12-2022

Using Landsat satellite imagery to estimate groundcover in the grainbelt of Western Australia

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Resource management technical report 428

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ISSN 1039-7205

Cover: Landsat total vegetation groundcover (processed image: Justin Laycock)

Recommended reference

Laycock J, Middleton N and Holmes K (2022) 'Using Landsat satellite imagery to estimate groundcover in the grainbelt of Western Australia', *Resource management technical report 428*, Department of Primary Industries and Regional Development, Western Australian Government.

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Acknowledgements

For many years, we have had a vison to use satellite imagery to monitor groundcover and erosion hazard across the grainbelt of Western Australia. Jeremy Wallace (CSIRO) and Buddy Wheaton in conjunction with Phil Goulding and Elvyn Wise (members of the Department of Primary Industries and Regional Development [DPIRD] GIS team) helped us to evaluate satellite groundcover monitoring options. While these options were not ultimately adopted, the process provided us with the momentum to evaluate the options detailed in this report.

Many thanks to Rebecca Farrell, Dr Peter Scarth and Rebecca Trevithick (Joint Remote Sensing Research Program) and Dr John Leys (The Australian National University) who provided direction and confidence to use the national Landsat fractional cover product.

A special thankyou to Paul Galloway for assisting in developing meaningful outputs from this research to use in DPIRD's annual reporting.

Thank you to Paul Findlater, Tim Overheu, John Simons and Pouria Ramzi for constructive feedback on report drafts. And thanks to Angela Rogerson (DPIRD) and Janet Paterson (Sciscribe) for editing this report.

Shortened forms

Short form	Long form
DPIRD	Department of Primary Industries and Regional Development
GB	gigabyte
GIS	geographic information system
ha	hectare
KPI	key performance indicator
m	metre
M ha	million hectares
TERN	Terrestrial Ecosystem Research Network
TVC	total vegetative cover
WA	Western Australia

Summary

Maintaining vegetative groundcover is an important component of sustainable agricultural systems and plays a critical function for soil and land conservation in Western Australia's (WA) grainbelt (the south-west cropping region). This report describes how satellite imagery can be used to quantitatively and objectively estimate total vegetative groundcover, both in near real time and historically across large areas. We used the Landsat seasonal fractional groundcover products developed by the Joint Remote Sensing Research Program from the extensive archive of Landsat imagery (USGS 2022). These products provide an estimate of the percentage of green vegetation, non-green vegetation and bare soil for each 30 m pixel across WA on a seasonal basis and can be downloaded from TERN (Terrestrial Ecosystem Research Network) Data Discovery Portal (JRSRP 2021).

The advantages the Landsat-derived fractional cover provides are:

- non-arable land can be removed (masked) from the analysis because of the relatively high 30-m pixel resolution
- the reported overall product accuracy is considered very good for remote sensing products (root mean square error of 11.6%)
- the product is accessible and ready for immediate use
- the large archive of past imagery dating back to 1987 is available for analysis of longer-term trends.

We processed the fractional cover data using a series of scripts (computer code written in Python programming language) to calculate the total vegetative groundcover for each pixel and determine the proportion of arable land in defined groundcover classes across the grainbelt or within areas of interest. This workflow delivers consistent outputs, including summary data tables and display graphics, answering the following questions:

- What is the current groundcover status on arable land? Output: the percentage of land with 'X' groundcover.
- Where is the highest erosion hazard? Output: a map of groundcover.
- How does current groundcover compare to previous years? Output: options for maps, tables and graphs.

We use outputs from this remote sensing workflow to report on key performance indicator (KPI) for groundcover and annual soil erosion hazard for the Commissioner of Soil and Land Conservation. The analysed imagery also enables us to provide valuable regional farming systems intelligence to guide targeted extension messaging to assist landholders to prevent land degradation and ensure farming enterprises are productive and sustainable.

1 Introduction

Groundcover can consist of living and dead plant material, gravel and stones, and is critical to reducing soil erosion, supporting biodiversity, and increasing soil water infiltration and carbon levels (Moore 2001; Anderson 2009; Leys et al. 2020). In WA's grainbelt (the south-west cropping region), vegetative groundcover on arable land is a function of seasonal weather conditions and land management practices, such as grazing, tillage and burning.

Inadequate groundcover presents a major risk for soil loss from erosion. As groundcover decreases, erosion hazard increases exponentially (Chepil and Woodruff 1963; Findlater et al. 1990; Fryrear and Bilbro 2018). The term 'soil erosion hazard' is used to describe how likely it is that a soil will erode when exposed to processes such as strong winds (wind erosion) or intense precipitation (water erosion). Other erosion hazard factors relate to the inherent properties of the soil and site, such as the soil type, topographic position, length of slope, degree of exposure, surface resistance, and depth of loose soil (Pennock et al. 2019). Land management practices can also strongly influence erosion hazard, particularly when groundcover is removed or the soil is disturbed.

Wind erosion adversely affects agriculture, the environment and the community. Loss of clay, organic matter and nutrients reduces soil fertility and crop yield (McFarlane and Carter 1989, Sharratt et al. 2018) and can damage emerging crops through sandblasting, or bury fences and watering points (Moore et al. 2001). Atmospheric dust particles can influence the climate, cause respiratory issues through inhalation or cause traffic accidents through reduced visibility, while dust deposition pollutes the natural environment and generates cleaning costs (Tozer and Leys 2013).

Water erosion is highly variable, both temporally and spatially, and most soil loss occurs during extreme events (Coles and Moore 2001). The negative agronomic and environmental effects are similar to wind erosion, with the addition of eutrophication of waterways.

Recent estimates of the financial impact of wind and water erosion are annual opportunity costs of $62 million and $3 million, respectively (Bennett 2021).

Quantifying erosion hazard using visual field surveys over arable land in the grainbelt is difficult given the large extent of land to be assessed and inability to access land. The 2013 report card on sustainable natural resource use in agriculture (Carter and Laycock 2013) used repeated biannual surveys from 2008 to 2012 to show that parts of the grainbelt had a consistent and very high erosion hazard, while other landscapes did not. However, the report acknowledged that lack of data from particular landscapes could lead to underestimating the erosion hazard. The survey program was subsequently halted because the survey demands exceeded capacity of available resources and the technique limited observations to specific points in the landscape, potentially missing nearby areas of erosion.

Satellite imagery can be used to measure and monitor changes in the vegetative component of groundcover over the entire grainbelt (Leys et al. 2020). The fractional groundcover algorithm developed by Scarth et al. (2012) has been applied to current

and archived Landsat imagery to quantify the percentage of photosynthetic vegetation, nonphotosynthetic vegetation and bare soil on a pixel by pixel basis.

While fractional groundcover imagery for each pass of the Landsat satellites is available from Geoscience Australia (DEA 2021), this imagery contains pixels with missing data because the sensor cannot penetrate cloud. To account for this, the Joint Remote Sensing Research Program (JRSRP) produces a seasonal groundcover product by calculating the medoid for each pixel (i.e. median pixel value) using multiple images collected over a season; for example, summer consists of December, January and February (Flood 2013).[1] These seasonal products are composite images, which means they are less affected by data anomalies such as cloud effects or missing data, and provide a more complete estimate of groundcover than images from a single date.

This report describes how we processed JRSRP seasonal fractional groundcover imagery to report on soil condition and erosion hazard across WA's grainbelt. Information from the monitoring process enables:

- the WA Commissioner of Soil and Land Conservation (the Commissioner) to evaluate seasonal erosion hazard and make informed judgements on the sustainable management of WA's soil resource
- DPIRD's dry season regional intelligence staff to deliver region-specific extension messages and facilitate local events to promote the importance of groundcover
- reporting of DPIRD's land resource condition, such as the KPI 'Percentage change in the spatial extent of the south-west cropping region that maintains sufficient year-round groundcover for protecting and improving soil health'
- development of soil health guidelines using the best available landscape information.

Landsat seasonal fractional groundcover is the most appropriate remote sensing product for monitoring groundcover levels across the grainbelt because:

- non-arable land can be removed from the analysis because of the relatively high 30 m pixel resolution
- the reported overall product accuracy of 11.6% RMSE (root mean square error) is considered very good for remote sensing products (Scarth et al. 2012)
- the imagery is available for immediate use
- the archive of imagery dating back to 1987 is available for analysis of longer-term trends.

Appendix A has a list of online imagery resources used by DPIRD for evaluating groundcover.

[1] See jrsrp.org.au/

1.1 Alternative fractional groundcover imagery

There are 2 other satellite-derived fractional groundcover products used to assess groundcover across Australia (Guerschman et al. 2018). Sentinel 2 (ESA 2022) imagery has analogous bands to Landsat and is increasingly being used in place of or with Landsat imagery because the images are captured with a higher temporal frequency, with higher spatial resolution (10 m) and with additional spectral bands (JRSRP 2018). However, it is only available from 2015 onwards and analysis-ready imagery is not available for WA. Given the importance of examining historical trends in groundcover, Landsat's longer time series (30+ years) is more critical for DPIRD's purposes than improving spatial resolution.

The second product, MODIS (Moderate Resolution Imaging Spectroradiometer) imagery, is available as an 8-day composite image but its spatial resolution of 500 m does not allow non-arable land to be effectively removed from groundcover analysis (Guerschman et al. 2009; Guerschman 2020). DPIRD uses Sentinel and MODIS from time to time and may incorporate them into future groundcover analysis.

2 Methods

2.1 Overview of image processing steps

The steps to produce groundcover products for DPIRD reporting are listed below. A more detailed description of the process, including the datasets and variable definitions we used, is provided in following sections of this report.

1. Download seasonal fractional groundcover satellite data from the TERN AusCover website (Section 2.2).[2] These datasets are analysis-ready with the following already applied:
    - preprocessing – raw Landsat images have been obtained from USGS and corrected for atmospheric effects and bi-directional reflectance and topographic effects (Flood 2013)
    - fractional groundcover algorithm – a constrained linear spectral unmixing model has been applied to determine bare soil, green vegetation and non-green vegetation (Scarth et al. 2012)
    - seasonal composite – the medoid (multidimensional median or middle point) for each pixel from all available images within each 3-month (seasonal) window has been selected (Flood 2013). Imagery is then made available through TERN AusCover (2021).
2. Process the fractional groundcover product to create a single-band raster of total vegetative cover (TVC). The TVC is the ‘green plus non-green’ vegetation fraction or the ‘100 minus percentage bare ground’ fraction (Section 2.3).
3. Define the parameters (Section 2.4) to be used in steps 4 and 5, and prepare the masks to:
    - remove ‘non-arable land’ from calculations by masking the imagery to show only ‘potentially arable land’
    - restrict the extent of the imagery to the grainbelt.
4. Analyse the single-season image to identify the area of arable land in the grainbelt between the specified percentage of groundcover classes in a given year (Section 2.5). Area measurements are then converted to percentage values for comparisons across years.

    The processed images are then used to create landscape maps:
    - depicting scaled groundcover from low to high
    - depicting groundcover level above and below critical groundcover thresholds.

    The maps are analysed by regions to generate data that summarise:
    - percentage of landscape above and below groundcover thresholds
    - median percentage of landscape below a threshold
    - graphs that show the change in the percentage of landscape above or below a groundcover threshold for all years included in the analysis.

2 qld.auscover.org.au/public/data/landsat/seasonal_fractional_cover/fractional_cover/wa/

5. Analyse time series (Section 2.6) using a series of seasonal images to determine:
    - frequency of available data for a pixel
    - groundcover median for each pixel across the time series
    - anomalies – the difference between the current season (e.g. autumn 2020) and the time series median for that same season
    - percentage of years below threshold – the percentage of years where groundcover is below a critically low threshold value.

2.1.1 Automating image processing

Image processing is repetitive and time-consuming. Different results can be obtained from the same images by varying parameters and variables during different steps of the analysis or using similar but different geoprocessing tools. To ensure image processing remained identical from season to season and year to year, we developed computer code to carry out each processing step in sequence and deliver consistent outputs including graphics and summary data tables. We wrote code in Python 2.7 (Python Software Foundation 2010) programming language and used ESRI's (2013) ArcPy site package to provide access to GIS analysis tools. Automated processing enabled the analysis to proceed independently, and in a reproducible manner once an operator had specified the location of the input data and defined the processing variables. At the moment, the process is limited to the Windows operating system because it relies on ESRI's ArcGIS Desktop software.

Before a script is run, several processing variables must be confirmed or updated to specify the time period, critical groundcover thresholds and supporting datasets, such as masks (Section 2.4). The location of some datasets may also need to be updated to reflect the user's directory structure.

The latest version of each script is available in the GitHub repository, which contains a short description of the code, and each module (or Python file) begins with a summary of what it does and the inputs required.[3]

2.2 Downloading Landsat seasonal fractional groundcover imagery

The Landsat satellite imagery has been processed at the national scale using an algorithm to produce an analysis-ready, seasonal fractional groundcover estimate of bare ground, photosynthetic vegetation (green vegetation) and nonphotosynthetic vegetation (non-green vegetation) for every pixel at 30 m resolution across the Australian continent (DEA 2021; JRSRP 2021; Scarth et al. 2012).

