image coverage of some regions, and to gather good data on some areas in the hill country.

The regions with the most winter forage cropping and intensive grazing in hill country were Otago (16,232 ha, 4226 polygons), Canterbury (10,844 ha, 1898 polygons) and Southland (7938 ha, 1148 polygons), with the national total being 42,082 ha (9044 polygons). This is 0.76% of the total area of agricultural hill country (7° slope or more) in New Zealand. Soil loss from these risky paddocks was estimated to be 689,921 tonnes.

This national analysis of high-risk agricultural practices in hill country in winter 2018 drew on MWLR's existing expertise in time-series satellite image analysis for agricultural land-use mapping, and existing processing pipelines for image calibration and cloud masking. However, it also required significant advances in data processing capability, particularly code and work-flow development on the NeSI high-performance computing facility. This enabled the processing of very large volumes of image data for time-series coverage of the whole country. It also required drawing together experience and methods from previous single-region projects to develop classification rules suitable for general application across all regions of New Zealand.

Specific conclusions in this regard are that:

- using medium-resolution satellite remote-sensing imagery was the most practical, realistic, cost-effective, and timely way to produce the information required by MfE (even though there was a lot of cloud in most of the imagery throughout the winter)
- data processing of each region separately worked well for managing the computing load, with concatenation of results to form national summary statistics at the end of the process.
- only limited comparisons with earlier mapping studies could be made due to differences in methodology and the years under investigation. However, where some comparison could be made with earlier work in Canterbury, Southland and Hawke's Bay, similar percentages of high-risk hill country were noted.

10 Recommendations

Based on the approach and analysis in this study, for further work of this kind we make the following recommendations.

- Gather ground-truth data of winter forage crops and pastures from several locations around New Zealand so that spectral analyses and temporal rule development can be calibrated using data that are relatively local. Sufficient ground-truth data should also be gathered for independent accuracy assessment of the results.
- Complete a study for all agricultural land, rather than restricting the analysis to slopes of 7° or more.
- Use a minimum mapping unit of 0.2 ha rather than 0.1 ha to reduce the number of false positive paddock polygons initially flagged (these were removed manually in the current project).
- Consider an investigation of the potential reduction in sediment loss if all high-risk hill country was grazed down-slope, rather than up-slope.

11 Acknowledgements

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Appendix 1 – Previous bare-ground and winter-forage mapping carried out by MWLR

MWLR has a long history of mapping vegetation cover and bare soil for a range of purposes in environmental modelling and primary production. Dymond et al. (1992) investigated the quantification of partial vegetation cover in degrading South Island rangelands using SPOT-1 satellite imagery. This study derived a relationship between percentage vegetation cover and the normalised vegetation index.

Subsequently, work began on mapping agricultural fallow ground location, duration and frequency on the Canterbury Plains as an input to the modelling of nitrate leaching into groundwater (Lilburne & North 2010). A regression relationship between percentage live vegetation cover and a satellite-image-derived vegetation index was also derived in this project. Classification rules were developed to assess the likelihood and timing of fallow ground by analysis of time series of Landsat satellite data.

In addition, MWLR has been researching erosion and sedimentation impacts for many years and has developed models to estimate erosion (sediment discharge) over a range of land-cover / land-use scenarios (Dymond et al. 2010; Dymond et al. 2016; Dymond & Vale 2018).

For some time MWLR has been developing methods to map agricultural land use and crop type using time-series satellite imagery. Projects have now been carried out for a range of regional councils, with mapping typically on a per-paddock basis and covering a whole region. A key element in this capability is our automated paddock boundary mapping method (North, Pairman et al. 2019) as well as methods in time-series analysis.

Regarding winter forage specifically, we first investigated mapping methods using a satellite image time series of Southland in winter 2013 (North et al. 2014). Working on a pilot study area, several methods were trialled, and available techniques for supressing terrain-induced radiometric variations were considered. In a subsequent project, winter forage in 2014 was mapped on a per-pixel basis for the agricultural areas across the full Southland Region (North & Belliss 2015). Land covers were classified in each satellite image of a time series, followed by rule-based reasoning to derive a final land-use classification for each pixel. Depending on the timing of image coverage available at any given location, the ideal is to observe a spectrally recognisable forage crop (such as kale or fodder beet) in late autumn imagery, followed by bare ground in late winter imagery.

A further step in methodology development was taken when a winter 2016 forage map was produced for the whole Canterbury Region in a contract for Environment Canterbury (North et al. 2017). In this project a GIS paddock boundary map was derived from the satellite image series, and the per-pixel land-use classification resolved within each paddock to yield a single land-use identification for each paddock polygon. This was the first time we used Sentinel-2 imagery as the primary data source, augmented by some Landsat-8 imagery.

Next, a winter forage map for 2017 was prepared for Environment Southland using a similar methodology as for the per-paddock winter forage map, albeit with classifications and rules designed for Southland crops and timings (North et al. 2018). The interests of Environment Southland extended outside the agricultural landscape due to their work on erosion and water flow patterns, so the per-image land-cover maps covered the whole Southland region and included classes for rock/scree/gravel, hill country bare soil, snow and ice, and alpine vegetation. Again, this image sequence used Sentinel-2 data as the primary image source, but it was a very cloudy winter so we had to use Landsat-8 imagery as well to gain a reasonable coverage.

Most recently we have prepared a winter forage map for Hawke's Bay agricultural land (North, Belliss et al. 2019) using the same methodology as that applied to the South Island regions but with classifications and rules designed for Hawke's Bay crops and conditions. For this work, now that there are two Sentinel-2 satellites operating and because there was an exceptionally cloud-free winter over Hawke's Bay, we used Sentinel-2 imagery alone for the analyses.

