International Journal of Applied Earth Observation and Geoinformation 57 (2017) 1–13

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Integrating age in the detection and mapping of incongruous patches in coffee (*Coffea arabica*) plantations using multi-temporal Landsat 8 NDVI anomalies

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ARTICLE INFO

Article history:
Received 19 June 2016
Received in revised form 9 December 2016
Accepted 14 December 2016

Keywords:
Monitoring
Multi-temporal landsat NDVI
Age
Coffee
Crop condition

ABSTRACT

The development of cost-effective, reliable and easy to implement crop condition monitoring methods is urgently required for perennial tree crops such as coffee (*Coffea arabica*), as they are grown over large areas and represent long term and higher levels of investment. These monitoring methods are useful in identifying farm areas that experience poor crop growth, pest infestation, diseases outbreaks and/or to monitor response to management interventions. This study compares field level coffee mean NDVI and LSWI anomalies and age-adjusted coffee mean NDVI and LSWI anomalies in identifying and mapping incongruous patches across perennial coffee plantations. To achieve this objective, we first derived deviation of coffee pixels from the global coffee mean NDVI and LSWI values of nine sequential Landsat 8 OLI image scenes. We then evaluated the influence of coffee age class (young, mature and old) on Landsat-scale NDVI and LSWI values using a one-way ANOVA and since results showed significant differences, we adjusted NDVI and LSWI anomalies for age-class. We then used the cumulative inverse distribution function ($\alpha \leq 0.05$) to identify fields and within field areas with excessive deviation of NDVI and LSWI from the global and the age-expected mean for each of the Landsat 8 OLI scene dates spanning three seasons. Results from accuracy assessment indicated that it was possible to separate incongruous and healthy patches using these anomalies and that using NDVI performed better than using LSWI for both global and age-adjusted mean anomalies. Using the age-adjusted anomalies performed better in separating incongruous and healthy patches than using the global mean for both NDVI (Overall accuracy = 80.9% and 68.1% respectively) and for LSWI (Overall accuracy = 68.1% and 48.9% respectively). When applied to other Landsat 8 OLI scenes, the results showed that the proportions of coffee fields that were modelled incongruent decreased with time for the young age category and while it increased for the mature and old age classes with time. We concluded that the method could be useful for the identification of anomalous patches using Landsat scale time series data to monitor large coffee plantations and provide an indication of areas requiring particular field attention.

1. Introduction

Perennial tree crops are important for economic development, food security and alternative energy development, particularly in the developing world, where they are mostly produced (Ghini et al., 2011; Lin, 2011). Coffee (*Coffea arabica* L.), an evergreen, perennial tree crop that typically grows up to 4 m tall under a variety of production systems in tropical montane areas, is one such important crop (Ortega-Huerta et al., 2012). As part of perennial agricultural systems, coffee plantations protect water resources, improve soil quality, buffer floods, sequester carbon dioxide and provide jobs for millions of people (Dixon and Garrity, 2013; Kahn et al., 2011; Omont et al., 2006). Coffee also represents a long-term capital investment as it is in production for longer periods and therefore requires a robust, reliable and cost effective monitoring strategy for diseases, pests, water stress, soil fertility and other crop stressors, to safeguard investments and other related ecosystem services. So far, there is however, a general paucity of fine-scale long-term datasets

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http://dx.doi.org/10.1016/j.jag.2016.12.007
0303-2434/

to monitor plantation tree crop stressors (Jeger and Pautasso, 2008). These types of data are required in tracking fingerprints of inter and intra-annual variations in crop conditions useful for plantation managers, investors, insurers and other stakeholders interested in monitoring crop performance. The current monitoring methods largely rely on spontaneous field inspections and sampling, which are not only labour intensive, but also conclusive once economic damage has been inflicted on the crop.

Remotely sensed data provides valuable opportunities for detailed crop condition assessments using the spectral, spatial and temporal domains of raw image bands or their derived vegetation indices or a combination of both. The normalised difference vegetation index (NDVI) because of its robustness is, for instance, one of the most commonly applied remote sensing indices in assessing plant condition i.e. health, growth and vegetation productivity (Ding et al., 2014; Glenn et al., 2008). The NDVI takes advantage of contrasting effects of vegetation on the red and near infrared portion of the spectrum to provide information of vegetation condition. It is a linear estimator of the fraction of photosynthetically active radiation (fPAR) intercepted by vegetation and thus useful in analysing patterns of net primary productivity (NPP) at different spatial and temporal scales (Alcaraz-Segura et al., 2009; Wang et al., 2004). However, NDVI is known to saturate under closed canopy and to be sensitive to atmospheric conditions and soil background (Xiao et al., 2003). Other vegetation indices such as the Land Surface Water Index (LSWI) and the Enhanced Vegetation Index (EVI) are thus also commonly used in land cover assessments and crop monitoring. The LSWI is especially used because it is more sensitive to equivalent water thickness as it is generated by ratioing spectral bands that are known to be sensitivity to vegetation, soil moisture and water properties (Torbick and Salas, 2014; Xiao et al., 2005).