Seasonal fractional groundcover images are hosted by TERN on the AusCover website and are downloaded manually each quarter. Each Australian state has their images stored in separate folders on the AusCover website and archives extend back to 1987. Each seasonal image is stored as a 4-band TIF, and the WA images are about 6 GB.[4]

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[3] GitHub script repository https://github.com/DPIRD-DMA/WheatbeltGroundCover

[4] Fractional groundcover for WA http://qld.auscover.org.au/public/data/landsat/seasonal_fractional_cover/fractional_cover/wa

The analysis method described in this chapter relies on the fractional groundcover data being downloaded and processed locally.

2.3 Creating the total vegetative cover input layer

The downloaded fractional groundcover imagery contains 4 bands:

- Band 1 = percentage bare ground + 100
- Band 2 = percentage green vegetation + 100
- Band 3 = percentage non-green vegetation + 100
- Band 4 = unmixing error (the model uncertainty, which was not used in this process).

The first 3 bands have percentages with a value of 100 added. So a value of 10% bare ground will be represented as a value of 110 in Band 1 of the downloaded TIF file.

The analysis process only requires TVC, which is the sum of the green (Band 2) and non-green vegetation (Band 3) bands.

To create the TVC, the script ‘fgc03_Create_TVC_input_layer.py’ reads the multiband fractional groundcover image and converts it to a single-band TIF image containing the summed Bands 2 and 3 values. This output contains pixel values that range from 0% to 100%, which represents the estimated percentage groundcover (green plus non-green or 100 minus percentage bare ground) for each pixel.

The naming convention for these outputs is ‘acfgcs_YYYYMMYYYYMM_TVCpc.tif’ (e.g. acfgcs_202003202005_TVCpc.tif), where:

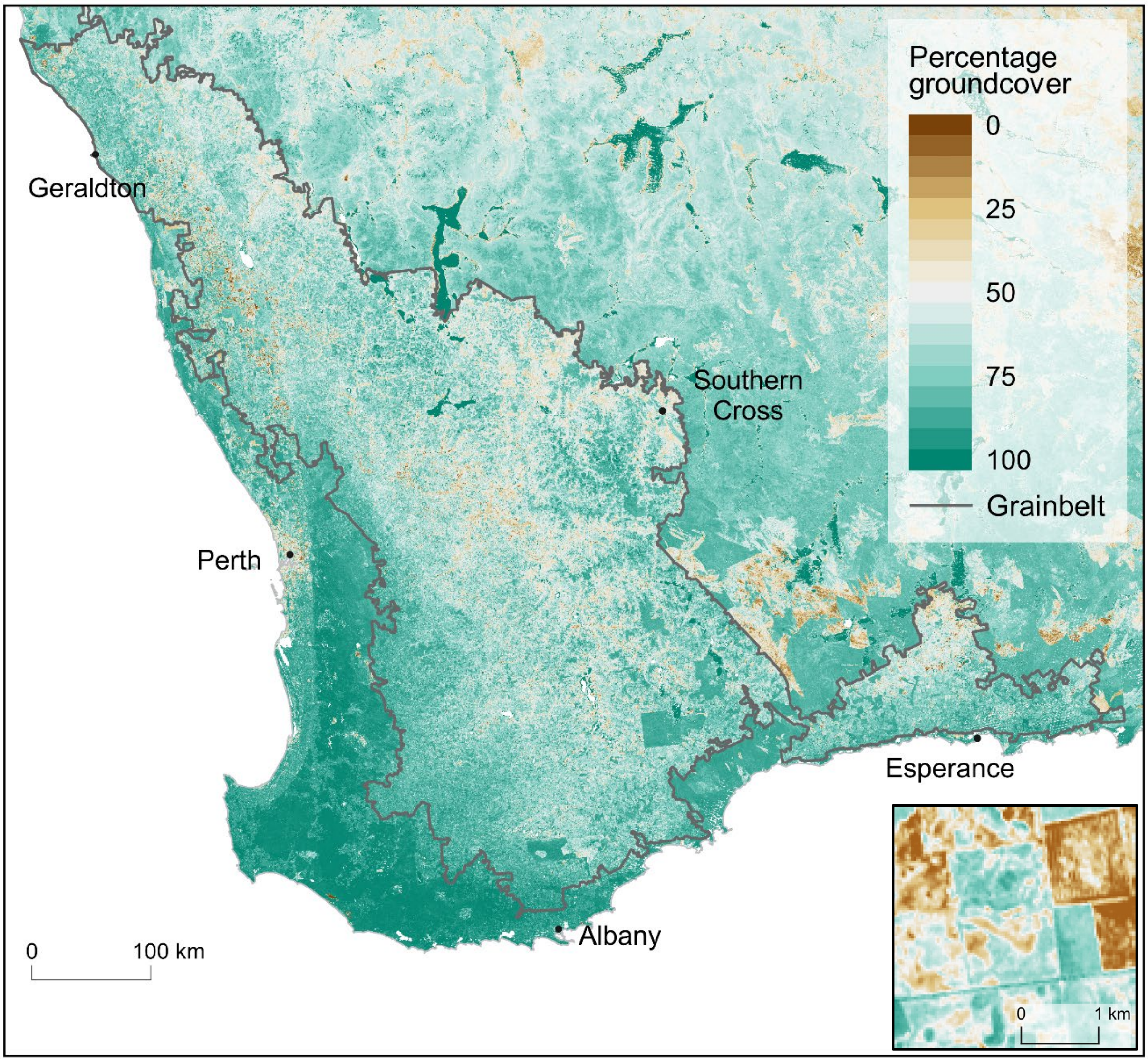
- ‘acfgcs’ is short for AusCover fractional ground cover seasonal
- ‘YYYYMMYYYYMM’ is the start year as a 4-digit number, followed by the start month as 2 digits and then the end year and month in the same format. For example, 202003202005 starts in March 2020 and includes April and May 2020, representing the Australian autumn
- ‘TVCpc’ is the output product, total vegetative cover (TVC) percentage (pc).

If required at this stage of the analysis, the script can also mask the output layer to a user-provided extent, such as arable land in the grainbelt.

As acknowledged above, a single-band TVC TIF image is generated for each annual seasonal period. The other outputs are individual TIF files for ‘bare soil (BS)’, ‘photosynthetic vegetation (PS)’, ‘nonphotosynthetic vegetation (NPV)’ and the ‘unmixing error (UE)’. These outputs are currently not used further, so they are not referred to again in this report.

At the broad scale (e.g. regional or local government areas), TVC can provide a general view of the variation in groundcover. With further investigation, it is possible to attribute some of this variation to the influence of climate, soil and land management. At a paddock scale, it is possible to visualise variations in groundcover and link them directly to soil and land management activities (Figure 2.1).

The latest version of the script for creating the TVC input layer is available in the GitHub repository.[5]



Note: The inset is an example of variability in groundcover at the paddock scale.

Figure 2.1: Example map showing total vegetative cover in the 2021 autumn before masking non-arable land and areas outside the grainbelt

5 GitHub script repository https://github.com/DPIRD-DMA/WheatbeltGroundCover

2.4 Processing variables

Time period

The Landsat archive dates to December 1987, enabling groundcover changes to be tracked over 35 years in relation to climate variability and land management.

For DPIRD reporting, a given season is compared with a typical year, which we define as the seasonal median of the previous 10 years. A time series median derived from the previous 10 years was considered adequate for capturing a range of climatic conditions, land management activities and current farming practices for a given pixel.

Percentage groundcover threshold(s)

Pixel values will range from 0% to 100% groundcover but only physically meaningful thresholds for erosion hazard are selected and reported (Leys et al. 2020). These thresholds are converted into groundcover classes and every pixel is classified as below, between or above each threshold value.

For example, the Commissioner requires summary statistics and maps for groundcover class intervals of 0–30%, 30–50%, 50–70% and 70–100% and associated threshold values of 30%, 50% and 70% (DPIRD 2021). The KPI reporting requires groundcover classes of 0–40% and 40–100%, and a single threshold value of 40% (DPIRD 2021). These parameters are adjusted in the code before running the script.

The physical meaning of these thresholds needs to be justified to ensure consistent reporting with clear land management implications and DPIRD responses. While definitive criteria have not yet been established for DPIRD or WA, clear guidelines are available from research in eastern Australia (Leys et al. 2020) and this is an area of ongoing research and policy development in DPIRD.

Grainbelt mask

The grainbelt boundary defines the area of dryland grain cropping within the south-west agricultural region of WA and is often referred to as the wheatbelt (Figure 2.1).

The western and southern limits were defined by interpreting the best available aerial photography. The dataset was created in August 2009 and updated in June 2012 to incorporate the 2011 recapture of the ‘clearing line’ to define the eastern limit of cropping (DPIRD 2018a).[6]

Arable land mask

The ‘potentially arable areas’ dataset is derived from several source datasets that remove non-arable land, such as Crown reserves, remnant vegetation, roads, infrastructure, severely saline land and water bodies, to determine the land potentially available for agriculture (DPIRD 2018b).[7] This dataset is applied to mask the fractional groundcover time series, ensuring that all analyses eliminate as much non-arable land

[6] Grainbelt mask dataset https://catalogue.data.wa.gov.au/dataset/wheatbelt-of-wa-dpird-028

[7] Arable land mask dataset https://catalogue.data.wa.gov.au/dataset/potentially-arable-land-dpird-026

as possible and calculate groundcover only on areas of managed production (Figure 2.1).

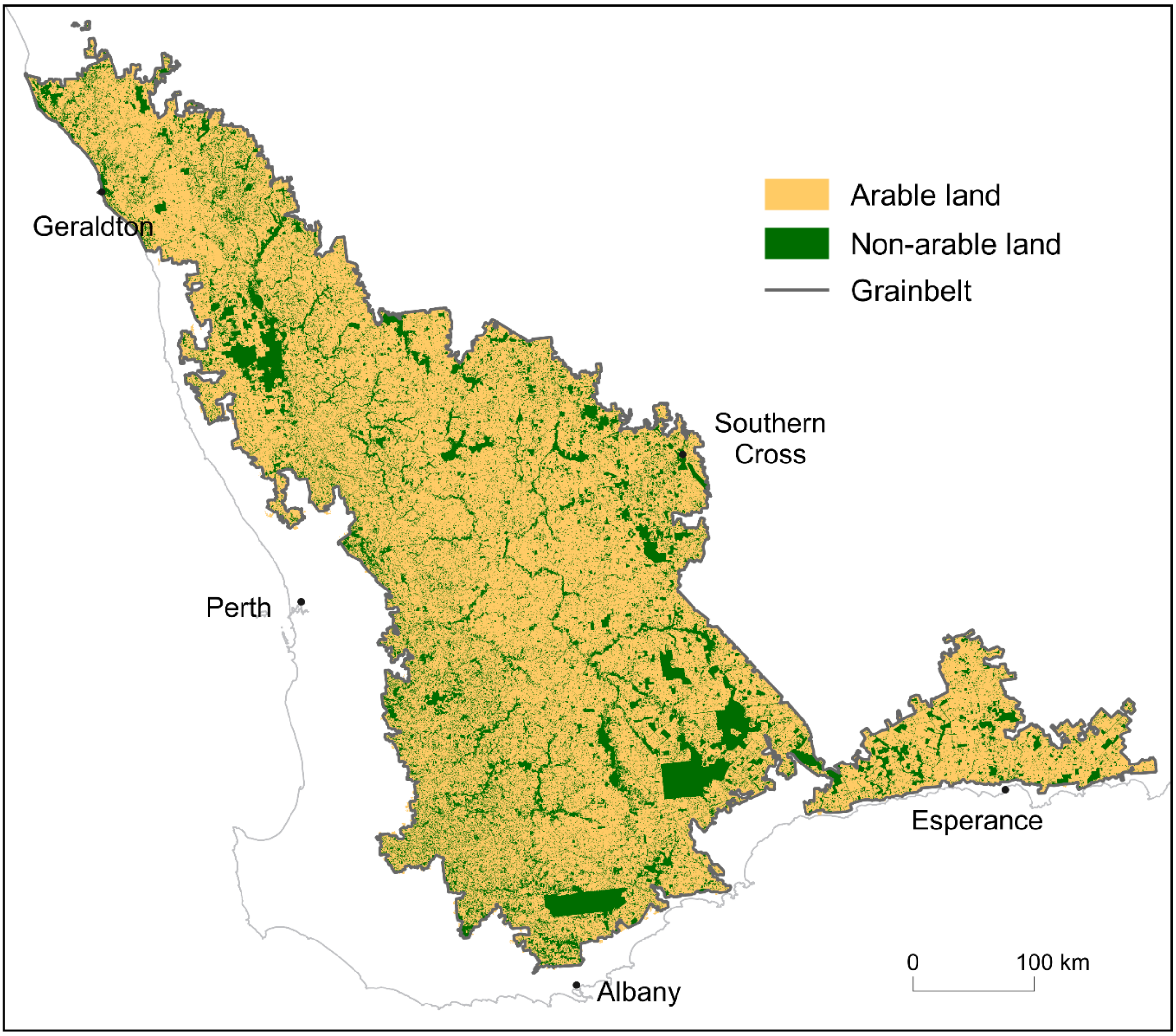


Figure 2.2: The grainbelt and arable land masks restrict analysis to broadacre farmland in the south-west of WA

Spatial units for reporting

Analysis and summary statistics can be processed for any areal extent and can include multiple areas of interest. For example, the KPI and annual Commissioner report require one spatial unit comprising all arable land in the grainbelt. However, such reporting does not differentiate the variance in groundcover due to soil type, climate or local land management over a large extent.

