Using satellite imagery to assess trends in soil and crop productivity across landscapes

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Abstract. Measuring different indicators of production and soil health over the long term will help build a picture of soil health and productivity across the landscape. This paper examines the potential contribution of satellite imagery to this area. This investigation undertook a very long time series analysis of Landsat imagery (approximately 40 years) and MODIS imagery (approximately 10 years). Novel datasets and approaches were used to assess areas based on land use history and land cover condition. Spring Normalised Difference Vegetation Index (NDVI), land cover maps based on NDVI thresholds, annual cumulative NDVI and fractional ground cover (FGC) were used to identify trends in vegetation cover change at a landscape scale, and their relationship with factors such as land use intensification history, geomorphology, rainfall, and land use. This work has improved the broad, baseline understanding of production variation across the landscape, while also providing a practical demonstration of the integration of a range of disparate data sources.

1. Introduction
Farming systems and land use changes, including production intensity and land management, can result in soil changes that compromise current and future capacity for primary production and provision of ecosystem services. Climate and land management affect net primary production (agricultural productivity), that in turn influences soil processes and health. Agricultural production impacts many soil properties such as soil structure, bulk density, soil microbes and soil carbon [1-4]. It is important to ensure soil health is not negatively impacted by agricultural practices to sustain productivity in the long term. Converting land use from native vegetation to agriculture production results in multiple changes, including increases in soil carbon and nutrients from crop residue and fertiliser inputs, and changes in soil microbial activity, plant production and other aspects of soil quality [4, 5].

Measuring different indicators of production and soil health over the long term will help build a picture of soil health and productivity across the landscape. This paper examines the potential contribution of satellite imagery to this area. Benefits of remotely sensed data include continual spatial coverage across the landscape, enabling variation within, and between, paddocks to be identified; long archives of data, allowing spatial trends over time to be monitored; readily available data acquired at frequent time intervals; and the ability to integrate information with other sources of spatial data such as soil and landform mapping, and climatic data. There are many different spatial
data sets available that can contribute to an understanding of land use and production history in Victoria, including soil and landform information, climatic data such as rainfall, long-term production history [6] and remotely sensed data. Investigations into the relationships between these types of data have improved understanding of the linkages between remotely sensed data and landscape and agricultural information, such as crop rotation, productivity, soil properties and land management practices [7-9].

Satellite imagery, which records information in the visible and near-infrared portions of the electromagnetic spectrum, captures conditions at the earth’s surface, such as vegetation cover. Variables derived from satellite imagery infer information about soil condition by observing what happens on the surface in terms of vegetation growth. Differences in vegetation cover linked to agricultural productivity in farming landscapes can be attributed to a number of factors, including climatic conditions, soil properties, geomorphological factors, that occur as gradations across the landscape, and also land cover and management, occurring as sharp transitions aligning with land parcels [8-10]. Information derived from remotely sensed data, such as the Normalised Difference Vegetation Index (NDVI), has been used as an indicator of green vegetation cover [8, 11-13]. Total NDVI accumulation within a year, Spring vegetation cover (NDVI) and fractional ground cover (FGC) are examples of measures that can be derived from remotely sensed data, and that may provide useful information about agricultural productivity and changes in soil health. FGC is also an important factor in wind and water erosion mitigation [4].

This study aims to improve our understanding of the influence of land cover history and various environmental factors on soil condition in the Wimmera region of north-west Victoria, by examining linkages between vegetation cover over time (derived from satellite imagery) and factors such as rainfall and production history. Identifying factors that affect agricultural production can highlight areas where production falls short of expectations, and provide insights into impacts from soil health and land management factors. An improved understanding of land cover history will increase our understanding of soil condition, and linkages between soil health and the productive capacity of Victorian agricultural landscapes.

2. Methods

2.1. Study area

The study area is located in the Wimmera and Southern Mallee region of Victoria (Figure 1). The study area is positioned in an ‘overlap’ area of the Landsat satellite acquisition path, meaning that images are potentially acquired at twice the frequency compared with areas not located in an overlap area. Data used to generate the annual cumulative NDVI product, rainfall data, and land privatisation information were available over a larger spatial extent and clipped to a wider area of interest (Figure 1).