Appendix 2 – Sentinel-2 satellites and the MWLR processing pipeline

MWLR now uses temporal sequences of Sentinel-2 imagery for much of its satellite image analyses. Sentinel-2 is a pair of satellites in a constellation (Sentinel-2A and -2B) that are, for all intents and purposes, identical. Sentinel-2A began service in late 2015 and Sentinel-2B in June 2017. The satellites have been placed in a carefully designed orbit so that they collect imagery over a series of 290 km-wide orbital tracks, repeating every 10 days and thus jointly providing a 5-day repeat pattern. These orbit tracks are shown in Figure 13. Having coverage of points in New Zealand every 5 days enables us to assemble temporally denser time series than was previously possible. Nevertheless, New Zealand still has a lot of cloud, so regular cloud-free image collection is not guaranteed.

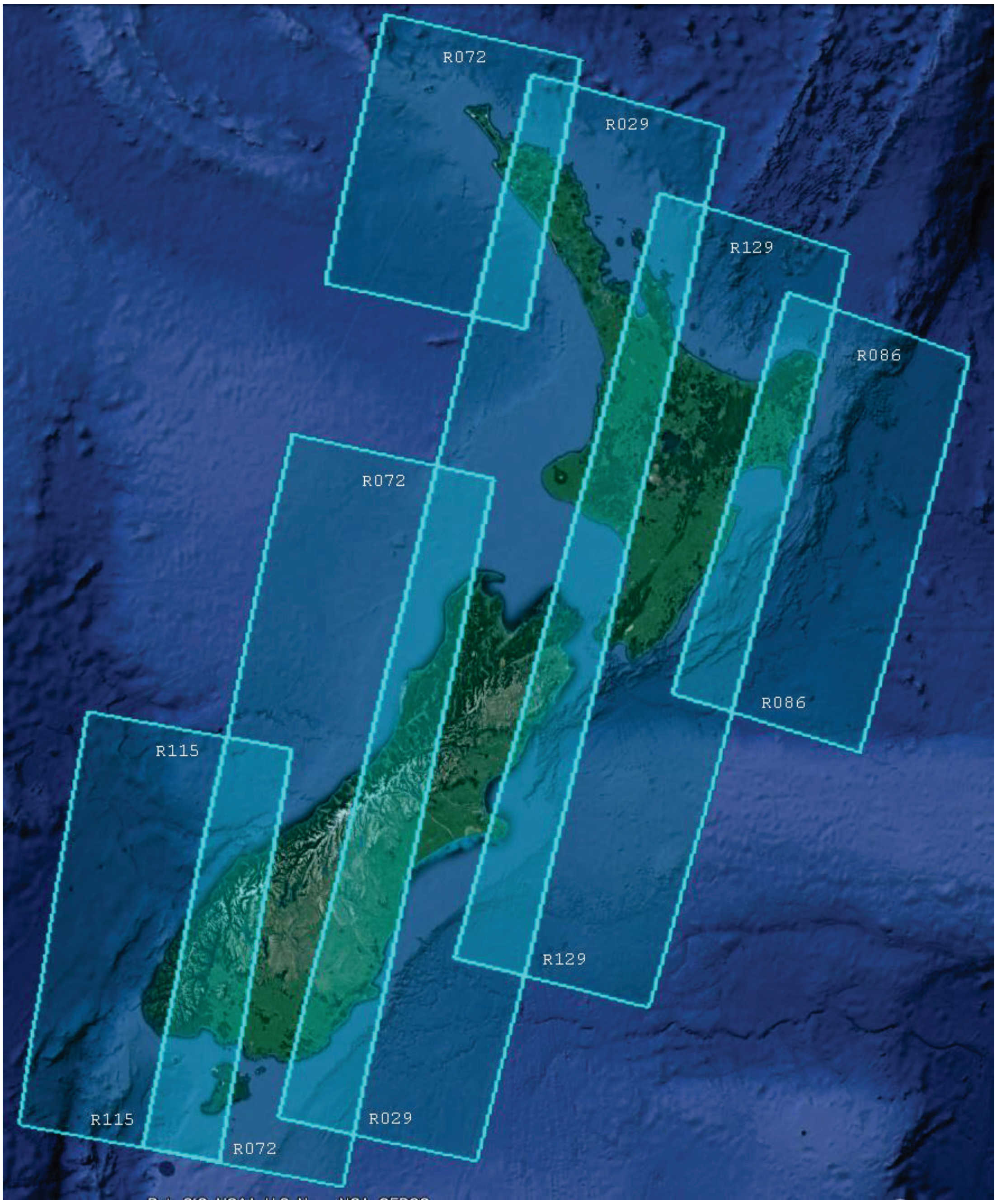

Figure 13. Sentinel-2 orbit tracks. This hill country mapping project covers the North and South Islands only; coverage of offshore islands was not required.

Table 10. Sentinel-2A and -2B spectral bands. Note that the spatial resolutions given are those for the raw satellite imagery, not the MWLR-processed imagery

Band	Centre wavelength (nm)	Bandwidth (nm)	Spatial resolution (m)	Band description
1	443	20	60	Calibration band (aerosol)
2	490	65	10	Blue
3	560	35	10	Green
4	665	30	10	Red
5	705	15	20	Red edge 1
6	740	15	20	Red edge 2
7	783	20	20	Red edge 3
8	842	115	10	Near infrared
8a	865	20	20	Near infrared 2
9	945	20	60	Calibration band (water vapour)
10	1380	30	60	Calibration band (cirrus)
11	1610	90	20	Short-wave infrared
12	2190	180	20	Short-wave infrared 2

Appendix 3 – List of Sentinel-2 satellite imagery selected for 2018 hill country mapping

For ease of use, imagery from 2017 has been listed separately from 2018 imagery.