The DPIRD soil-landscape zones (van Gool et al. 2005) provide a more detailed and interpretable geographic assessment of groundcover because they align with regional soil characteristics and seasonal climatic conditions (DPIRD 2019).[8] Localised assessments are also possible by using smaller spatial units, such as paddock

8 Soil-landscape zones https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-best-available

boundaries, property boundaries or detailed soil polygons. The scripts require the spatial units as a vector GIS dataset, such as a shape file.

2.5 Processing individual seasons

The following procedure is used to produce data to answer:

1. Where in the landscape is groundcover above or below a groundcover target, or between 2 groundcover thresholds? (i.e. Where is it?).
2. What percentage of a landscape is above or below a given groundcover target, or between 2 groundcover thresholds? (i.e. How much is it?).
3. What is the groundcover difference between a landscape in one year or season compared to another or the median of a given time period? (i.e. Is this year typical?)

To process individual seasons, the script 'fgc04_Process_Individual_Seasons.py' reads the TVC TIF file(s), assesses against the groundcover percentage threshold(s) provided by the user to classify the image(s) (question 1) and summarises the data in each spatial unit before building tables for reporting (question 2). A subsequent calculation converts the areas to percentage values to enable comparisons between years and calculate the longer-term median (question 3).

The following datasets and their local paths must be specified in the script:

- percentage groundcover threshold(s) – a single percentage groundcover threshold or a range of thresholds must be specified to create TVC classes for processing. For instance, a single value [40] will create 2 groundcover classes of 0–40% and 41–100%, and multiple values [30, 50, 70] will become 0–30%, 31–50%, 51–70% and 71–100% groundcover classes
- TVC image(s) to process
- a mask layer – this option is available to restrict the calculations to particular landscapes, such as arable land
- polygon spatial dataset for reporting (spatial units) and the field name that contains the identifier for each polygon.

This process is repeated on all images in the specified directory to produce individual seasonal outputs, which can also be used for temporal comparisons. From this process, 2 outputs are generated:

1. a TIF file (*.tif) for each season with each pixel value corresponding to the percentage groundcover threshold(s) defined above. If 2 threshold values are specified (e.g. 0–40 and 41–100), then the pixel values will be '1' for the lower threshold and '2' the higher threshold. The pixel values in Figure 2.3 are 1, 2, 3 or 4 and represent 0–30%, 31–50%, 51–70% or 71–100% groundcover.
2. a summary table (*.csv file) is written to disk and given the name 'All_tabulate_records_acfgcs.csv'. The first column of the table is the field name of the polygon spatial dataset with the list of polygon identifiers (Table 2.1). Then a series of columns with the area in metres for each threshold, the image date, and a series of columns with the threshold criteria values in the heading and the associated area in hectares.

The tabulated output includes the area in square metres and hectares. However, we recommend that the percentage value (calculated after running the scripts) is used to compare one year with another, since the total area is not consistent through time because of missing data from cloud effects and other minor differences or variations.

The latest version of the script for processing individual seasons is available in the GitHub repository.[9]

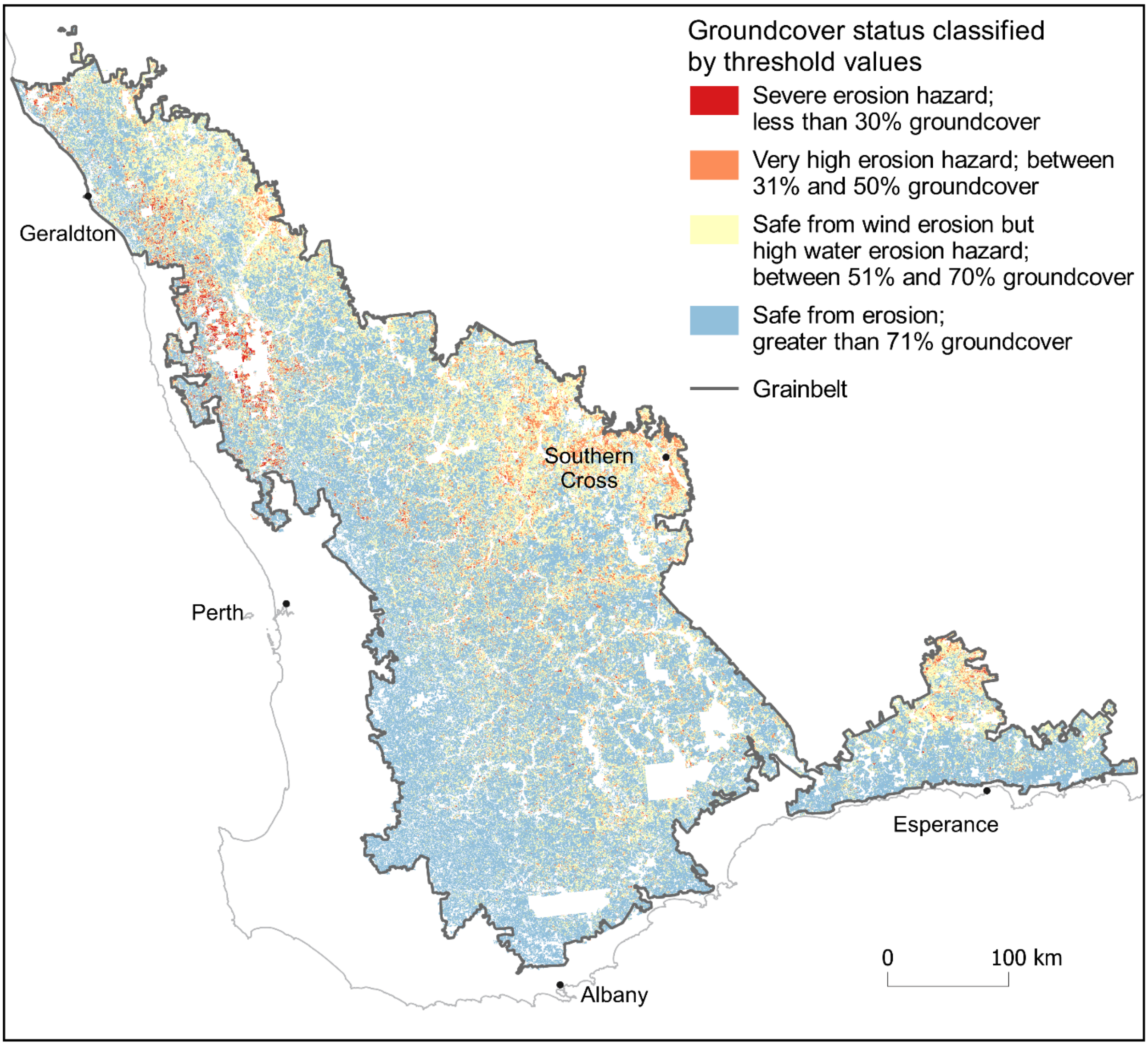


Figure 2.3: Example of an output map showing 4 groundcover classes for arable land in the grainbelt

9 GitHub script repository https://github.com/DPIRD-DMA/WheatbeltGroundCover

Table 2.1: Example of the tabulated output from processing total vegetative cover TIFs for the soil-landscape polygons

Polygon field name	Area for each groundcover class (m^2)				Total area (m^2)	Image date range (YYYYMM YYYYMM)	Area for each groundcover class (ha)			
MU_NAME	VALUE_1	VALUE_2	VALUE_3	VALUE_4	total_area	Image date	a0_30	a30_50	a50_70	a70_100
Bassendean Zone	42,407,100	49,343,400	79,433,100	166,421,700	337,605,300	s_202012 202102	4,241	4,934	7,943	16,642
Pinjarra Zone	933,300	2,424,600	10,745,100	124,709,400	138,812,400	s_202012 202102	93	242	1,075	12,471
Perth Coastal Zone	4,308,300	4,222,800	4,850,100	5,729,400	19,110,600	s_202012 202102	431	422	485	573

2.5.1 Storing processed data

Processing individual TVC images can take several minutes to several hours when processing multiple images and groundcover thresholds and complex spatial units or a detailed mask. For this reason, all the output tabular data is saved in a Microsoft Access database [Analysis_GroundCover_outputs.accdb], and the latest imagery analysis is continually added. This database is currently not publicly available.

We have processed all available archive imagery from 1987 to present with thresholds applied at each 10% increase in groundcover. The soil-landscape mapping polygons have been used as the reporting unit for arable land in the grainbelt (DPIRD 2018a, 2018b, 2019).[10] The multiyear dataset (All_tabulate_records_acfgcs.csv) is imported to the [ArcOutputcsv] table within the Access database. An ‘append query’ adds the new data to the [Cover] table, along with additional columns for the ‘Ag Soil zone’, ‘year’, ‘first month of the season’ and ‘season name’.

We use Microsoft Access queries to amalgamate and summarise the tabular data for reporting, that is, soil-landscape zones are aggregated to Ag Soil Zones (DAFWA 2013) or as one large unit, which meets the requirements of the KPI and annual report to the Commissioner. This dataset provides flexibility to address new questions as they arise without needing to reprocess the imagery.

2.6 Analysing time series

The purpose of the analysing time series is to statistically interrogate individual pixels for a particular season (e.g. summer) over several years. The outputs consist of several sets of raster-based images:

- number of years of data available per pixel (Section 2.6.1)
- number of valid pixels below a user-nominated threshold (Section 2.6.2)

[10] Soil-landscape mapping https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-best-available; arable land https://catalogue.data.wa.gov.au/dataset/potentially-arable-land-dpird-026; grainbelt https://catalogue.data.wa.gov.au/dataset/wheatbelt-of-wa-dpird-028

- the percentage of years that a pixel is below the threshold (Section 2.6.3)
- the median TVC for a pixel across the period (Section 2.6.4)
- how anomalous the TVC of a specified date is from the median TVC (Section 2.6.5).

To analyse time series, the script ‘fgc05_Time_Series_Analysis_by_Season.py’ compares a single season against the same season from previous years (Section 2.3) and has the option of using a mask to restrict the calculations to specific landscapes, such as arable land. The path to a comparison TVC.tif (typically the current season) must be specified to calculate the anomaly, which compares one image date to the median (typical) groundcover percentage. Examples of each of these outputs are described below.

The latest version of the script for analysing time series is available in the GitHub repository.[11]

2.6.1 Number of years of available data

Direct comparisons of ‘area’ can be misleading because the total area assessed (e.g. hectares) varies between seasons and from year to year. Calculating the percentage enables a reliable comparison between seasons and years. To calculate the percentage of years below a threshold (Section 2.6.3), the number of years of available data per pixel is needed.

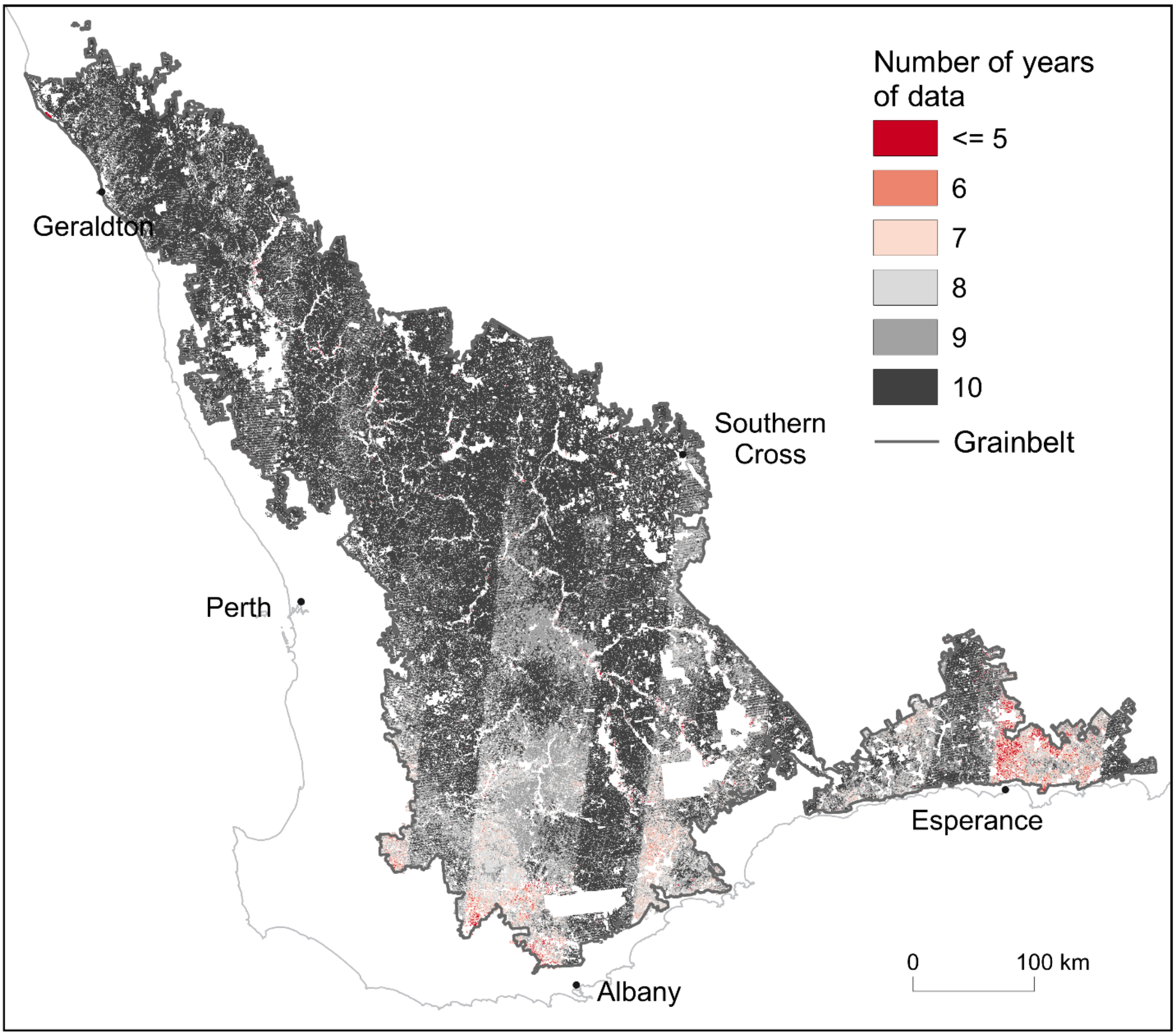
Landsat has a revisit orbit interval of 16 days, or images captured every 8 days when 2 satellites are functioning. Pixels affected by cloud, cloud shadow or snow are automatically removed (masked) when calculating the fractional groundcover of each revisit image. If there are less than 3 valid observations for a season, there is insufficient data to calculate the medoid and the pixel value will be null (Flood 2013).

