

Crop phenology based on MODIS satellite imagery as an indicator of plant available water content

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Abstract: Maintaining agricultural productivity into the future is one of the most important goals of our society. The world's vast grain production areas in arid environments have a high sensitivity to climate change, thus demanding accurate future predictions. Management and decision making depends on an understanding of complex spatial and temporal interactions between rainfall, temperature and soils, but detailed soil information is extremely costly and generally unavailable.

Crop phenology, the timing of plant growth and developmental stages, is the combined response to environmental factors such as soil, water and temperature. Crop phenology plays an important role in crop growth models and agronomic management. In Mediterranean environments like South Australia, water is the driving factor for crop growth. In these rain-fed farming systems, water availability largely depends on rainfall amount and seasonality and the capacity of the soil to retain rainfall inputs and hence make water available for crops. Plant Available Water Capacity of soil (PAWC) is an important measure of the spatial and temporal variability of crop growth and yield, but there is a paucity of detailed maps at a management relevant spatial resolution and extent.

In this study, different phenological metrics derived from MODIS NDVI imagery were assessed over sites of known PAWC and cropping history. We used the metrics:

- NDVI at the onset of greenness (Onset) and time of Onset (OnsetT)
- NDVI at peak greenness (MaxV) and time of maximum greenness (MaxT)
- The length of the growing season (WidthGS)
- Rate of greenup (GURate)

The green up rate of the curve (GU-rate) showed the most consistent difference between soils of different PAWC. The Rate of Green up is higher for the soil points with relatively low PAWC. Some of the variability in the difference between sites with low and high PAWC can be explained with rainfall amount and seasonality but the relationship is complex.

The results indicate that the crop phenology derived from MODIS satellite imagery is consistently different and may therefore provide useful information about site conditions, which would allow improvements to the spatial detail in soil maps.

Keywords: *Digital Soil Mapping (DSM), remote sensing, satellite imagery, spatio-temporal*

1. INTRODUCTION

Soil information is very important information for policy making and various environmental practices. Most global and regional environmental models need soil information as one of the input parameters (Asseng *et al.*, 1998, Henderson *et al.*, 2005). Missing this information at the global or local scale leads to uncertainty in the basic sustainability decision makings (FAO *et al.*, 2009).

Field measurements of plant available water capacity (PAWC) are expensive and time consuming (Morgan *et al.*, 2000) and there is the need to estimate PAWC through relatively easily measurable soil properties (Mullins, 1981, Morgan *et al.*, 2000, Jiang *et al.*, 2008). Seasonal variability of the crop growth is theoretically related to PAWC variability but it is difficult to extract this information because of the number of factors that influence dynamics of water availability and crop growth.

Vegetation condition and crop growth timing is strongly influenced by underlying soil conditions. The spatial variability of soil PAWC and its interaction with the rainfall seasonality is considered a major cause of the growth variability (McDonald, 2006, Oliver *et al.*, 2006, Wong *et al.*, 2006a, Wong *et al.*, 2006b). In turn, improved understanding of the growth dynamics may allow inferences about the soil's water condition. Vegetation phenology, the timing and seasonality of the plant growth stages, could be a useful indicator of different environmental factors including soil (Reed *et al.*, 1994, Zhang *et al.*, 2003). In non-irrigated agricultural area, phenological phenomena reflect how plants respond to short term weather events (Reed *et al.*, 1994).

The Normalized Difference Vegetation Index (NDVI) has been used in many vegetation phenologic studies, including global land cover classification (Lloyd, 1990, DeFries *et al.*, 1995), crop classification (Wardlow *et al.*, 2007, Wardlow *et al.*, 2008, Sun *et al.*, 2012), and agricultural productivity estimation (Hill *et al.*, 2003, Kouadio *et al.*, 2012). Moderate Resolution Imaging Spectroscopy (MODIS), mounted on the NASA Earth Observation System's Terra Spacecraft, provides vegetation indices with the resolution of 250m – 1km. The NDVI data from MODIS is one of the most widely used satellite images for time series analysis (Rodrigues *et al.*, 2011). Despite the usefulness of MODIS NDVI for understanding of the plant and environmental conditions, little evidence exists if NDVI dynamics can be used as a spatial indicator for environmental factors that control the plant growth such as soil conditions.