- Green = imagery used for paddock boundary mapping.
- S2A = Sentinel-2A and S2B = Sentinel-2B satellite.
- R029 or another number = the orbit track of that image date. In some cases a region is contained within a single orbit track (e.g. Marlborough); in other cases, parts of the region are covered by one orbit track and parts with another (e.g. Otago, which has coverage from orbit track R072, but also some coverage of the eastern side from R029 and of the western side from R115).

Note: all dates are expressed in Universal Time (UT), which is behind New Zealand Standard Time (NZST). For example, a date of 10 January UT equates to 11 January NZST.

Table 11. Image lists

Region	1 September – 31 December 2017	1 January 2018 – 30 November 2018
Northland	6 June S2B R072	9 Jan S2A & 24 Jan S2B R029
	8 Nov S2B R072	12 April S2A R072
	5 Dec S2B R029	29 May S2A R029
	18 Dec S2B R072	8 June S2A R029
	20 Dec S2A R029	3 July S2B R029
		4 October S2B R072
		25 November S2A R029
Auckland	5 December S2B R029	29 January S2A R029
		19 &29 May S2A R029
		8 & 28 June S2A R029
		3 July S2B R029
		23 July S2B R029
		6 September S2A R029
		16 &26 September S2A R029
Waikato	3 September S2B R129	3 February S2B R029
	13 September S2B R129	15 February S2A R129
	3 October S2B R129	25 March S2B R029
	13 October S2B R129	11 April S2B R129
	18 October S2A R129	29 May S2A R029
	17 November S2A R129	8 June S2A R029
	22 November S2B R129	8 September S2B R129
	5 December S2B R29	11 September S2B R029
	20 December S2A R29	18 October S2B R129
	27 December S2A R129	22 November S2A R129

Region	1 September – 31 December 2017	1 January 2018 – 30 November 2018
Bay of Plenty	3 September S2B R129 18 October S2A R129 22 November S2B RR29	15 February S2A R129 12 March S2B R129 1 & 11 April S2B R129 6 April S2A R129 6 May S2A R129 5 June S2A R129 5 July S2A R129 9 August S2B R129 8 September S2B R129 13 September S2A R129 18 October S2B R129 22 November S2A R129
Gisborne	23 September S2B R129 3 October S2B R129 13 October S2B R129 15 October S2A R086 20 October S2B R086 4 December S2A R86	8 January S2B R086 23 January S2A R086 5 & 15 February S2A R129 12 March BR129 6 April S2A R219 11 April S2B R129 18 April S2B R086 9 August S2B R129 13 September S2A R129 18 October S2B R129 14 November S2B R086
Hawke's Bay	3 September S2B R129 23 September S2B R129 3 October S2B R129 13 October S2B R129 22 November S2B R129	12 March S2B R129 1 April S2B R129 11 April S2B R129 18 April S2B R086 26 April S2A R129 15 June S2A R129 22 June S2A R086 5 July S2A R129 10 July S2B R129 15 July S2A R129 1 August S2A R086 24 August S2A R129 26 August S2B R086 13 September S2A R129 15 September S2B R086 18 October S2B R129 20 October S2A R086

Region	1 September – 31 December 2017	1 January 2018 – 30 November 2018
Taranaki	26 October S2B R029 20 November S2A R029 22 November S2B R129 5 December S2B R029 20 December S2A R029	3 February S2B R029 10 March S2A R029 25 March S2B R029 4 &24 April S2B R029 1 & 31 May S2B R129 2 &29 August S2B R029 11 September S2B R029 21 September S2B R029 18 October S2B R129 12 November S2A R129
Manawatū	13 October S2B R129 18 October S2A R129 17 November S2A R129 22 November S2B R129 27 November S2A R129 20 December S2A R029	3 February S2B R029 23 February S2B R029 10 March S2A R029 17 March S2A R129 25 March S2B R029 1 April S2B R129 14 April S2B R029 21 April S2B R129 29 May S2A R029 1 May S2B R129 8 & 28 June S2A R029 6 July S2A R129 29 August S2B R129 11 September S2B R029 18 October S2B R129
Wellington	23 September S2B R129 3 October S2B R129 13 October S2B R129 18 October S2A R129 22 November S2B R129 7 December S2A R129	12 March S2B R129 10 July S2B R129 24 August S2A R129 13 September S2A R129 18 September S2B R129 18 October S2B R129 12 November S2A R129
Nelson & Tasman	11 October S2A R029 16 October S2B R029 5 December S2B R029 20 December S2A R029	24 January S2B R029 8 February S2A R029 4 April S2B R029 29 May S2A R029 28 June S2A R029 6 September S2A R029 6 October S2A R029 5 November S2A R029

Region	1 September – 31 December 2017	1 January 2018 – 30 November 2018
Marlborough	11 September S2A R029	24 January S2B R029
	13 October S2B R129	8 February S2A R029
	16 October S2B R029	10 March S2A R029
	21 October S2A R029	28 June S2A R029
	5 November S2B R029	11 September S2B R029
	15 November S2B R029	21 October S2B R029
	22 November S2B R129	5 November S2B R029
	30 November S2A R029	
	5 December S2B R029	
	7 December S2A R129	
	10 December S2A R029	
West Coast	1 September S2A R029	21 February S2A R072
	21 September S2A R029	8 March S2B R072
	26 October S2B R029	10 March S2A R029
	27 October S2A R115	18 June S2A R029
	18 November S2B R072	1 June S2A R072
	3 December S2A R072	4 September S2B R072
	5 December S2B R029	6 September S2A R029
	28 December S2B R072	14 September S2B R072
		21 September S2B R029
		20 November S2B R029
Canterbury	11 October S2A R029	14 January S2B R029
	16 October S2B R029	22 January S2A R072
	19 October S2B R072	29 January S2A R029
	21 October S2A R029	3 February S2B R029
	31 October S2A R029	8 February S2A R029
	5 November S2B R029	23 February S2B R029
	15 November S2B R029	10 March S2A R029
	18 November S2B R072	13 March S2A R072
	30 November S2A R029	29 May S2A R029
	7 December S2A R129 (BP)	2 August S2B R029
	3 December S2A R072	25 August S2B R072
	10 December S2A R029	11 September S2A R029
		14 September S2B R072
		21 September S2B R029
		21 October S2B R029
		26 October S2A R029
		5 November S2A R029
		13 November S2B R072