The proportion of null (or invalid) pixels over a time period is greatest over winter when there is increased cloud cover, particularly in southern parts of the grainbelt. Furthermore, Landsat 7 has a faulty sensor (USGS 2019, 2021) that generates data gaps, decreasing the total area captured by 22%. Because of this, Landsat 7 data is only used when no other valid data is available.

The number of years of available data is calculated for each pixel, by stacking the TVC input layer(s) and summing the number of valid observations. The output file nomenclature is ‘validpixelcount_SeasonYYYY_to_YYYY.tif’, where ‘Season’ is the season of interest and ‘YYYY’ refers to the first and last year of the stack of images.

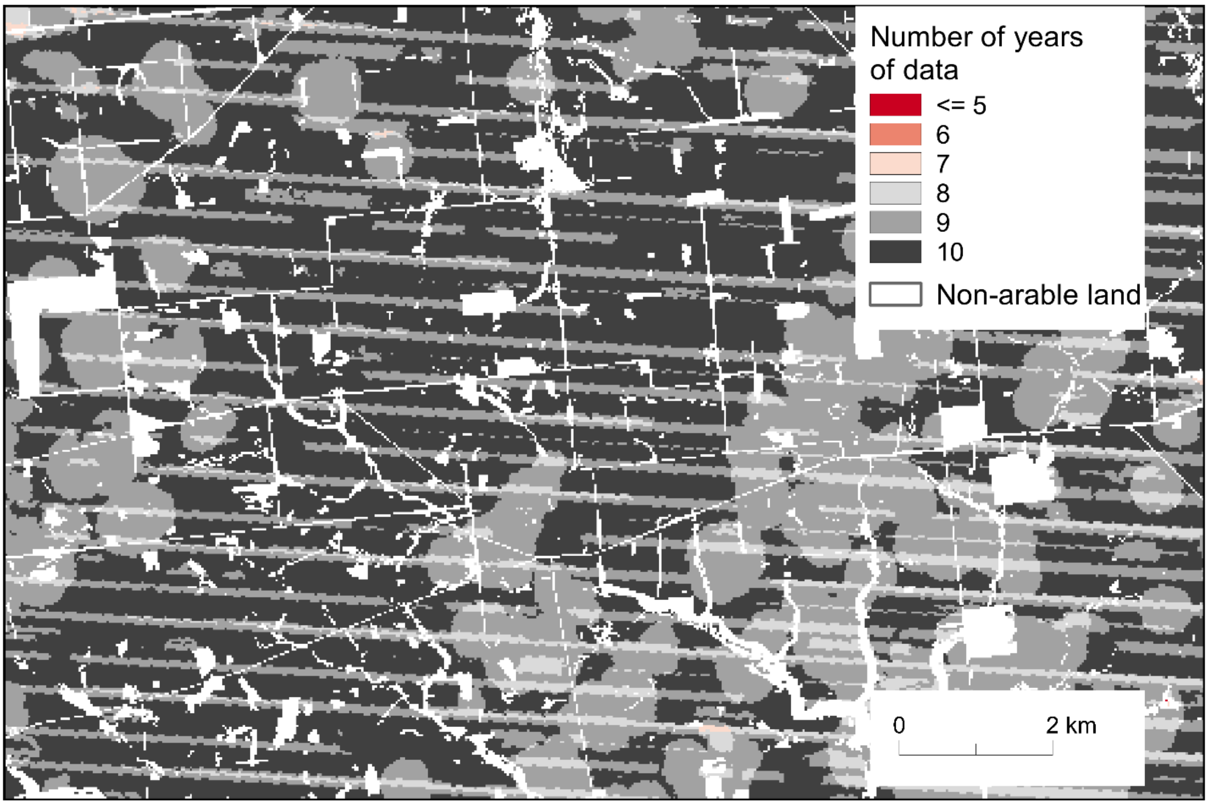
An example output from this processing is shown in Figure 2.4, which highlights the variability in available data throughout the grainbelt over 10 autumn images (2010–2019). Figure 2.5 shows an example output at the property scale.

[11] GitHub script repository https://github.com/DPIRD-DMA/WheatbeltGroundCover



Note: The south-west corner of the grainbelt and an area east of Esperance have a high proportion of pixels with less than 7 years of data (red patches). The grey strip running north–south through the centre of the grainbelt suggests that cloud impeded the view of the landscape in one year, while surrounding areas were not affected.

Figure 2.4: Example map showing the number of years of data available for analysis of each pixel in the grainbelt over autumn, 2010–2019



Note: The east–west stripes of missing data were caused by the faulty Landsat 7 sensor not capturing data. The circular patterns indicate where clouds and surrounding pixels were removed from a composite seasonal image.

Figure 2.5 Example showing the number of years of available data at the property scale

2.6.2 Number of years below a threshold

A common question for time series analysis is ‘how often is the landscape below a particular groundcover threshold?’ To perform this calculation, each pixel is assessed as equal to or below the threshold specified in the Python script (i.e. 50, which is the recommended percentage groundcover to prevent wind erosion). This is performed on all TVC input layer(s) (years) and then the total number of occurrences is calculated for each pixel. This output does not account for null values recorded in some years, and consequently we do not recommend this output for reporting.

The output raster is saved as ‘BelowThresholdCount_SeasonYYYY_to_YYYY.tif’, where ‘Season’ is the season of interest and ‘YYYY’ refers to the first and last year of the stack of images. This raster is used to calculate the percentage of years below a threshold.

2.6.3 Percentage of years below a threshold

We use groundcover targets to assess the sustainability of the soil resource. An example of a target would be ‘95% of the grainbelt maintaining 50% groundcover every year.’ If groundcover is repeatedly below the target, the soil may be at risk of erosion or of entering a negative feedback loop that degrades the soil resource, depleting topsoil nutrients and carbon stocks.

The percentage of years below a threshold is calculated for each pixel using the previous outputs from processing. The ‘Number of years below a threshold’ is divided by the ‘Number of years of available data’ and multiplied by 100. The output raster is saved as ‘PcYrBelow_50pc_SeasonYYYY_to_YYYY.tif’, where ‘Season’ refers to the season of interest and ‘YYYY’ refers to the first and last years of the stack of images used to calculate the 2 input layers.

The percentage calculation is a better measure than the number of years that TVC was below a threshold as it accounts for missing data in some years (Figure 2.6). However, the results of this analysis should be considered in conjunction with the number of years of available data, as shown in Figure 2.4 and Figure 2.5.

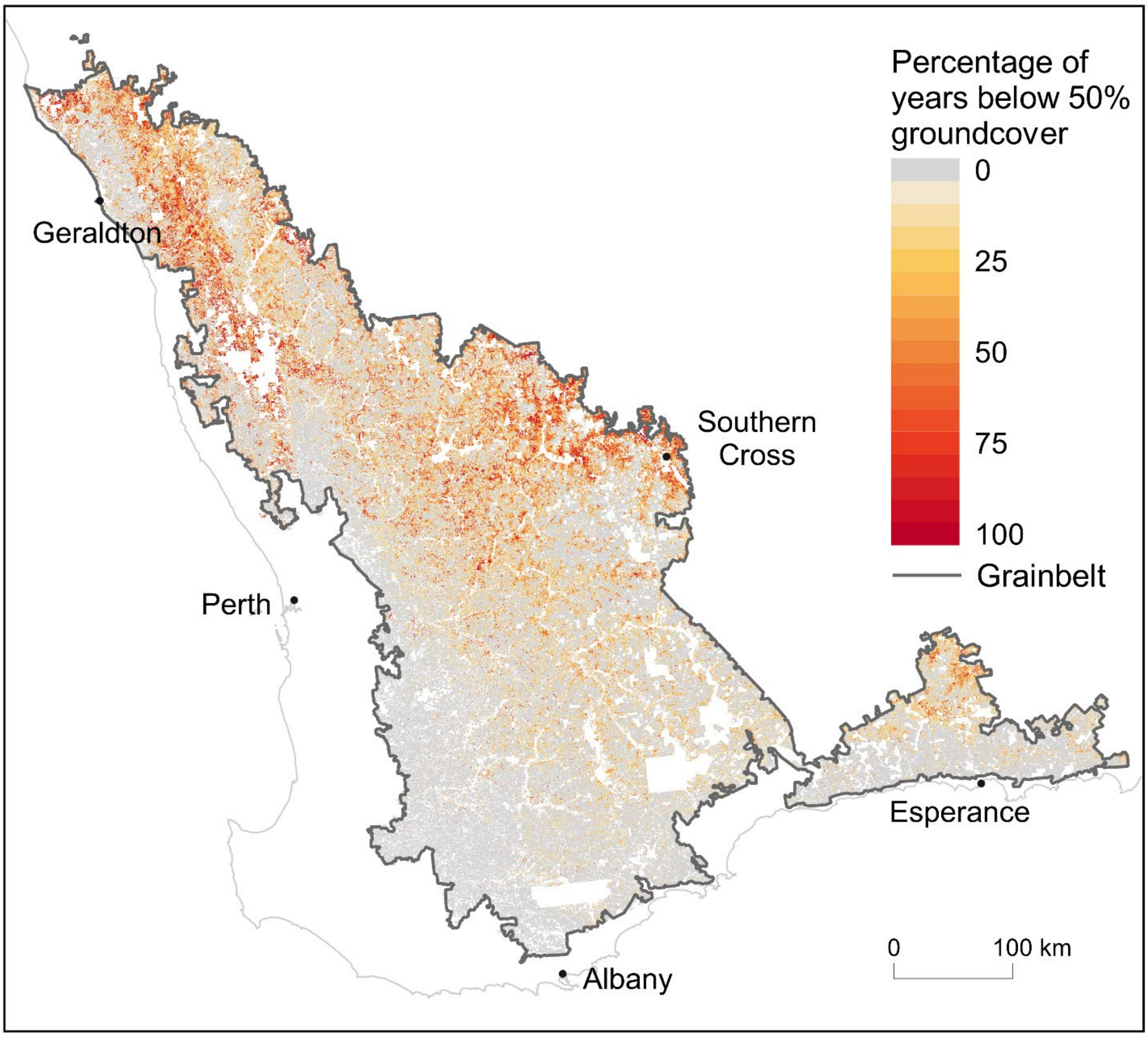


Figure 2.6: Example map showing the areas where groundcover in the grainbelt fell below the 50% threshold target over autumn, as a percentage of years between 2010 and 2019

2.6.4 Median TVC

The pixel median groundcover is calculated from the time series of images. The median is selected over the mean as it removes the bias due to extreme groundcover levels that might be associated with crop failure, wildfire or extreme climate events. These situations significantly reduce TVC and may not reflect typical groundcover of that pixel. The output raster from this analysis is saved as ‘median_SeasonYYYY_to_YYYY.tif’, where ‘Season’ refers to the season of interest and ‘YYYY’ refers to the first and last years of the stack of images.

The median TVC product can be used to visualise typical or baseline vegetative groundcover levels over the landscape (Figure 2.7) or to compare with a single season to calculate the change in groundcover, that is, the anomaly (Section 2.6.5).