In this paper we assess plant dynamics within two cropping paddocks in different climate zones that have marked differences in PAWC and area sufficiently large to be used with MODIS imagery. We have derived phenological metrics from the time series MODIS NDVI images are used to explore the seasonal variation of vegetation and its interaction with the climatic conditions to examine the response of the soil PAWC to different rainfall amount and seasonality.

2. MATERIALS AND METHODS

The study was carried out on two paddocks around Wharminda and Minnipa towns in the upper Eyre Peninsula, South Australia. The sites were selected for their setting with the soil types which may represent wider area coverage of the Eyre Peninsula region (Eyre Peninsula Farming Systems, 2009). Both of these farms have been studied as the focus site of the Eyre Peninsula Agricultural Research Foundation (EPARF)(Eyre Peninsula Agricultural Research Foundation 2011). Average annual and growing season rainfall is 325mm and 242mm, respectively.

The paddock around Wharminda (Wharminda Paddock) is situated at 33°9'30"S, 136°19'47"E. It is characterized by siliceous sand over sodic clay soil, which approximately represent 455,000 ha area of the Eyre Peninsula(Eyre Peninsula Agricultural Research Foundation 2011). These sands are reported to be a challenge for the farmers due to their uneven wetting nature at the beginning of the growth seasons. This uneven wetting is worse in the deep sand soils. It results in uneven germination at the beginning of the growing season(Eyre Peninsula Farming Systems, 2009). The Minnipa Paddock, N1 at Minnipa Agricultural Center (MAC) is located at 32°48'47"S, 135°9'55"E.

3. DATASETS

MODIS NDVI data (MOD13Q1 16 days composites) was used to estimate phenological indices. The imagery is available from NASA's Earth Observing System (EOS), with ground resolution of 250m. These composites were calculated using Constrained View angle – Maximum Value Composite (CV-MVC) and Maximum Value Composite (MVC) techniques (Solano *et al.*, 2010). The MODIS NDVI data is available since 2000. Thus we will have 273 images (23 images per year except 2000 at which only 20 images available).

Rainfall data (daily gridded data with 5km resolution) was provided by the Australian Government Bureau of Metrology (BOM).

Soil data from APSoil was used in this study. The APSoil was developed for regional use with the Agricultural Production Systems Simulator (APSIM) (The APSIM initiative). The APSoil database is a point based soil characterization. There are around 69 points in the South Australian Agricultural region. The points used in this study are #394 and #395 from Wharminda and #354 and #353 from Minnipa stations, respectively.

The paddocks were zoned based on yield and Electro Magnetic Survey (EM38) surveys (Eyre Peninsula Agricultural Research Foundation 2011). The representative soil points were taken from the zones of both paddocks. Table 1 shows the PAWC measurement of these soil points and the soil type at the location. The closest pixels to these soil points were chosen and the NDVI time series data were extracted for those pixels. The chosen pixels are within the representing zones and are the closest possible pixels for the soil points. Moreover, the pair soil points are within the same paddock, which means that the compared MODIS time series are under the same management with constant seeding and fertiliser rates.

Table 1. Soil points at the study sites

Paddock at Wharminda		
APSOil ID	PAWC	Soil type
394	166mm	Shallow sand over clay
395	95mm	Loam over rock
Paddock at Minnipa		
APSOil ID	PAWC	Soil type
353	57mm	Red Sandy Clay Loam
354	209mm	Red light Sandy Clay Loam

3.1. Phenological metrics

We evaluated five different phenological metrics that may be used as indicators for biophysical conditions (Figure1): Onset of greenness, time of Onset of greenness, Maximum greenness, time of maximum greenness, offset of greenness, and time of offset of greenness.