Region	1 September – 31 December 2017	1 January 2018 – 30 November 2018
Otago	21 September S2A R029	12 January S2A R072
	29 September S2B R072	14 January S2B R029
	9 October S2B R072	11 February S2A R072
	11 October S2A R029	6 February S2B R072
	29 October S2B R072	13 March S2A R072
	31 October S2A R029	16 March S2A R115
	15 November S2B R029	4 April S2B R029
	18 November S2B R072	22 April S2A R072
	21 November S2B R115	5 August S2B R072
	30 November S2A R029	25 August S2B R072
	3 December S2A R072	4 & 14 September S2B R072
	13 December S2A R072	21 October S2B R029
		2 October S2A R115
		5 November S2A R029
Southland	2 October S2B R115	13 March S2A R072
	4 October S2A R072	22 April S2A R072
	7 October S2A R115	30 May S2B R115
	17 October S2A R115	5 August S2B R072
	27 October S2A R115	18 August S2B R115
	29 October S2B R072	4 September S2B R072
	18 November S2B R072	17 & 27 September S2B R115
	26 November S2A R115	4 October S2B R072
	6 December S2A R115	17 October S2B R115
	13 December S2A R072	26 November S2B R115
	21 December S2B R115	
	26 December S2A R115	

Appendix 4 – Information about the provisional, work-in-progress, supply of candidate paddock polygons to MfE

Early supply of candidate paddock polygons by 22 February

At this stage in the processing we used only the Normalised Difference Vegetation Index (NDVI) to detect candidate paddock polygons. NDVI is a ratio of the red and near-infrared bands, which very effectively highlights the difference between vegetated and non-vegetated surfaces. We calculated NDVI at a per-pixel level for all images in the time series for all regions. For each image date with more than 10% of a paddock visible, we then calculated the percentage area of each paddock polygon (using the buffered boundaries) below a specified NDVI threshold (0.45, indicating no, or a very low level of, green vegetation) and flagged it if 20% or more of the pixels were 'bare' (below the NDVI threshold).

We then calculated two summary flags for each paddock polygon: (1) if the paddock is flagged as 20% bare (or more) in any one image between May and September inclusive; and (2) if there is a significant drop (of at least 0.3) between the maximum NDVI in the March–May period and the minimum NDVI in the June–September period.

We required the paddock polygon to meet both the above criteria, and to be above a certain minimum paddock size, in order to be flagged as possibly high risk. We found that these criteria – requiring at least one 'bare' date in winter, and a significant reduction in green vegetation between autumn and winter – did detect winter forage paddock polygons successfully. However, they also detected paddocks polygons that had low green cover in winter for other reasons; for example, poor hill country pasture/tussock land that became brown/dead in the winter due to the effects of frost and snow were also flagged.

Total number of candidate paddocks = 41,981

On 22 February MfE was supplied with a geodatabase – HighRiskHillCountry.gdb – containing four layers of provisional information:

- NZ_validAgriculture – a mask of areas considered to be agricultural land
- NZ_sevenDeg – within the agricultural land, paddock polygons that averaged 7° or greater, dissolved into a single mask
- NZ_highRiskCandidates – within the 7° mask, paddock polygons that were identified as potentially high risk using simple NDVI-based rules
- NZ_combination – the information above combined into a single layer.

These provisional candidate paddock polygons, identified by simple NDVI-based rules that looked for their NDVI to be below a certain threshold (0.45) in at least one winter image, plus a significant NDVI drop (of 0.3) from autumn to winter/early spring, included a large number of false positives. Some of these were due to the simple methodology used at this early stage of the processing: the NDVI threshold used to identify 'bare' paddocks also captured dead/brown vegetation. This confusion was addressed in later stages of the processing, where bare soil and dead vegetation were separated using spectral classification.

Other false positives were due to remaining thin cloud in the imagery. After an adjustment to the cloud mask to account for cirrus cloud, the candidate paddock polygon selection process was re-run and the geodatabase resupplied to MfE by the end of February, containing a reduced number of false positives.

Total number of candidate paddock polygons = 32,591

Supply of provisional statistics by 31 March

On 29 March, MfE was supplied with a set of regional summary statistics, derived from the high-risk paddock polygon layer as it stood at the time. At this stage, the full spectral classification methodology was being used (as opposed to the simple NDVI-based method used initially), but some final refinements to the rules had not been implemented and visual checking had not yet been carried out. The summary statistics are listed in Table 12. The area of risky agricultural land over 7° is the total area of hill country land identified as winter forage that appears to have gone bare by the end of September. The level of certainty for this classification has not been factored into these summary totals; this refinement formed part of the final delivery.