The study area is dominated by rain-fed dryland cropping production systems. Approximately 97% of the study area is privately owned, being used largely for cropping (approximately 90%) and grazing. There are smaller areas of irrigation agriculture and timber production. A small proportion of the study area remains as Crown Land, including parks, reserves and riparian vegetation consisting of remnant native vegetation.
2.2. Data

This study used 97 Landsat images acquired between 1973 and 2012, sourced from the United States Geological Survey (USGS) Landsat archive. Landsat images have a swath (approximately 170 km x 180 km) large enough to deliver landscape scale information, and a spatial resolution (approximately 30 m – 60 m) which is able to deliver information at a paddock and sub-paddock scale. The ‘overlap’ area of the Landsat satellite acquisition path between two Landsat scenes (path/row: 94/85 and 95/85) was used for the study area as this increased the potential frequency of image acquisitions. The duration of the image series (i.e. over 40 years) enables longer-term trends of vegetation growth and land use change to be detected. Imagery captured by Landsat sensors 1-7 were used, with each image calibrated to top of atmosphere reflectance using published coefficients [14]. Current advancements in processing of the Landsat image archive have led to a reliably calibrated data set, with a consistent absolute radiometric scale between Landsat sensors and total uncertainties of under 10% for most sensors and bands [15, 16]. Further geo-rectification was undertaken as required and all images resampled to a 30 m spatial resolution to provide a consistent spatial unit across the time series. Clouds and shadow were masked from each image and NDVI calculated using red and near-infrared (NIR) reflectance using equation (1):

\[
NDVI = \frac{NIR - Red}{NIR + Red}
\]

Where: 
NIR = near-infrared reflectance
Red = red reflectance

Each year was considered in terms of seasons: Summer (December to February), Autumn (March to May), Winter (June to August) and Spring (September to November) and, where available, one
cloud-free image per season was acquired. This process generated a series of 97 NDVI images spanning from 1973 to 2012. Over this 40 year time period, 29 images were acquired during Summer, 20 in Autumn, 18 during Winter, and 30 in Spring. This study examined Spring vegetation cover, with dense green vegetation considered to have an NDVI value greater than 0.65. This threshold was estimated based on observations of local information and published NDVI crop growth curves [11, 12, 17]. The time series of 30 Spring images was grouped into five-year time intervals, and the percentage of time a pixel was covered by green vegetation (NDVI>0.65) was calculated, producing a measure of high NDVI frequency.

A Fractional Ground Cover (FGC) product was generated using the Joint Remote Sensing Research Program algorithm, hosted on the AusCover web site [18] that estimates bare ground (BG), photosynthetic vegetation (PV) and non-photosynthetic vegetation (NPV) from Landsat imagery across different seasons. This study used Autumn seasonal median NPV product.

In addition to information derived from Landsat imagery, MODIS imagery was also utilized. The MOD13Q1 16-day vegetation product (NDVI) was downloaded from the USGS archive for 2003-2012. A single MODIS image tile provides complete spatial coverage of the state of Victoria. The MODIS NDVI images were clipped to Victoria and re-projected, and the data was then summed within a calendar year to create an annual cumulative NDVI product for 2003-2012. This product is used as a surrogate measure of biomass accumulation. The MODIS cumulative NDVI product provides a summation of all NDVI values within a year, which is distinct from the Landsat NDVI product which is based on NDVI for a single image date. Therefore the two NDVI-based products are measured on different scales, both of which are unitless.

Other spatial data used included land privatization (i.e. when land tenure initially changed from Crown Land to privately owned land), and land use in 2005, estimated from Landsat images acquired between 1989 and 2005 [6]. Land privatization was considered according to three time periods: before 1866 (early pastoralism), between 1866 and 1888, and after 1888 (Victorian gold rush and agricultural expansion) [6]. Detailed of the development of the data set and sources of data used to compile this information are published in [6]. Annual rainfall data was obtained from the Bureau of Meteorology and was interpolated from point data to form a 5 km gridded data set. Rainfall classes used in this study were: <300 mm, 300-350 mm, 350-400 mm and >400 mm.