Vegetation indices can be used to map vegetation and crop conditions over a large area and to detect these changes over time. This is because if the fPAR intercepted by vegetation for the 'healthy' vegetation condition is estimated, then the departure from this indicates an anomaly. For example, Rulinda et al. (2012), used MODIS NDVI anomalies to detect drought-hit areas in east Africa, by applying threshold values to assess the spatial and temporal transition into drought condition. Funk and Budde (2009), using NDVI time-series data for drought assessment, concluded that smoothening, masking and phenological adjustments provide scale-invariant quantitative and visual drought assessment results that are consistent across sub-national, national and regional spatial aggregations. However, the downside of the commonly used hyper-temporal NDVI data in assessing crop condition is that its spatial resolution is very large (>250 m) for localized applications due to the mixed pixel effect (Atzberger, 2013; Rembold et al., 2013). Furthermore, most hyper-temporal sensors, such as MODIS, have wide viewing angles that result in significant Bi-Directional Reflectance Distribution Function (BRDF) (Hansen and Loveland, 2012). This confound such time-series data making them less attractive for field scale applications.

With the high costs and limited coverage of alternative high resolution imagery and the aforementioned issues with course resolution time series data, research efforts have started shifting towards the utilisation of medium resolution multispectral data such as Landsat data series in mapping crop area and condition assessments. These efforts are meant to enable updating of currently available coarser agricultural inventories (e.g. national data) to localized scales (e.g. fields) that help in better understanding of crop dynamics. For example, Dangwal et al. (2016), used Landsat TM data for monitoring water stress in wheat and the use of Landsat derived vegetation indices yielded promising results (RMSE = 0.12, R^2 = 0.65). This concluding remark was also validated by a couple of studies across the globe which showed that Landsat NDVI anomalies can be successfully used for identifying land degradation hotspots in the Eastern Tibetan Plateau, China (Fassnacht et al., 2015) and in Basilicata, Italy (Lanfredi et al., 2015). In a comparative study, Ding et al. (2014) concluded that the use of values NDVI data produces the greatest observable heterogeneity in the early stage of crop growth at Landsat spatial resolution of 30m. They also concluded that this significantly decays with increase in the spatial resolution of imagery. This observation is further confirmed by Venteris et al. (2015), whose work successfully showcased the ability of applying the 26 year Landsat data in identifying and mapping anomalous patches (i.e. abnormal vegetation conditions) in soybean and corn at field level, based on their deviation from the expected NDVI. In addition, Tatsumi et al. (2015) demonstrated that Landsat time series can be used for agricultural crop mapping in homogeneous areas by harnessing spatial and temporal characteristics (Overall accuracy of 81% and Kappa of 0.71).

Many studies have developed remote sensing-based phenological metrics such as onset of greenness, time of peak NDVI, senescence period, among others, for monitoring growth and conditions of annual crops. However, the spectral characteristics and growth behaviour of annual crops is very different from that perennial tree crops that have cumulative growth characteristics, making remotely-sensed distinctions more difficult (Atzberger, 2013). Therefore, much of the focus of remote sensing-based anomaly detection applications in agriculture have been on annual crops, such as wheat, maize and soybeans and yet these are in the field for a relatively shorter period to make same crop assessments (Wang et al., 2011). In addition, in annual crops, unlike in perennial tree crops, it is difficult to interpret season by season anomalies because of potential differences introduced by planting new cultivars, different planting dates and different management between seasons and years, which can contribute to observed NDVI anomalies. Consequently, attempts to apply course-resolution time series NDVI anomalies to map perennial tree crops, such as coffee have not been as widespread and as successful as in annual crops. For example, Vancutsem et al. (2009) using monthly SPOT Vegetation composite data in mapping perennial croplands in tropical Africa, observed incongruent results with those from reference datasets. In a separate study, Stibig et al. (2007), used the same data to map expanding coffee plantations in southern Asia and concluded that results were not consistent as coffee areas were rather mapped as shrubland. This therefore shows that course-resolution hyper-temporal data, such as MODIS and SPOT vegetation are only limited to the discrimination and characterisation of land cover types that explicitly exhibit seasonality and that have very contrasting growth cycles, such as annual crops and deciduous species. Medium resolution Landsat data, given the spectral improvements on Landsat 8 may therefore, provide opportunities for the development of detailed spatial datasets on coffee areas and where sequential data is available, to monitor growth or lack thereof.

There is currently more potential in utilising the Landsat 8 imagery for crop condition assessment than what was possible with TM and ETM+. This is because the Landsat-8 satellite, launched on February 11th, 2013, installed into orbit the multispectral operational land imager (OLI) which has many significant technical improvements when compared to its predecessors. These improvements include a higher signal-to-noise ratio (increased by a factor of at least eight compared to ETM+), a higher radiometric resolution (12 bits compared to 8 bits on ETM+) and better radiometric sensitivity from tens of thousands of highly sensitive detectors (Dube and Mutanga, 2015; Roy et al., 2014). In addition, it has an improved geometric accuracy from an on-board global positioning system and an improved combination of pre-launch, on-board and vicarious calibration procedures for a better sensor fidelity (Roy et al., 2014). The Landsat 8 OLI imagery also has an added coastal band designed for atmospheric correction and this is particularly useful in tropical areas where many perennial tree crops are produced. The