Table 12. Pre-checking summary regional statistics

Region	Area (ha)	Area of agricultural land (ha)	Area of agricultural land >7° (ha)	Area of risky agricultural land >7° (ha)	Winter sediment load in rivers (t)	Soil lost in winter from risky agricultural land >7° (t)
Northland	1,251,464	606,068	311,314	2568	6,227,471	26,056
Auckland	494,263	245,483	107,372	65	227,446	886
Waikato	2,457,849	1,315,005	593,926	2863	2,823,227	61,738
Bay of Plenty	1,228,109	286,288	103,428	659	795,524	8415
Manawatū	2,222,313	1,306,468	896,059	65	5,238,146	3093
Taranaki	725,448	390,959	157,471	364	1,353,656	9221
Hawke’s Bay	1,419,079	747,188	518,726	1800	3,874,615	38,778
Wellington	811,946	371,914	243,469	123	2,453,479	2654
Tasman	964,948	130,946	57,007	246	1,177,962	3996
Nelson	42,219	5810	4474	1	14,730	13
Marlborough	1,047,055	300,070	211,567	513	718,081	12,717
West Coast	2,332,151	156,003	8069	38	20,452,631	1649
Canterbury	4,520,800	2,467,905	1,006,923	10,986	6,879,106	242,242
Otago	3,190,755	2,017,428	1,111,477	15,261	7,600,743	199,417
Southland	3,184,242	1,067,143	394,650	5336	3,138,228	106,448
Gisborne	838,583	372,923	335,093	344	16,850,499	17,554

Appendix 5 – Examples of accepted and rejected high risk paddock polygons examined during the map accuracy checking process

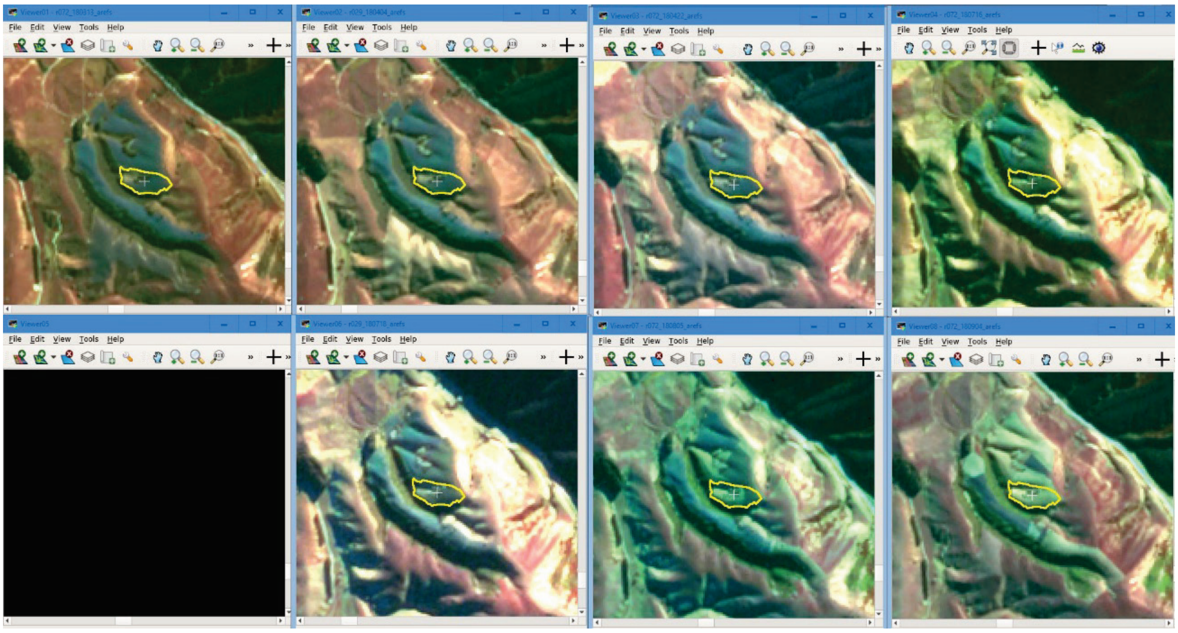

Figure 14. A paddock polygon of brassicas within an area that is vegetated right through the image sequence March–August. Paddock polygon classed as risky. Locality = Otago.