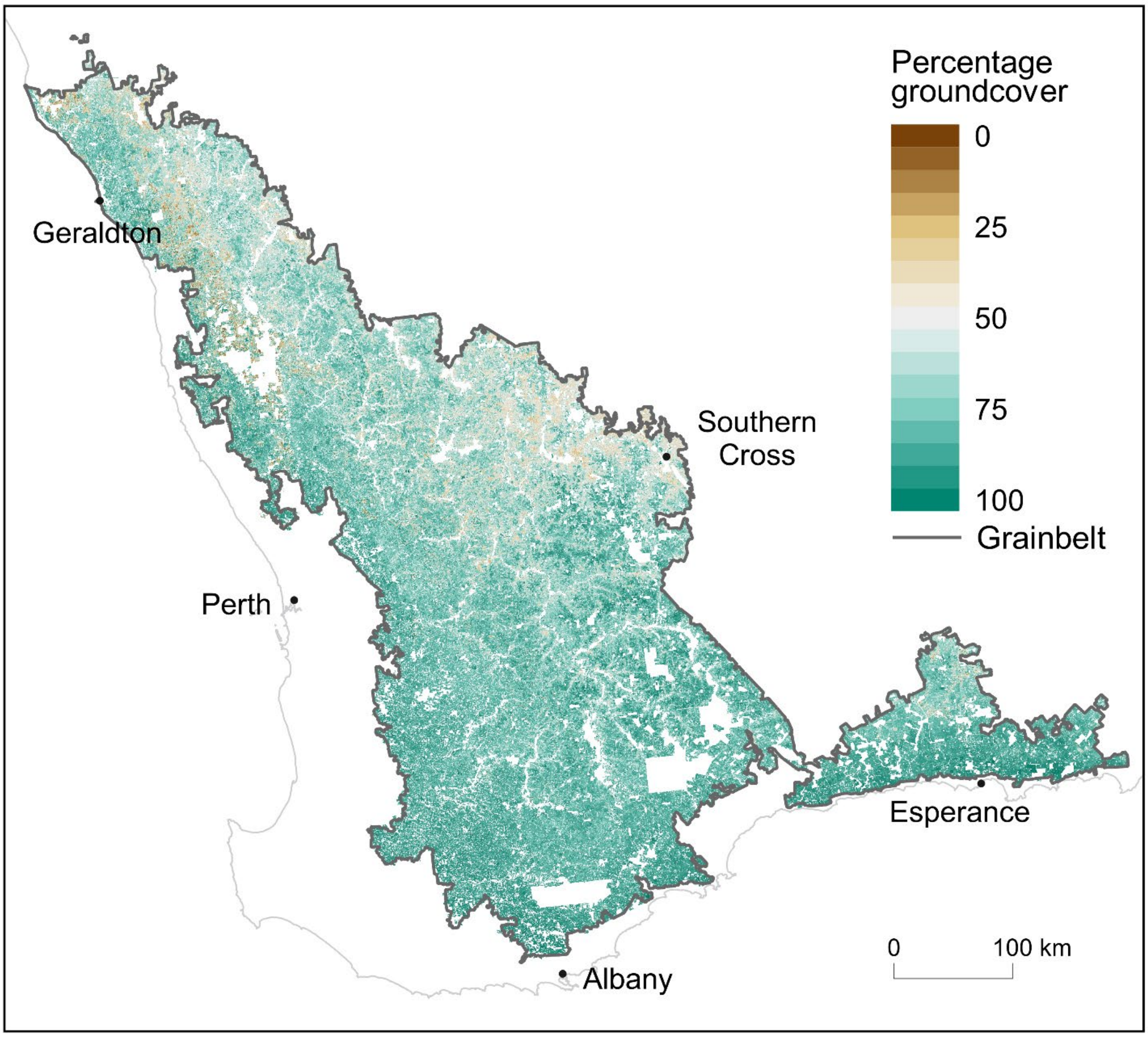


Figure 2.7: Example map showing median groundcover levels in the grainbelt over autumn 2011 to 2020

2.6.5 Identifying groundcover change anomalies

The Landsat time series 'anomaly index' calculates the pixel difference between a single image date (the comparison TVC) and the 10-year median value of the same pixel. The units are percentage groundcover. For example, if the calculated autumn median groundcover value is 40% and the autumn 2020 value is 50%, then the anomaly value is +10. The output raster is saved as 'anomaly_AnYYSeasonYYYY_to_YYYY.tif', where 'AnYY' refers to the anomaly year, 'Season' refers to the season of interest, and 'YYYY' refers to the first and last years of the time series.

The groundcover anomaly helps to identify areas where farming systems may be under a potential stress. Therefore, a relative decrease in groundcover indicates there is less groundcover than is typical. It is important to recognise that a decreasing value (negative anomaly) does not necessarily mean low groundcover and high erosion risk.

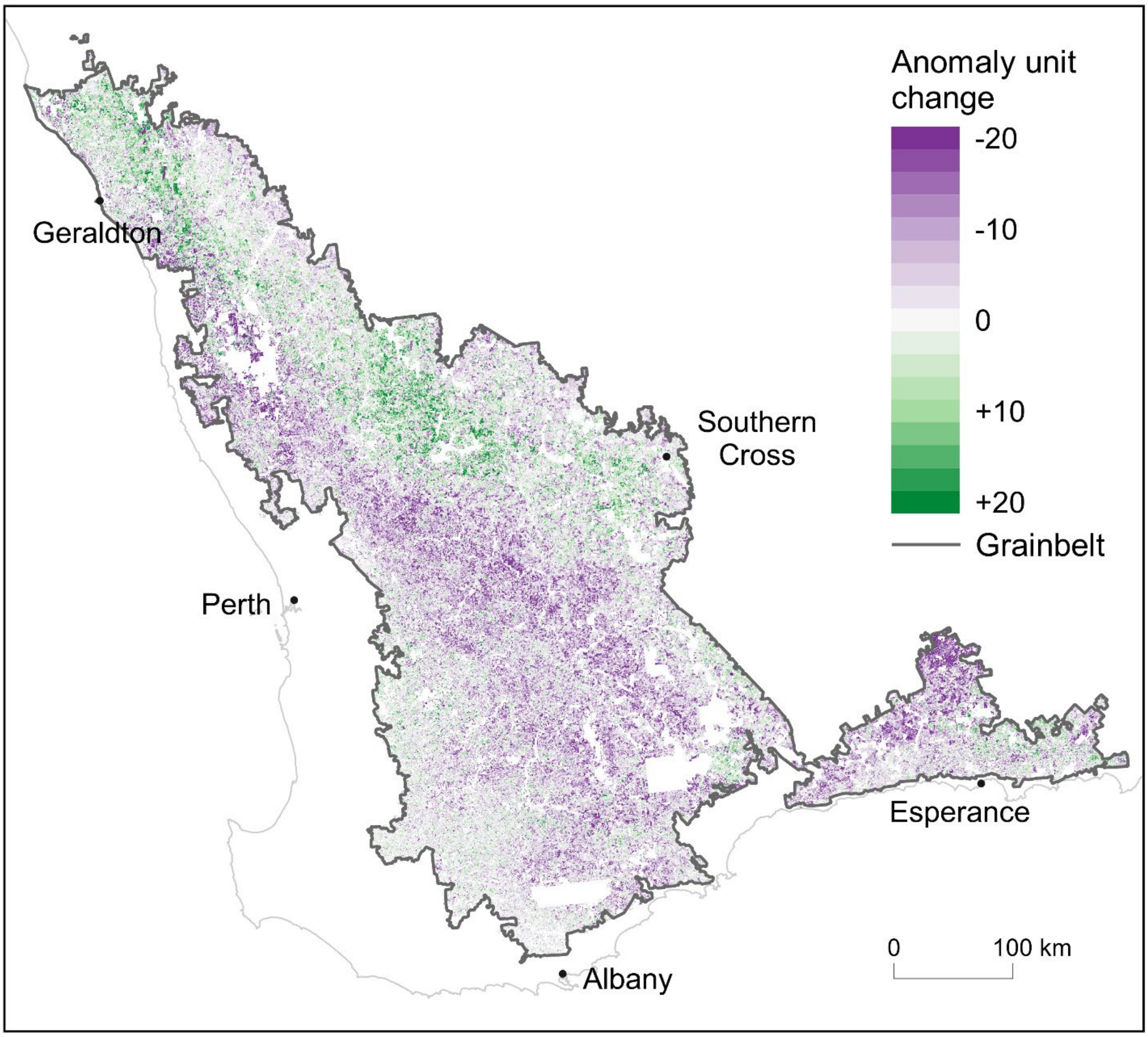


Figure 2.8: Example of an anomaly map showing the difference between the total vegetation cover in summer 2020 and the previous 10-year median vegetation cover for each pixel in the grainbelt

3 Visualisation and interpretation for reporting

The following discussion presents worked examples from 2020–2021 groundcover imagery. Analysis of the imagery contributed to DPIRD's annual report (2021) – the groundcover KPI and reporting on land degradation hazard for the Commissioner – and quarterly reports to the DPIRD Regional Intelligence working group.

Landsat fractional groundcover can be analysed and presented in many ways, over different spatial scales, regional boundaries, time periods and TVC classes. The following data visualisations (statistical summary tables, graphs and maps) provide objective metrics for evaluating the current season groundcover levels in more detail and comparing them to groundcover levels recorded over the last 10 years.

The information can be used to identify areas of concern, either at the very broad regional or landscape scale or at the detailed property and paddock level scale. Strategic follow-up field inspections are required to collect more information and validate the mapping products.

3.1 Groundcover to protect against wind erosion

DPIRD recommends that land managers maintain 50% or more vegetative groundcover at all times to reduce wind erosion hazard to an acceptable level. This value has been determined from field trials across Australia (Carter et al. 1992; Findlater et al. 1990, Leys 1999). Less than 50% groundcover may be inadequate to prevent erosion.

The 50% groundcover threshold is a single measure that provides 2 simple reporting metrics:

1. the percentage of landscape with inadequate groundcover; for example, 17% of the grainbelt had inadequate groundcover in the summer of 2020–2021 to prevent erosion
2. spatial information identifying landscapes with inadequate groundcover; for example, a map showing the landscape with groundcover above and below 50%.

Figure 3.1 shows an example of these metrics. These 2 metrics provide a high-level overview of erosion hazard, which is used in the annual report to the Commissioner. The figure includes absolute hectares in each groundcover class to emphasise the severity of the problem because the relative percentage value may seem insignificant.

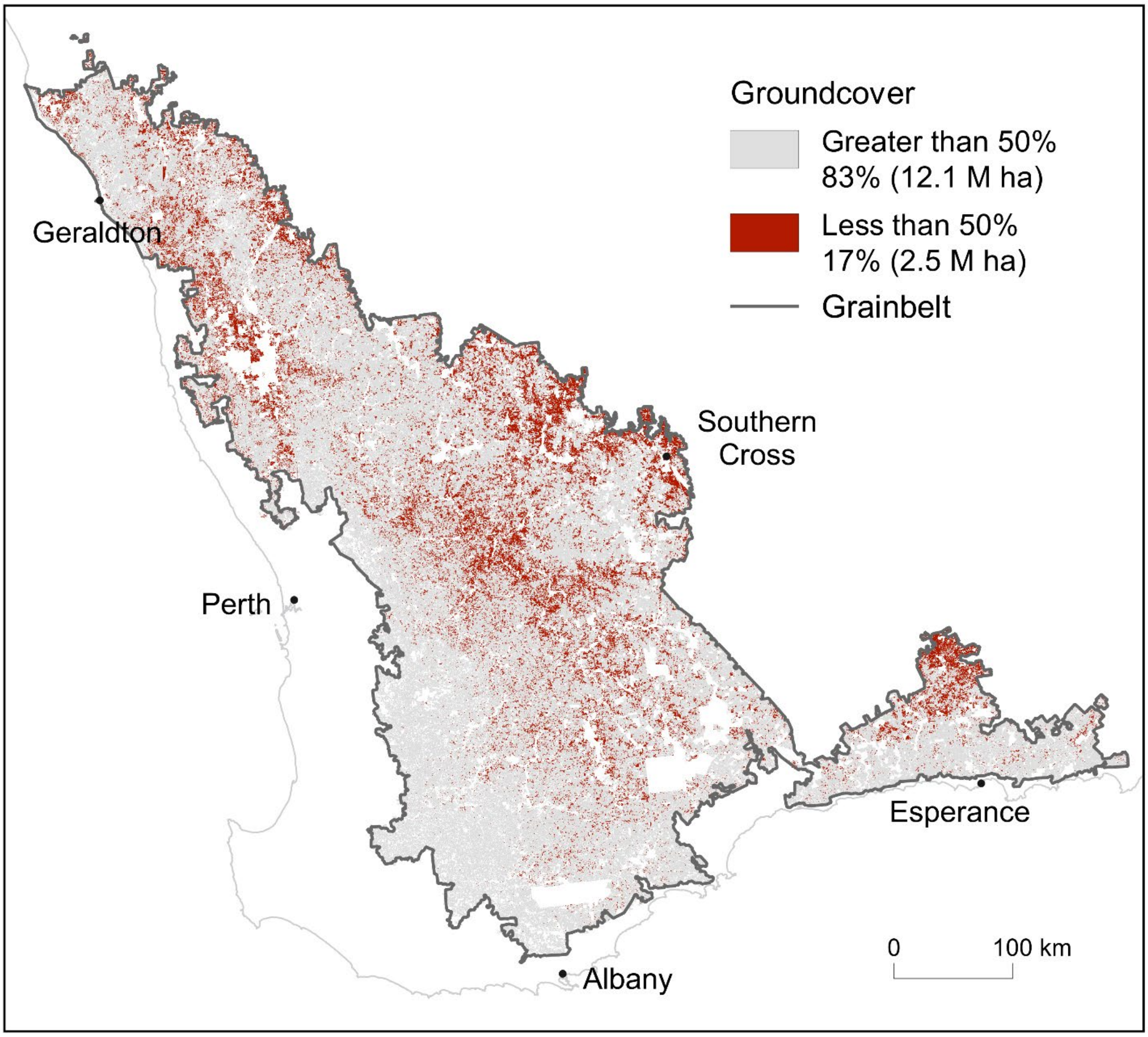


Figure 3.1: Example map showing total vegetation cover above and below the erosion hazard threshold of 50% across the grainbelt in summer 2020–2021

The metrics (1) and (2) are suitable for reporting on a single season but lack the context of other seasons and years. Table 3.1 shows the variation in groundcover throughout a year. The 2020 summer and autumn seasons had 3 times more land with less than 50% groundcover than in winter and spring. This seasonal pattern is typical and explains why more erosion occurs during the dry (summer and autumn) seasons. Beware of the seasonal variability in the total area due to missing data.