In this study, the onset of greenness was defined as the point where the highest slope observed between two consecutive NDVI values, on the period of March – June. The maximum greenness is the highest NDVI value and loosely correlated with the phenologic period of Anthesis. The offset of greenness (Offset) and time of offset (OffsetT) are defined as a point at which the crop loses its greenness and gets ready for harvest. This point is defined as the point where lowest slope observed in the time series curve. This phenologic event loosely corresponds to the Maturity phenologic stage. Similarly, the time of offset is defined as the time when the offset of greenness is recorded. The length of the growing season (LengthGS) is defined as the duration of the period between the Onset of greenness and offset of greenness. The rate of greenup (GURate) is defined as the rate at which the NDVI increased from onset to the maximum greenness. It is calculated as the slop of the straight line between the onset of greenness and the maximum NDVI i.e (Maximum NDVI-Onset of greenness)/ (time of maximum greenness-time of onset).

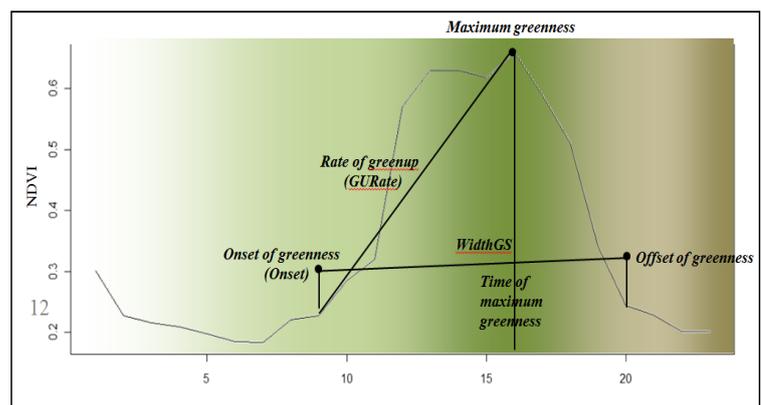


Figure 1. Phenological metrics used in this study

4. RESULTS

A comparison of time series of NDVI of twelve years (2000 – 2011) at the soil sites in both stations shows noticeable differences (Figure 2).

In Wharminda paddock, the MaxV for all the years from Pixel 395 (low PAWC) was higher than that of Pixel 394. Maximum NDVI was also observed to appear 15 – 30 days earlier than that of 394. Similarly the OnsetT also showed marked differences. In most of the years both Onset of greenness and maximum NDVI were earlier at low PAWC. However the difference is not consistent in all the years.

Similarly, in Minnipa paddock, the region with low PAWC (Pixel 353) was characterized by a higher maximum in most of the years. Onset of greenness and maximum NDVI was also observed to be earlier at low PAWC.

The Rate of Greenness (GURate) depends on the onset of greenness and the timing and magnitude of the maximum NDVI. The soil points with relatively lower PAWC, Pixel 395 (Wharminda Paddock) and Pixel 353 (Minnipa paddock), have a higher GURate compared with their corresponding points. However, GURate differed markedly between years, possibly related to rainfall amount and seasonality.