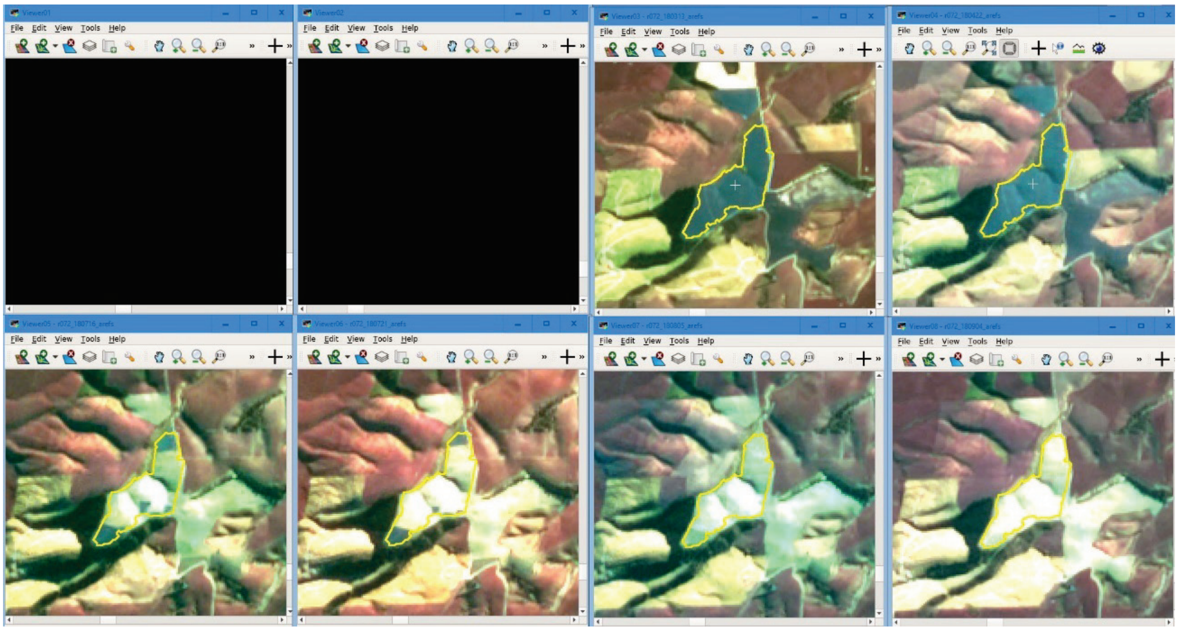

Figure 15. A large paddock polygon of brassicas that was starting to be eaten sometime between May and early July, and completely bare by early August. Paddock polygon classed as risky. Locality = Otago.

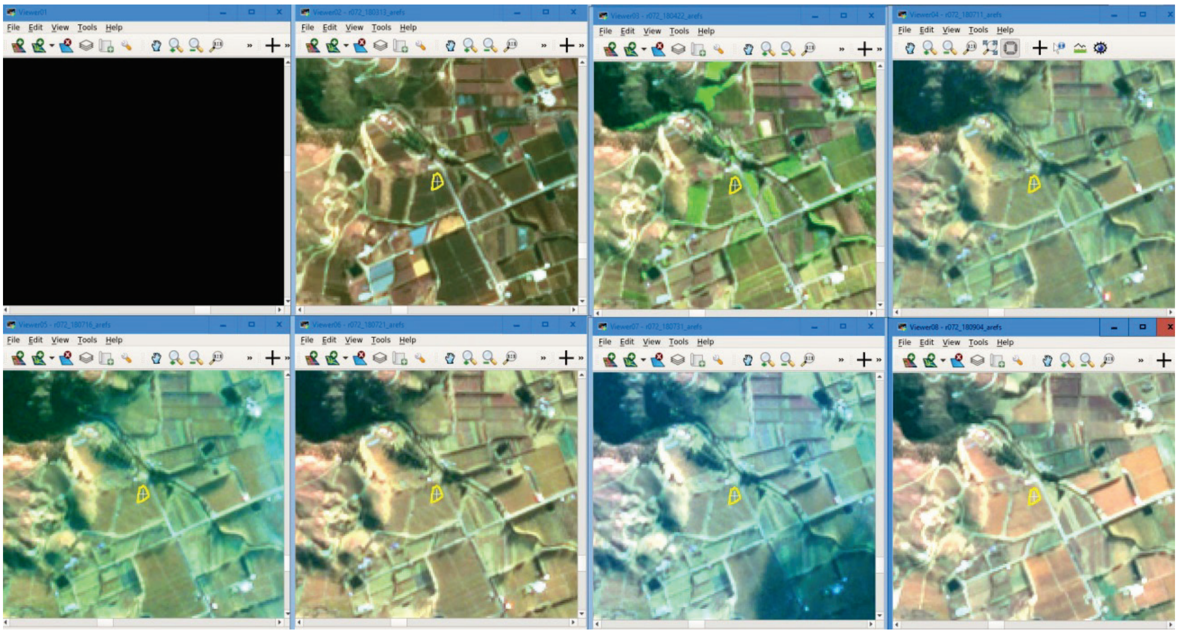

Figure 16. An area of orchard that has been misclassified as cropland. The de-vegetation classification has been triggered by the loss of leaves in autumn. Paddock polygon rejected from high-risk paddock list. Locality = Otago.

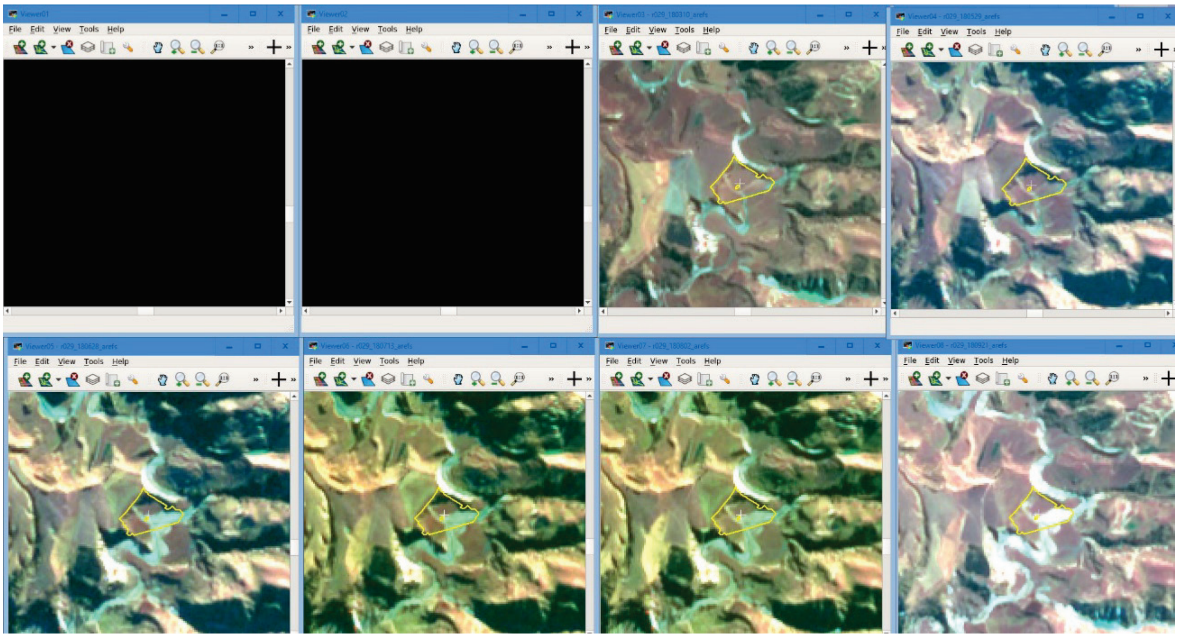

Figure 17. Here, a river has breached its banks and covered part of the paddock polygon with sediment. Polygon rejected from high-risk paddock list. Locality = Canterbury.