3. Results and discussion

Factors that affect the soil environment in agricultural settings include land management (cultivation and post-harvest stubble practices), agricultural inputs (fertilisers, chemicals, and animal waste if the crop is grazed), crop or pasture type, and climate variables such as rainfall and temperature. Agricultural production impacts many soil properties such as soil structure, bulk density, soil carbon and soil nutrients, which influence plant production and soil quality [1-5]. Long term productivity is also linked to the soil microbial population, which is influenced by crop type and land management options such as stubble retention [5].

Measuring different indicators of production and soil health over the long term builds a picture of soil health and productivity across the landscape. Annual accumulated NDVI and Spring vegetation cover are examples of measures able to be derived from remotely sensed data which may provide useful information about agricultural productivity and changes in soil health. In this study, crop frequency is used as an indicator of production intensity, while annual accumulation of NDVI is used as an indicator of production biomass.

Figure 2 illustrates fluctuations in vegetation cover over time, and differences between land uses. Dryland agriculture and grazing show similar patterns with small fluctuations over time, while irrigated agriculture shows more variability in high NDVI frequency, most likely related to water availability. Timber production shows less frequent fluctuations, related to harvesting and planting cycles within the plantations. Vegetation located on Crown Land, which is predominantly native woody scrub vegetation, had a low average percentage of time with a Spring NDVI<0.65 and very little fluctuation between time periods (Figure 2), suggesting that vegetation cover on Crown Land,
while typically lower than agricultural land, has remained relatively steady over the past four decades. This also illustrates how agriculture has changed vegetation cover trends within the landscape.

**Figure 2.** Average percentage of time with a Spring NDVI value $>0.65$ (five-year average), from 1973 to 2012, based on land use in 2005 (land use classes from [6]).

The remaining results relate to dryland agriculture land use only. Figure 3 compares annual accumulated rainfall classes with the percentage of time the Spring NDVI is $>0.65$ in a 5-year time period. The trend is variable, but six of the eight time periods show that areas that recorded the highest amount of rainfall also had the highest percentage of time with dense Spring vegetation. The association between cumulative NDVI and rainfall class varies between years but generally higher rainfall results in higher annual cumulative NDVI (Figure 4). Variation between rainfall classes is inconsistent, with smaller variation in some years (2005) compared with others (2008 and 2012). This variation may be influenced by the change in spatial location of the rainfall classes over time. There is a general gradient of lower rainfall in the north to higher rainfall in the south, but the spatial distribution of the different rainfall classes changes annually. The data shows that not every year has all rainfall classes, such as in 2010 when the entire study area had an annual accumulated rainfall in excess of 400 mm. Therefore, the rainfall classes incorporate a different mix of soil types and land management histories in each year which will contribute to the variation seen in the data. There is a strong link between accumulated NDVI and rainfall $>400$ mm in all years except 2006.
Land use history, including production intensity and land management, can result in soil changes that compromise current and future capacity for primary production, provision of ecosystem services, and soil properties such as carbon content [2-4]. A challenge in documenting these impacts is that they occur over extended periods of time. Differences in agricultural vegetation cover can be attributed to a number of factors, including climatic conditions and soil properties, that occur as gradations across the landscape, and also land cover and management, which are often seen as sharp transitions aligning with land parcels [8-10].

Trends in vegetation cover were also analysed with respect to land privatisation. Both Spring vegetation cover and annual accumulated NDVI show a clear stable response to privatisation date throughout the whole time series. These analyses identify some factors that affect agricultural production and highlight areas where production falls short of expectations. Land put into agricultural production earlier had a higher percentage of time with dense Spring vegetation in a five-year time period compared with land that was privatised later (Figure 5). Six out of the eight time periods in the
40 year history showed this trend (Figure 5). This response is influenced by the relationship between land privatisation and rainfall gradient and a potentially higher frequency of crops.