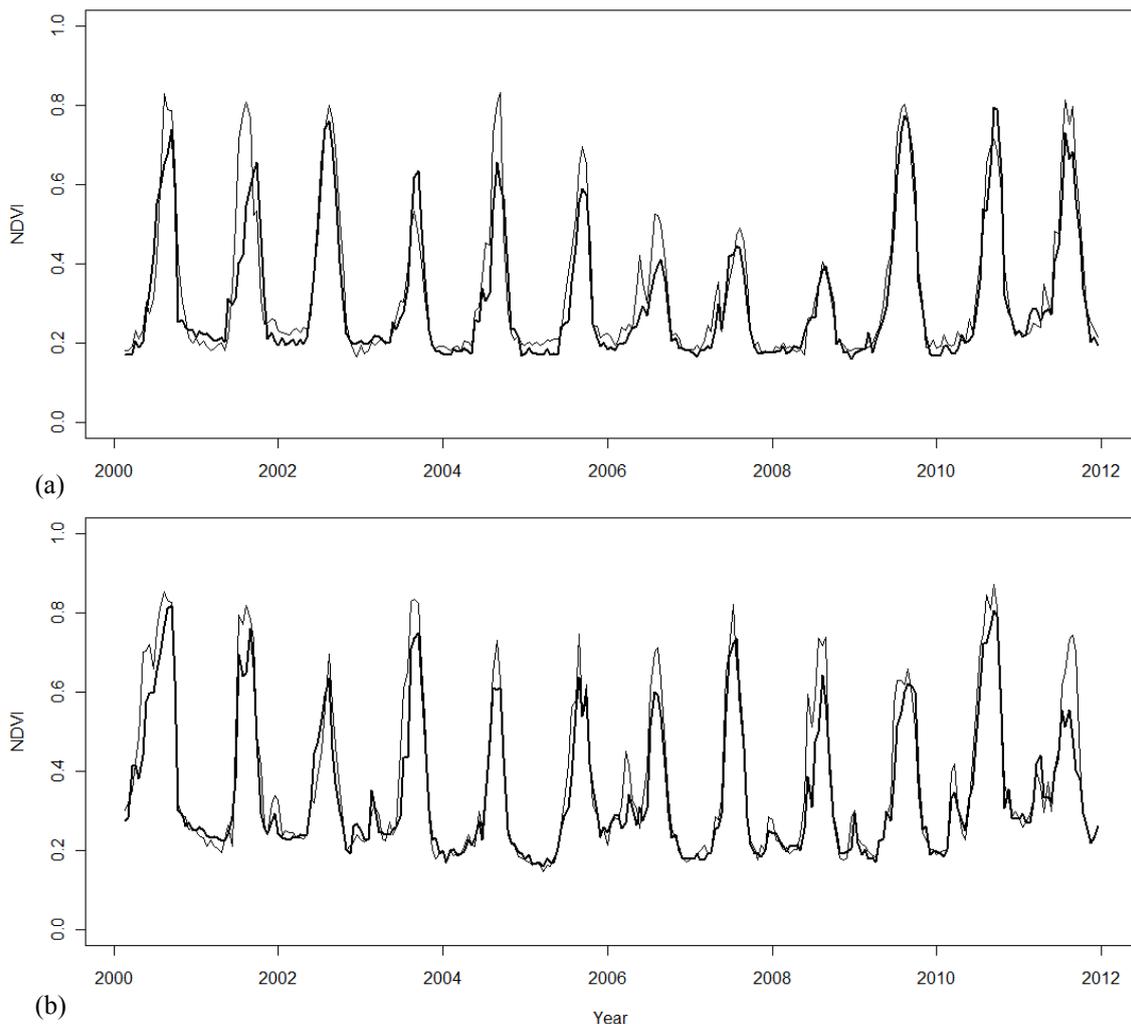


Figure 2 Time series of NDVI at (a) Minnipa and (b) Wharminda. The darker lines show NDVI of pixels with high PAWC.

4.1. Relationship between Phenologic metrics and rainfall amount and seasonality

The rainfall seasonality interacting with PAWC reflects differences in the vegetation growth. This is exemplified for Wharminda in Figure 3. The illustration compares 16 days cumulative rainfall variability with the difference of the rate of vegetation growth between the two representing pixels. Reflecting rainfall seasonality and amount, NDVI around the soil points showed substantial variability. On both paddocks, locations with lower PAWC (Pixel 395 of Wharminda and Pixel 353 of Minnipa) show a faster increase of NDVI compared to locations with higher PAWC.

NDVI of Pixel 395 generally peaks earlier than that of Pixel 394 (Figure 3). In some years (e.g. 2006 and 2007), the rainfall was more dominant in the earlier seasons. Early rainfall filled the soil profile to support the

vegetation growth during the low rainfall season. The greater water holding capacity of the sandy soil supports faster plant growth than the loam over clay soil.