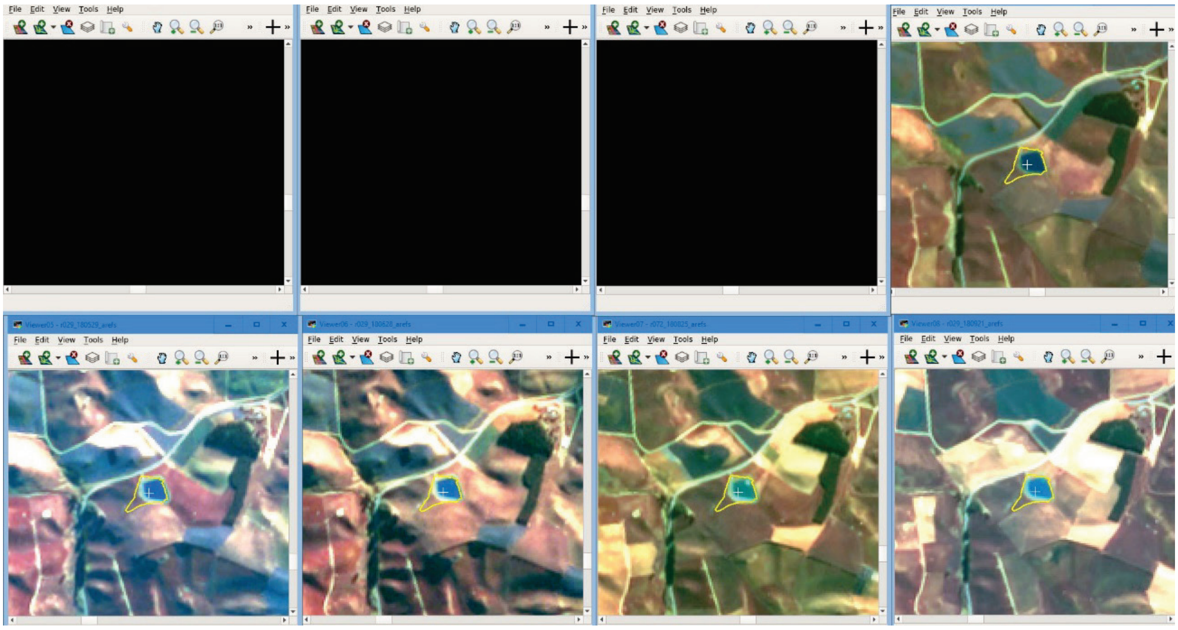

Figure 18. A pond misclassified as a brassica paddock. Paddock polygon rejected from high-risk paddock list. Locality = Canterbury.

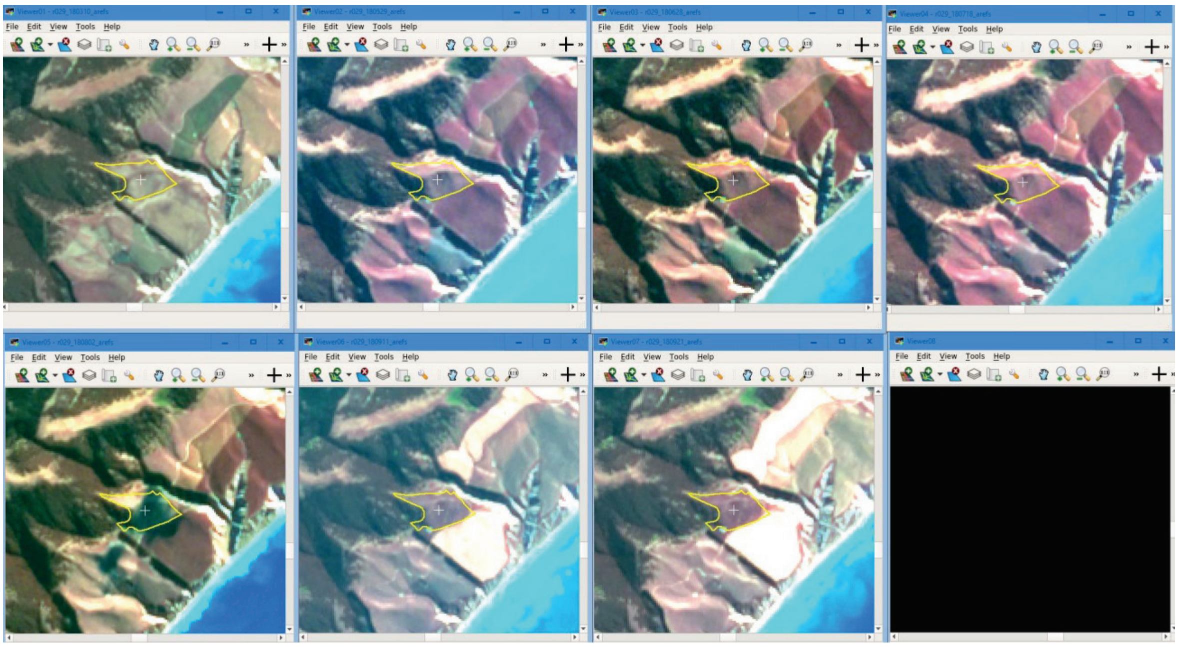

Figure 19. A cloud shadow has triggered the paddock polygon to be classified as brassicas. Polygon rejected from high-risk paddock polygon list. Locality = Canterbury.