There is a strong consistent relationship between land privatisation period and annual cumulative NDVI, with areas privatised from Crown Land before 1866 always showing higher cumulative NDVI than areas privatised later (Figure 6). This is similar to trends shown in the 40 year Landsat data, although differences appear to be more consistent in the MODIS imagery. This may be due to the improved temporal resolution of the MODIS data. Land which falls into the first privatisation date class, i.e. prior to 1866, covers less than 2% of the study area, which reduces the variation in this class compared with the other two land privatisation periods (1866-1888 and after 1888). However, the relationship between privatisation date and vegetation production holds for the second and third periods. The link between increased vegetation cover and privatisation date seems to be mostly due to rainfall gradient, as rainfall is a dominant factor in vegetation growth. However, in 2010 the entire study area received a similar amount of rainfall (Figure 4), but there are clear differences in biomass accumulation when land privatisation date is considered (Figure 6). This demonstrates that other factors such as soil health and land management may also influence these trends. Understanding that there are inherent limitations to production in the landscape suggests that strategies to improve soil condition and productivity need to be recommended on a regional basis, and land use history can provide a simple and effective method of identifying properties which may face similar challenges.

Figure 5. Average percentage of time with a Spring NDVI value >0.65 (five-year average), from 1973 to 2012, based on time privatised from Crown Land holdings (dryland agricultural land)

Land management practices such as post-harvest cover retention, combined with crop rotation management, have been shown to increase production biomass and soil microbial activity, and assist in long term maintenance of soil health [19]. NPV ground cover in Autumn is used as an indicator of ground cover retention post-harvest as soil surface cover is a key factor for a number of soil physical properties, stabilises soil, provides protection from wind and water erosion, nutrient retention, organic matter content and carbon fixation [1, 2, 4]. NPV remaining after harvest is also a source of nutrients for soil microorganisms [5]. Less crop biomass reduces the quality and quantity of post-harvest stubble, which is a major source of soil organic carbon [4]. Stubble retention can also indicate particular land management practices, such as minimum tillage.
Trends in NPV ground cover and biomass accumulation showed that higher biomass accumulation in the preceding year led to higher levels of NPV ground cover in the following Autumn. To further explore this variation, and establish the effects of ground cover retention on crop productivity in subsequent years, further analysis of the season, crop type and biomass accumulation is necessary. Areas with higher NDVI accumulation from the previous year (i.e. >80,000) showed consistently higher NPV cover in the following Autumn compared to areas with lower biomass accumulation from the previous year (Figure 7). The pattern is similar to that shown in accumulated biomass from the following year (Figure 8), however further investigation of climatic factors and land management practices may explain some observed discrepancies in this relationship (i.e. 2003 and 2011).

**Figure 6.** Annual cumulative NDVI (calculated from MODIS imagery) for dryland agriculture between 2003 and 2012 based on time privatised from Crown Land holdings

**Figure 7.** Autumn average FGC: NPV for dryland agriculture from 2003 to 2012, based on annual cumulative NDVI derived from MODIS imagery from the previous year.
4. Conclusion

Measuring different indicators of production and soil health over the long term will help build a picture of soil health and productivity across the landscape. This paper examined the potential contribution of satellite imagery to this area by examining trends in total NDVI accumulation within a year, Spring vegetation cover and FGC over an extended period of time (i.e. 10-40 years). Benefits of remotely sensed data include continual spatial coverage across the landscape, enabling variation within and between paddocks to be identified; long archives of data, allowing spatial trends over time to be monitored; readily available data acquired at frequent time intervals; and the ability to integrate information with other sources of spatial data. This study aimed to improve our understanding of soil health in the Wimmera region of north-west Victoria, by examining linkages between vegetation cover over time and factors such as rainfall and production history.

Vegetation growth was strongly linked with annual rainfall, with higher rainfall generally corresponding with higher annual cumulative NDVI and more frequent dense Spring vegetation growth. However, variations within this general pattern suggests other factors contribute to vegetation growth. Both Spring vegetation cover and annual accumulated NDVI show a clear stable response to land privatisation date throughout the time series, suggesting that land privatisation has an influence on production and therefore soils, either as a legacy of the base characteristics of the land or as a consequence of long-term management of the land. Trends in NPV ground cover and biomass accumulation showed that higher biomass accumulation in the preceding year led to higher levels of NPV ground cover in the following Autumn, which has important consequences for both soil health, erosion mitigation, and agriculture production. Identifying factors that affect agricultural production can highlight areas where production falls short of expectations, and provide insights into soil health and land management factors. An improved understanding of land cover history will increase our understanding of soil condition, and linkages between soil health and the productive capacity of Victorian agricultural landscapes.

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