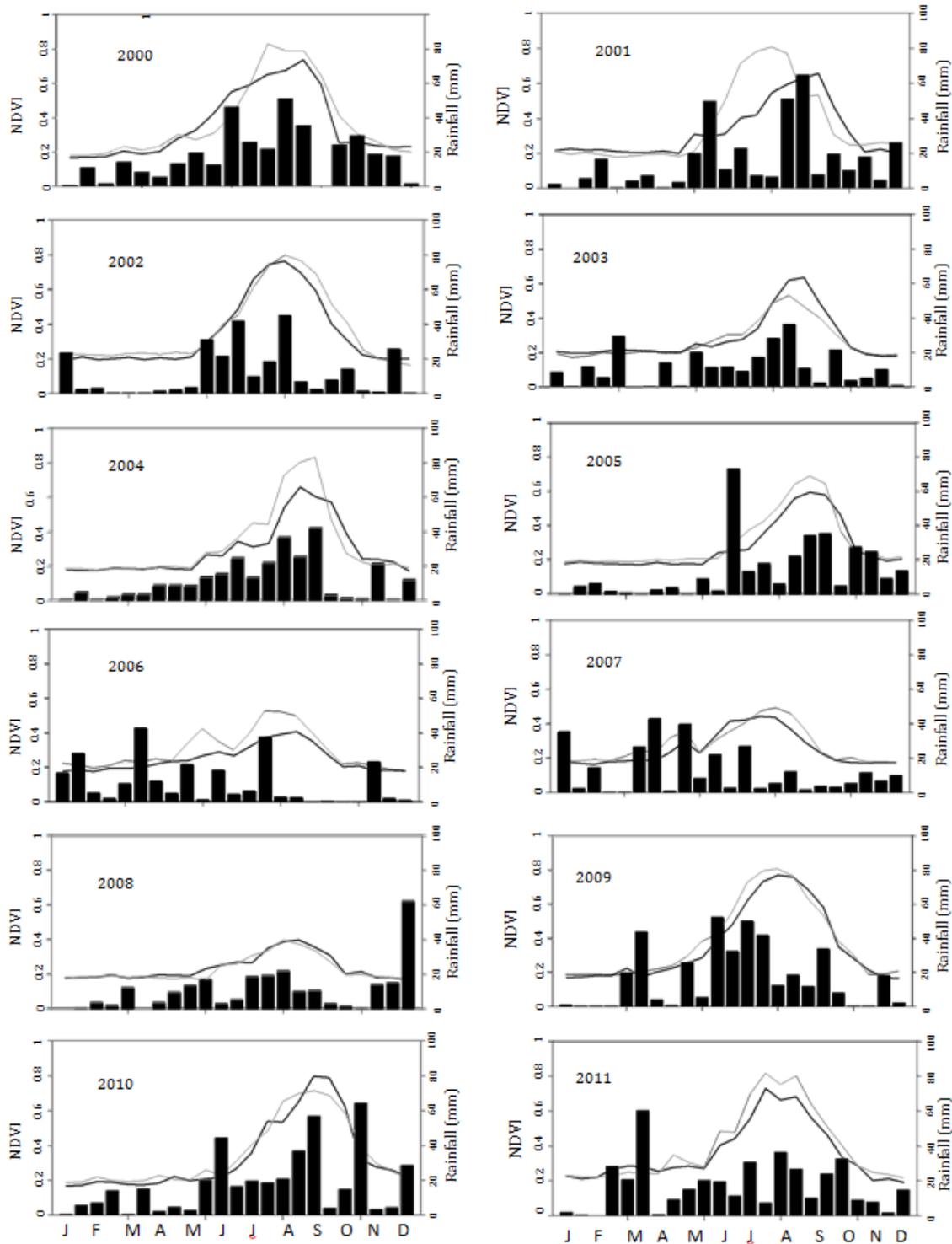


Figure 3 Time series of NDVI and rainfall at Wharminda. The darker lines show NDVI of pixels with high PAWC.

In the year 2006, rainfall was dominated towards the warmest summer seasons, which may be lost through evaporation due to the high temperature during the summer season. The April-May rainfall was low, following the fair rainfall in the beginning of May. The NDVI of Pixel 395 sets to onsets before the vegetation at Pixel 394. The year 2007 was also with very low rainfall throughout the growing season. The vegetation in both soil type reached to Onset at a similar time, followed by steep NDVI increment in the loam

soil as a result of low June and July rainfall. The years 2008 and 2009 were characterized with lower early rainfall in April and May, results early onset and maximum greenness for the vegetation from Loam soil (Figure 3).