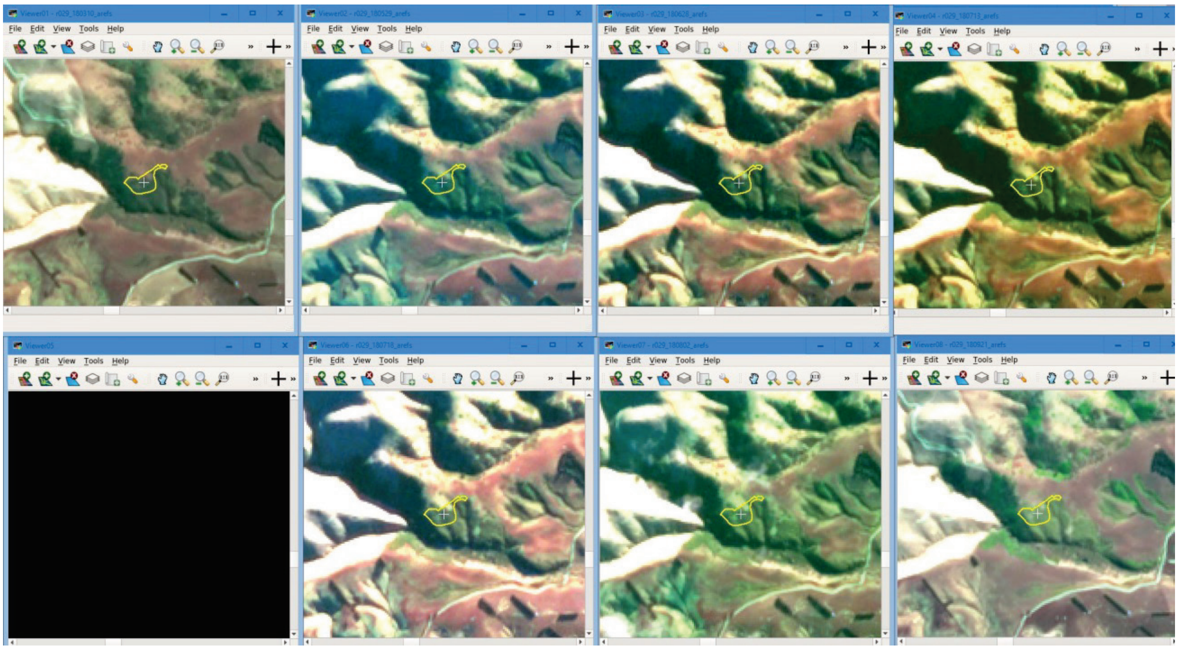

Figure 20. Shrubland misclassified as forage. Polygon rejected from high-risk paddock polygon list. Locality = Canterbury.

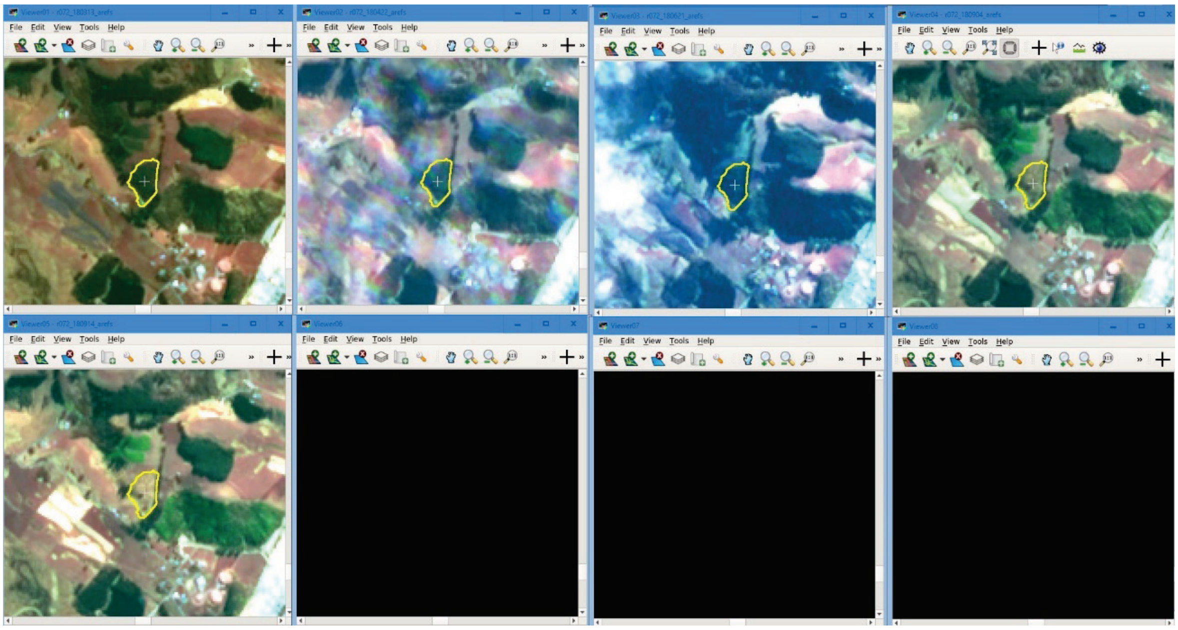

Figure 21. Shrubland removed from an area between June and September. Polygon rejected from high-risk paddock polygon list. Locality = Otago.