Table 3.1: Total area and percentage of the grainbelt with less than 50% groundcover in the autumn, winter, spring and summer of 2020–2021

Season	Area of the grainbelt (ha)	Area with <50% groundcover (ha)	Area with <50% groundcover (%)
Autumn 2020	14,158,000	2,513,000	17.8
Winter 2020	14,571,000	698,000	4.8
Spring 2020	14,255,000	849,000	6.0
Summer 2020–2021	14,604,000	2,487,000	17.0

3.2 Understanding groundcover (TVC) classes

A single statement of ‘percentage of the landscape with less than 50% groundcover’ does not differentiate the extreme erosion hazard of 0% groundcover from 49% or even 51% groundcover. Displaying a wider range of groundcover classes better describes and quantifies the erosion hazard. Table 3.2 presents examples of groundcover classes that may be used for erosion hazard reporting. To visualise the difference in groundcover, Figure 3.2 contains a series of photos of cereal stubble taken during the field validation.

Another important consideration is the percentage of the landscape within a groundcover class because this can affect the overall landscape erosion hazard and DPIRD’s response. Figure 3.3 outlines a landscape in 2 different seasons with groundcover divided into 10 classes. The overall distribution of both years is skewed towards the higher groundcover classes, although the peak and the left tail vary significantly between the 2 years. This type of information can be used to choose the most appropriate groundcover classes for reporting in different years or at different scales. The selection of which groundcover classes used in reporting may differ between seasons and years depending on the percentage of landscape in that class, or how DPIRD may respond to an increase in the percentage of land in that class (Table 3.2).

The final selection of groundcover classes must be meaningful for land management and policy development and meet the needs of the end user.

Note: An image product error of ±12% means there will be uncertainty in all groundcover estimates, and care needs to be taken when assessing status using a hard threshold. Field verification may be required to determine if a DPIRD response is needed.

Table 3.2: Examples of groundcover classes and the importance of monitoring and evaluating land in each class

Groundcover class	Effect on erosion hazard and importance for monitoring
Very little to none 0–10%	Typically, less than 1% of the grainbelt has less than 10% groundcover in summer. While the likelihood of erosion is very high, the severity will depend on the depth of detached soil and proportion of coarse fragments. Very little groundcover can be a result of wildfires, deliberate complete burns, soil inversion, tillage, confinement feeding, overgrazing or fallow. Understanding the reason and seasonal timing of the low groundcover will determine if the erosion hazard is justifiable or not.
0–30%	All soils are highly susceptible to erosion when there is less than 30% groundcover. Typically, less than 3% of the grainbelt has less than 30% groundcover, although this can increase to more than 10% at the subregional scale. Very little groundcover can be a result of wildfires, deliberate complete burns, soil inversion, tillage, confinement feeding, overgrazing, failed crops or fallow. Understanding the reason and seasonal timing of the low groundcover will determine if the erosion hazard is justifiable or not.
0–50%	Soil is likely to erode when there is sufficient wind, and when the soil is in an erodible state. DPIRD recommends that 50% groundcover is the minimum level to prevent wind erosion. This degree of groundcover provides only a moderate level of protection from water erosion.
40–50%	About half of all land in the grainbelt with less than 50% groundcover has 40–50% groundcover (Figure 3.3). Because this class is on the threshold between enough and not enough groundcover, it should be closely monitored because: • for some soils, 40% groundcover is adequate to prevent erosion, particularly if the vegetation is attached to the soil; some tall stubbles can provide good protection even when groundcover is below 40% (Raupach et al. 1993; Fryrear and Bilbro 2018) • vertical vegetation structure, particularly stubbles, may prevent erosion even if the TVC is below the recommended 50% threshold • land managers might practice sustainable agricultural practices yet inadvertently overestimate groundcover resulting in actual groundcover being below 50%; field assessments of increased awareness of the erosion risks may be required • sowing the next crop reduces groundcover to below 50%; the risk of erosion will depend on rainfall and the time taken for crop establishment • natural decomposition of groundcover could lead to less groundcover and a greater erosion hazard • an error of ±12% means the pixel might have adequate groundcover.
50–60%	While a groundcover of 50–60% is above the DPIRD recommendation for preventing wind erosion, the soil can still erode under severe weather conditions. This groundcover class must be monitored because: • natural decomposition of groundcover or disturbance due to tillage can result in groundcover dropping below 50% • the seasonal groundcover is a median of multiple dates; it is not the minimum groundcover for that period • an error of ±12% means the pixel might have inadequate groundcover. Groundcover is still below the recommended 70% groundcover to prevent water erosion.

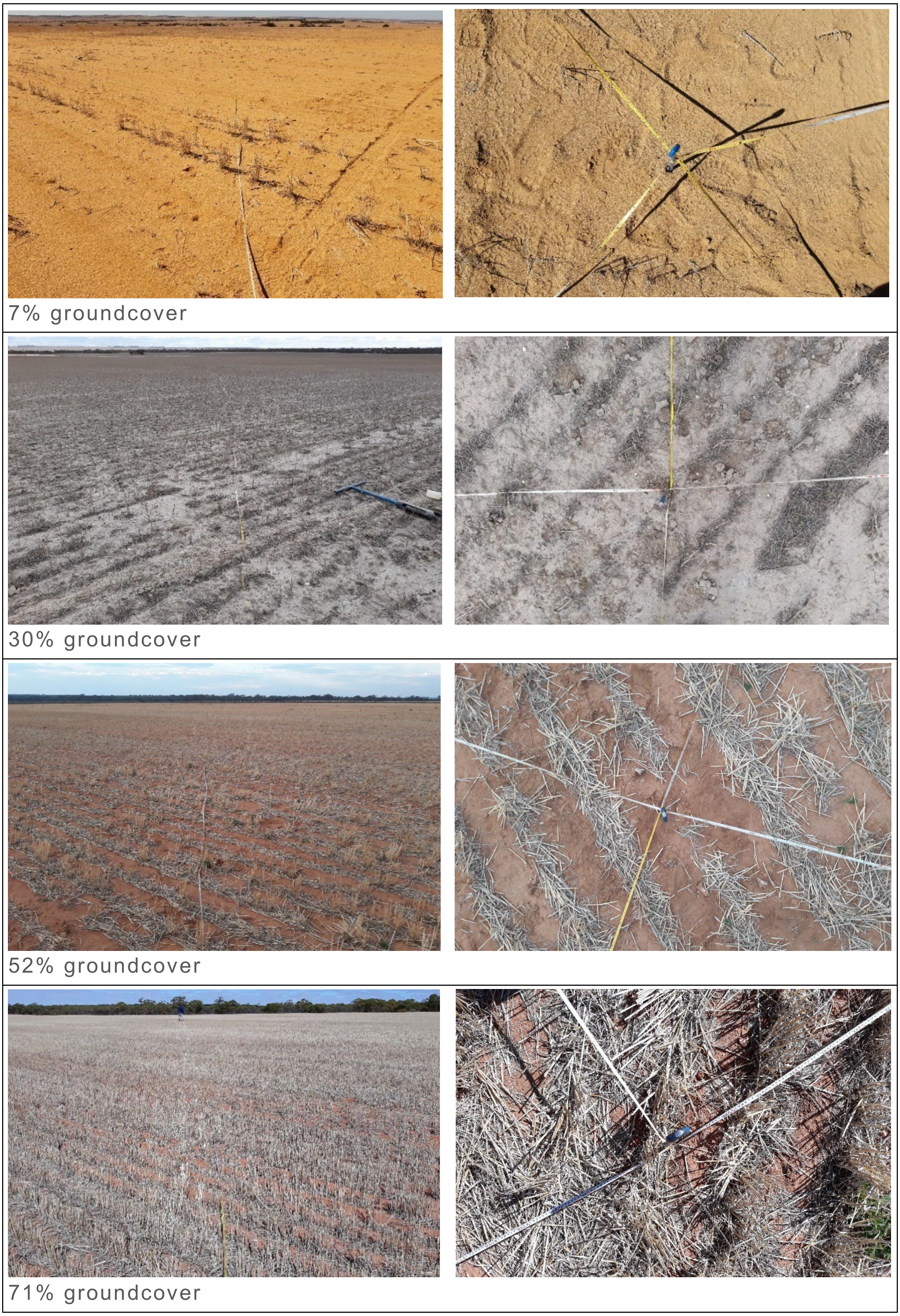


Figure 3.2: Examples of percentage groundcover in the field

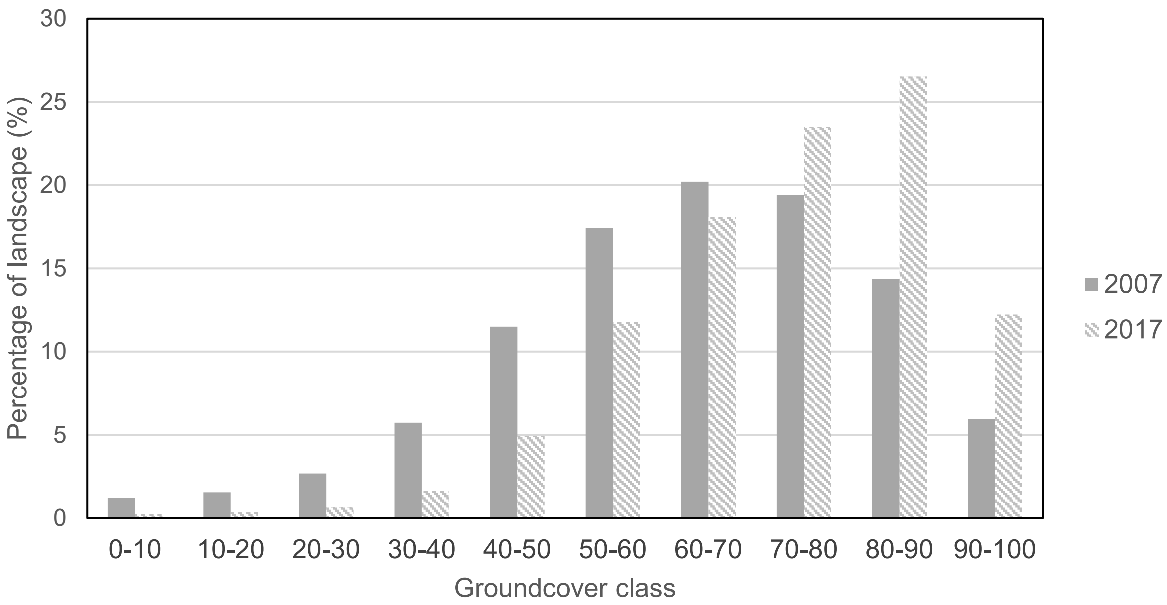


Figure 3.3: The distribution of groundcover in 10% increment classes for 2 very different years

Communicating groundcover classes needs to vary according to the intended end user. For the Commissioner, we use 2 approaches:

- the status of groundcover over the previous year using 4 groundcover classes (Table 3.3)
- a single map displaying the spatial distribution of groundcover classes, including a bar chart of the classes to clarify the percentage of the landscape within each class (Figure 3.4).

Together, these outputs provide the Commissioner with enough information to quickly assess the erosion hazard (4 groundcover classes and percentage of land in each class) and identify the landscapes most at risk (map) and the short-term change in groundcover (table).