5. DISCUSSION AND CONCLUSIONS

The PAWC is a controlling factor for vegetation growth in dryland agriculture, especially in arid and semiarid farming area like South Australia and determines phenological events. Understanding how growth variability is affected by rainfall seasonality and soil PAWC interactions may allow us to work towards inverse modeling schemes that infer about soil conditions based on the spatio-temporal differences in satellite imagery. Growth dynamics can be quantified as variability of the phenological stages including the time of maximum NDVI (MaxT), time of Onset (OnsetT) and combined effect on the rate of growth (GURate).

The GURate was observed to be higher in low PAWC corresponding with an earlier onset and higher maximum NDVI than the relatively higher PAWC soils. This corresponds with observations by Robertson *et al.*, (1994) who studied wheat crop under water deficit during early, mid and late phenologic periods and found that the timing of heading phenologic stage is highly affected by the water deficit. The stressed crop (Robertson *et al.*, 1994) reached heading and anthesis stages approximately 5 and 3 days earlier than the non-stressed crops. Moreover, the study showed that the early stress had the largest effect on developmental timing comparing to the mid and late stresses (Robertson *et al.*, 1994). Numbers of similar experimental research works have been done to assess the effect of inadequate water availability, at various growth stages, on the growth of different crops. These research projects indicate that the timing of growth stages and duration are highly influenced by water availability. Faster crop growth rate is one of the evident effects of water stress during crop growth (McMaster *et al.*, 2003, McMASTER, 2005, McMaster *et al.*, 2011).

The low PAWC soils in both paddocks meant that these soils stored less water and at the time of water scarcity, the soil with higher storage capacity could sustain plant growth compared to low PAWC soils. Thus the vegetation on low PAWC soil faces water stress earlier than the high PAWC soils, which cause the vegetation to accelerate growth to the next growth stages. This can be seen a fast raising curve in the NDVI time series curve, which is measured as GURate for the lower PAWC soils.

Comparing the differences in the growth stages, the maximum is observed at the time maximum NDVI (MaxT). These agreed with the observation made by previous researchers (Angus *et al.*, 1977, Robertson *et al.*, 1994, McMaster *et al.*, 2003, Brisson *et al.*, 2005, McMaster *et al.*, 2008) on the fact that the water deficit affected the anthesis phenological stage, which could loosely correspond to the maximum NDVI (MaxV and MaxT), is more than the other stages. At Wharminda we also observe a higher nutrient concentration in the shallow loam, producing a higher establishment rate and higher initial biomass without yield improvement (Eyre Peninsula Farming Systems, 2009). Potential improvements in inverse modeling of yield may come from focusing on the later part of the season to distinguish bucket size from other growth factors that influence leaf area development. NDVI during the earlier part of the season may be more strongly influenced by moisture content and nutrient concentrations in the upper soil layers rather than the total available water.

There appears to be a strong soil-related signal in the NDVI dynamics. However, the complexity of soil-rainfall interactions may require a very large sample size to allow for an automated extraction of site conditions from the time series of NDVI for empirical models. Furthermore, there is substantial variability within a MODIS pixel that is averaged out in the NDVI time series and higher resolution imagery may be useful to assess this spatial variability. Another factor that needs to be considered is the scale issue of having a single soil sample that may or may not be representative (Ostendorf, 2011).

The results presented here allow suggestion for the structure of future PAWC models based on NDVI dynamics. Inverse models of PAWC from NDVI should include the rate of greening and the relative timing of the peak NDVI with a stronger consideration of the later part of the season. Whilst there is potential, validation using larger sets of soil core data needs to carefully evaluate if the soil samples are truly representative of a paddock area at the size of the MODIS pixel. Though, this technique can potentially used to zone paddocks based on the MODIS NDVI time series growth pattern.

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