Table 3.3: Percentage of arable land in the grainbelt in each groundcover class from autumn 2020 to summer 2020–2021

Season	Percentage of land in the groundcover class (%)			
	0–30%	31–50%	51–70%	71–100%
Autumn 2020	3.1	14.7	42.3	40.0
Winter 2020	1.3	3.4	14.5	80.7
Spring 2020	0.8	5.2	35.7	58.3
Summer 2020–2021	2.4	14.6	44.0	39.0

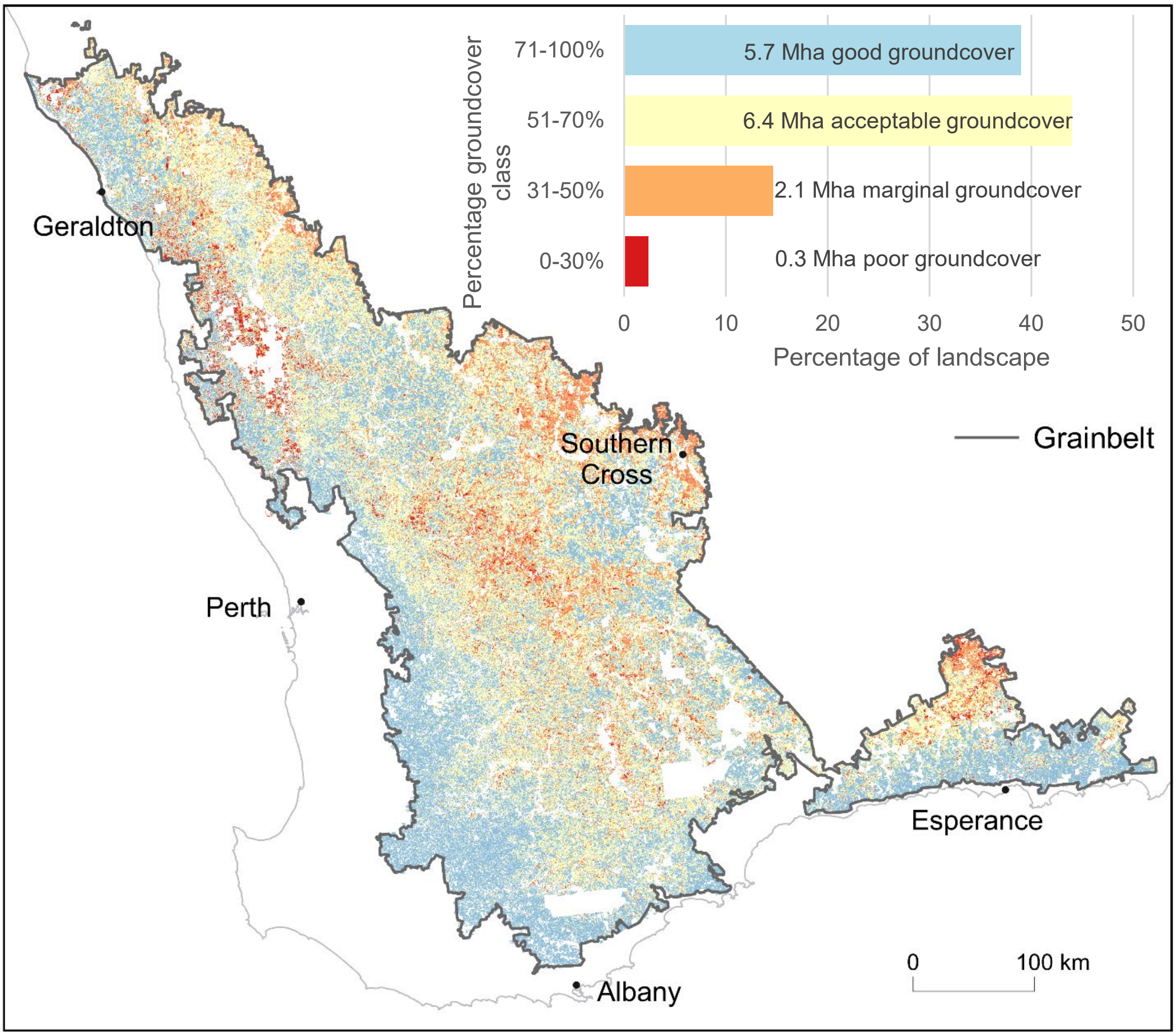


Figure 3.4: The spatial coverage of total vegetative cover and a bar chart displaying the percentage and hectares of the landscape within each groundcover class for summer 2020–2021

3.2.1 Groundcover comparison through time

Using the Landsat archive enables groundcover to be reviewed through time. These temporal changes can portray trends, including how groundcover is affected by long-term changes in climate or changes in farm management practices. Annual trends can provide early warning that vegetative groundcover is likely to decrease to levels that may render the landscape prone to erosion during the coming season. Such information can be valuable for planning extension and compliance campaigns.

To address this, we use a stacked bar chart and box and whisker plot to present how groundcover varies within and between years.

Stacked bar chart

The stacked bar chart in Figure 3.5 uses the same data in

Table 3.3, but presents the information as a time series of stacked bars for individual seasons. Typically, we compare the current season with the previous 10 years.

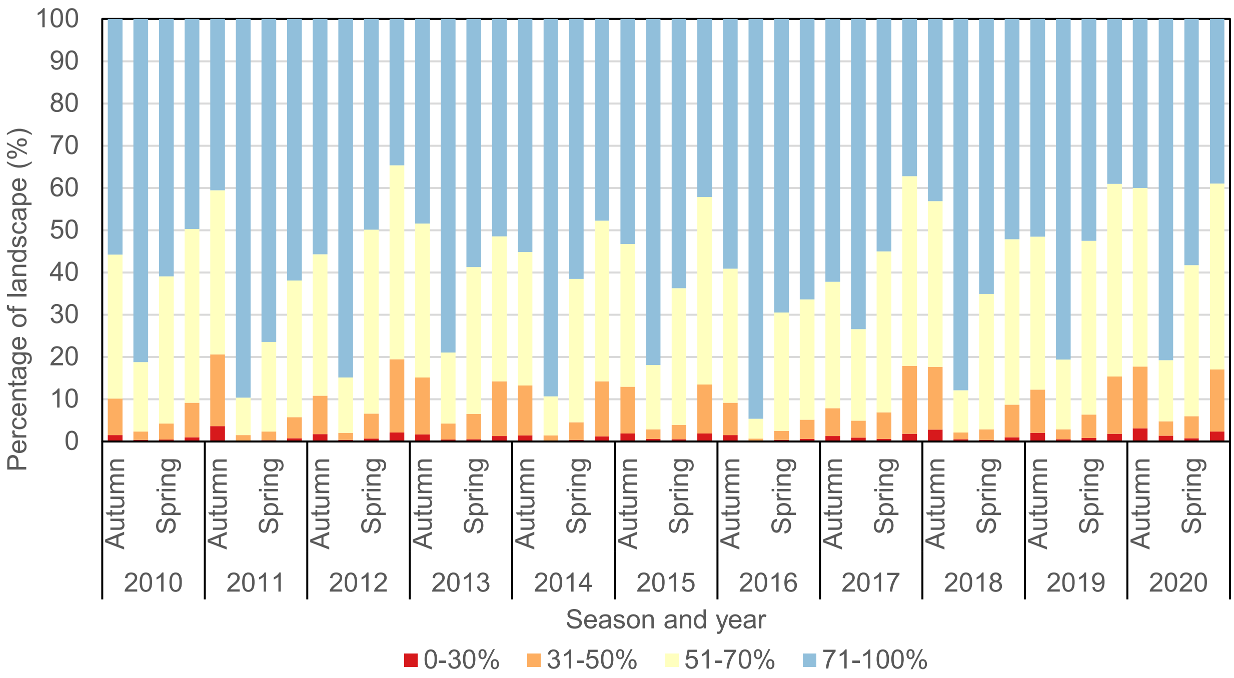


Figure 3.5: Stacked bar chart of groundcover classes on arable land in the grainbelt for autumn, winter, spring and summer from 2010 to 2020

Box and whisker groundcover probability distribution

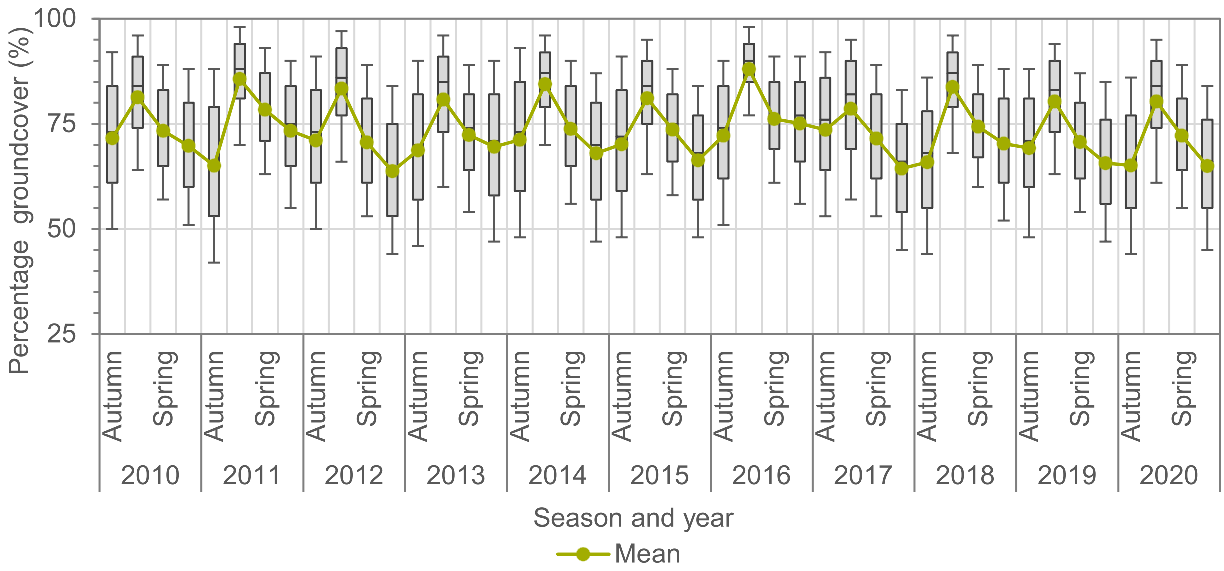
Box and whisker time series plots summarise the groundcover data into broad divisions using percentiles. The percentile value indicates the percentage of landscape below that value. For example, autumn 2010 had a 25th percentile of 62% groundcover, which means 25% of the landscape had 62% or less groundcover.

The data for the box and whisker plot in Figure 3.6 consists of:

- median groundcover of all pixels in a polygon, which is the middle point of a box
- upper and lower quartiles, which determine the length of a box
- whiskers, that extend down to the 10th percentile and up to the 90th percentile; the 10th and 90th percentiles were selected over the maximum and minimum because groundcover will always be 0% (e.g. farm dam) or 100% (e.g. perennial vegetation) somewhere in the landscape
- mean of all pixels, as a coloured line.

A Python script 'fgc06_Percentiles_as_batch.py' is available to calculate the percentiles, median, average, maximum, minimum, count and standard deviation of each image in a folder. This process uses the TVC images produced in Section 2.5. The latest version of the percentiles as batch script is available in the GitHub repository.[12]

[12] GitHub script repository https://github.com/DPIRD-DMA/WheatbeltGroundCover



Note: The whiskers extend to the 10th and 90th percentile values.

Figure 3.6: Box and whisker plot of total vegetative cover on arable land in the grainbelt in autumn, winter, spring and summer from 2010 to 2020

3.3 The difference between typical and current groundcover (anomaly)

The anomaly is the TVC difference calculated on each pixel, between a time series median and a single date. Dry seasonal conditions typically produce a negative anomaly (lower groundcover than is typical) and wetter seasons tend to produce a positive anomaly (higher groundcover than is typical). At a paddock scale, differences in groundcover occur as a normal part of rotational farming – diverse crops and pastures combined with management activities will produce different quantities of groundcover each year. However, at both the property and regional scale, a decrease in groundcover may indicate that the farming system is stressed and may have reduced feed for stock and reduced returns from lower yielding crops. Further interrogation of groundcover anomalies (Section 2.6.5) can highlight where the soil resource and farming systems may be deteriorating and require intervention or assistance. While a positive anomaly indicates an increase in groundcover, this increase could still be inadequate and the landscape could remain susceptible to erosion.

The anomaly at a given location needs to be compared with the surrounding area. For example, a positive anomaly surrounded by negative anomalies may indicate that farm management has changed to increase groundcover, which is a desirable response.

Combinations of pixel anomaly values, time series median TVCs and single date TVCs can be combined to identify areas of concern and if a response is required (Table 3.4). The combinations use 50% groundcover to distinguish desirable and undesirable condition in the interpretation.

Land management, soil type and environmental factors influence groundcover levels and the anomaly. Field assessments are needed to clarify if a response is required. For example:

- A sudden change in vegetation type (perennials to annuals) may produce a large negative anomaly.
- Harvesting crops closer to the ground may result in satellite estimates of lower groundcover than with taller stubbles
- Stock flattening stubbles while grazing can increase estimated groundcover and further grazing will deplete groundcover. Hence, the timing of grazing and the date of image capture may produce an unexpected groundcover anomaly.
- Some landscapes, such as around dams or saline areas, may always have inadequate TVC and little or no potential of increasing it.
- Some soil amelioration practices (e.g. soil inversion) remove all groundcover; however, the benefits may outweigh the short-term severe erosion hazard.
- Wildfires and deliberate burning reduce groundcover, requiring different responses from DPIRD and the landowner.

Table 3.4: Combinations of pixel anomaly, median TVC and single date TVC, and the associated interpretation and possible response

Median (long-term) TVC	Single date TVC	Interpretation	Response
Positive anomaly			
Above 50%	Above 50%	Desirable – groundcover is usually adequate and remains adequate to prevent erosion.	Likelihood of wind erosion is low. Continue with existing messaging and programs to improve farming systems.
Below 50%	Above 50%	Desirable – percentage groundcover is typically below the target of 50% (undesirable), but groundcover has increased and is now adequate to prevent wind erosion.	Continue with targeted messaging and education programs to improve farming systems and monitor the situation in following years.
Below 50% (e.g. 20%)	Below 50% (e.g. 40%)	Undesirable – groundcover levels are below what is needed to prevent erosion and although the current level is an improvement, it is still inadequate to prevent erosion.	A positive anomaly may indicate an improvement in groundcover management, but a consistently low TVC is cause for concern. Start or continue development of farming systems matched to the land capability. Continue with existing messaging and monitor the situation in following years.
Neutral anomaly			
Above 50%	Above 50%	Desirable: – groundcover levels continue to prevent wind erosion.	Likelihood of wind erosion is low. Continue with existing messaging and programs to improve farming systems.
Below 50%	Below 50%	Undesirable – groundcover levels remain below what is needed to prevent wind erosion.	Implement farming systems that match land capability. Continue with existing messaging and monitor the situation in following years.
Negative anomaly			
Above 50%	Above 50%	Desirable – groundcover is adequate to prevent wind erosion; however, the groundcover is less than the median TVC.	Likelihood of wind erosion is low. Continue with existing messaging and programs to improve farming systems.
Above 50%	Below 50%	Undesirable – groundcover levels are inadequate to prevent wind erosion, despite typically being above 50% TVC.	Investigate circumstances leading to the anomaly and initiate changes to the farming system, if appropriate. Continue existing messaging and programs to improve farming systems and monitor the situation in following years.
Below 50% (e.g. 40%)	Below 50% (e.g. 20%)	Undesirable – groundcover levels remain below what is needed to prevent wind erosion.	The declining anomaly and typically low groundcover are cause for concern. Undertake field verification to identify the cause of the low groundcover and groundcover product accuracy. Implement farming systems matched to land capability. Continue with existing messaging and monitor the situation in following years.

TVC = total vegetative cover

4 Future research

More work is required to increase accuracy and confidence in using satellite groundcover products and making them better suited for tactical use as alerts to seasons of potential high erosion risk. Areas of ongoing research include:

- annual field validation to ensure fractional groundcover imagery is accurate and interpretable across WA landscapes
- targeted field surveys to investigate the root cause of consistently low groundcover identified via remote sensing of groundcover
- combining groundcover with soil and landscape information to improve the interpretation and assessment of the erosion hazard. For example:
    - combine groundcover estimates with measures of inherent erosion susceptibility in the soil quality landscape maps and associated database (van Gool et al. 2005)
    - map hazard assessments at higher spatial resolution by combining groundcover estimates with soil properties relevant to erosion from digital soil maps
    - combine groundcover estimates with terrain attributes derived from digital elevation models such as water accumulation, flow paths and velocity, to isolate landscapes most susceptible to water erosion
- identifying susceptible landscapes with inadequate groundcover, which may be more informative than groundcover alone. Alternatively, feeding this data into a hazard matrix to calculate a multifactor erosion hazard, which can then be developed into an erosion risk matrix to determine the sustainability of the soil resource
- combining groundcover with weather information such as wind speed and duration or rainfall and intensity to enable:
    - development of predictive maps for susceptible landscapes where erosive weather events intersect with inadequate groundcover
    - predictions of erosion based on past, current or forecast weather information
- exploring the benefits of other satellite platforms and products that provide higher spatial and temporal resolution imagery to enable reporting at different scales
- developing near real-time groundcover assessment using individual date imagery to assess the short-term changes in groundcover due to specific management actions or a rainfall event.

Appendix A Groundcover imagery access resources

Name	Location	Description
Digital Earth Australia (DEA)	https://www.dea.ga.gov.au/	DEA is a program of Geoscience Australia, an agency of the Australian Government. DEA creates free and open satellite data products for Australia. Imagery can be downloaded direct from the website or via the Open Data Cube, which can also be used to process the imagery
DPIRD Job Archive – An internal server to store project files	Database location (internal network): \\gisdataserver\job_archive\2019\2019365_KPI 7.1b Ground cover change_JLaycock	This link provides access to the inputs, scripts and outputs from the processing of the fractional groundcover imagery for DPIRD staff
GitHub code repository	https://github.com/DPIRD-DMA/WheatbeltGroundCover	An online, publicly available code repository. The scripts can be downloaded and used to replicate the methods described in this report
Geoglam RaPP	https://map.geo-rapp.org/	Geoglam RaPP (Rangeland and pasture productivity) Map is a free online tool providing time series data on vegetation and environmental conditions, allowing national and regional reporting of vegetation cover change. RaPP Map is the spatial data platform for the National Landcare Regional Partnerships Program. It is hosted by CSIRO’s Data61
TERN AusCover seasonal fractional groundcover	http://qld.auscover.org.au/public/data/landsat/seasonal_fractional_cover/fractional_cover/	TERN AusCover delivers earth observation data and products that describe important land-surface and environmental characteristics derived using satellite and airborne imagery. The web page link allows users to download the analysis-ready seasonal fractional groundcover imagery for each state
VegMachine	https://vegmachine.net/	VegMachine is an online tool that uses Landsat satellite imagery to summarise decades of change in Australia’s grazing lands. It will: • generate comprehensive groundcover monitoring reports • measure groundcover change or estimate soil erosion rates • view satellite image land groundcover products enable a better understanding of the links between management, climate and groundcover on grazing land

References

Anderson G (2009) ‘The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia’, *Bulletin 4786*, Department of Agriculture and Food, Western Australian Government.

Bennett A (2021) *Investing in sustainable agricultural resource use in Western Australia – reference metrics,* Department of Primary Industries and Regional Development website, Western Australian Government, accessed 22 August 2022.

Carter D, Findlater P and Porritt S (1992) ‘Stubble retention for control of wind erosion’, *Journal of the Department of Agriculture, Western Australia*, Series 4, 33(1):15–17.

Carter D and Laycock J (2013) ‘Wind erosion’ in Department of Agriculture and Food, Western Australia (2013) *Report card on sustainable natural resource use in agriculture: status and trend in the agricultural areas of the south-west of Western Australia*, DAFWA, Western Australian Government.

Chepil WS and Woodruff NP (1963) ‘The physics of wind erosion and its control, Contribution from Soil and Water Conservation Research Division, Agricultural Research Service, USDA, with Kansas Agricultural Experiment Station cooperating. Department of Agronomy Contribution No. 795.’, in Norman AG (ed) *Advances in Agronomy*, 15:211–302, doi:10.1016/S0065-2113(08)60400-9.

Coles N and Moore G (2001) Runoff and water erosion', in Moore G (ed) 'Soilguide (Soil guide): a handbook for understanding and managing agricultural soils', *Bulletin 4343*, Department of Agriculture, Western Australian Government.

DAFWA (Department of Agriculture and Food, Western Australia) (2013) *Report card on sustainable natural resource use in agriculture: status and trend in the agricultural areas of the south-west of Western Australia*, DAFWA, Perth.

DEA (Digital Earth Australia) (2021) *DEA fractional cover (Landsat)*, Geoscience Australia website, accessed 1 October 2021.

DPIRD (Department of Primary Industries and Regional Development) (2018a) *Wheatbelt of Western Australia (DPIRD-024)* [GIS dataset], Data WA website, accessed 1 December 2021.

DPIRD (2018b) *Potentially arable land (DPIRD-026)* [GIS dataset], Data WA website, accessed 1 December 2021.

DPIRD (2019), *Soil-landscape mapping – best available (DPIRD-027)* [GIS dataset], Data WA website, accessed 1 December 2021.

DPIRD (2021) *Annual report 2021: Department of Primary Industries and Regional Development*, WA.gov.au, accessed 1 December 2021.

ESA (European Space Agency) (2022) *Sentinel 2: Colour vision for Copernicus,* ESA website, accessed 22 August 2022.

ESRI (Environmental Systems Research Institute) (2013) *ArcPy* [python programming package], ESRI, Redlands, CA, USA.

Findlater P, Carter D and Scott W (1990) 'A model to predict the effects of prostrate ground cover on wind erosion', *Australian Journal of Soil Research*, 28(4):609, doi:10.1071/SR9900609.

Flood N (2013) 'Seasonal composite Landsat TM/ETM+ images using the medoid (a multi-dimensional median)', *Remote Sensing*, 5(12):6481–6500, doi:10.3390/rs5126481.

Fryrear DW and Bilbro JD (2018) *Mechanics, modeling, and controlling soil erosion by wind*, Routledge, doi:10.1201/9781315136912-3.

Guerschman J (2020) *Fractional Cover – MODIS, CSIRO algorithm, Version 3.1*, [dataset], Terrestrial Ecosystem Research Network website, accessed 1 December 2021.

Guerschman JP, Hill MJ, Renzullo LJ, Barrett DJ, Marks AS and Botha EJ (2009) 'Estimating fractional cover of photosynthetic vegetation, non-photosynthetic vegetation and bare soil in the Australian tropical savanna region upscaling the EO-1 Hyperion and MODIS sensors', *Remote Sensing of Environment*, 113(5):928–945, doi:10.1016/j.rse.2009.01.006.

Guerschman J, Leys J, Rozas Larraondo P, Henrikson M, Paget M and Barson M (2018) *Monitoring groundcover: an online tool for Australian regions*, CSIRO, Canberra, doi:10.25919/5bf84026e556d.

JRSRP (Joint Remote Sensing Research Program) (2018) *Seasonal fractional cover – Sentinel-2, JRSRP algorithm, Eastern and Central Australia coverage', Version 1.0.0* [dataset], Terrestrial Ecosystem Research Network website, accessed 1 December 2021.

JRSRP (2021) *Seasonal fractional cover – Landsat, JRSRP algorithm, Australia coverage', Version 1.0.0* [dataset], Terrestrial Ecosystem Research Network website, accessed 1 December 2021.

Leys JF (1999) 'Wind erosion on agricultural land' in Goudie AS, Livingston I and Stokes S (ed), *Aeolian Environments, Sediments and Landforms*, John Wiley and Sons, England, pp 143–166.

Leys JF, Howorth JE, Guerschman JP, Bala B and Stewart JB (2020) *Setting targets for National Landcare Program monitoring and reporting vegetation cover for Australia*, NSW Department of Planning, Industry and Environment.

McFarlane DJ and Carter DJ (1989) 'The effect of erosion on soil productivity in south-western Australia', workshop at *5th Australian Soil Conservation Conference*, Perth, Australia.

Moore G, Findlater P and Carter D (2001) 'Wind erosion', in Moore G (ed) 'Soilguide (Soil guide): a handbook for understanding and managing agricultural soils', *Bulletin 4343*, Department of Agriculture, Western Australian Government.

Pennock D, Pennock L and Sala M (2019) *Soil erosion: the greatest challenge for sustainable soil management*, Food and Agriculture Organization website, accessed 22 August 2022.

Python Software Foundation (2010) *Python programming language, Release 2.7*, Python Software Foundation website, Beaverton, OR, USA.

Raupach MR, Gillette DA and Leys JF (1993) 'The effect of roughness elements on wind erosion threshold', *Journal of Geophysical Research: Atmospheres*, 98(D2):3,023–3,029, doi:10.1029/92JD01922.

Scarth P, Roder A and Schmidt M (2012) *Tracking grazing pressure and climate interaction – The role of Landsat fractional cover in time series analysis*, figshare, doi:10.6084/m9.figshare.94250.v1.

Sharratt BS, Kennedy AC, Hansen JC and Schillinger WF (2018) 'Soil carbon loss by wind erosion of summer fallow fields in Washington's dryland wheat region', *Soil Science Society of America Journal*, 82(6):1,551–1,558, doi:10.2136/sssaj2018.06.0214.

TERN (Terrestrial Ecosystem Research Network) AusCover (2021) *Fractional cover WA* [dataset], TERN AusCover website, accessed 1 December 2021.

Tozer P and Leys J (2013) 'Dust storms – what do they really cost?', *The Rangeland Journal*, 35(2):131, doi:10.1071/RJ12085.

USGS (United States Geological Survey) (2019) *Landsat 7 (L7) data users handbook*, USGS website, accessed 22 August 2022.

USGS (2021) *Landsat 7*, USGS website, accessed 1 October 2021.

USGS (2022) *What is the Landsat satellite program and why is it important?*, USGS website, accessed 22 August 2022.

van Gool D, Tille PJ and Moore GA (2005) 'Land evaluation standards for land resource mapping: assessing land qualities and determining land capability in south-western Australia', 3rd edn, *Resource management technical report 298*, Department of Agriculture, Western Australian Government.