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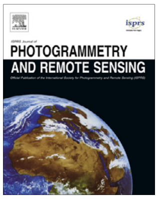

Mapping spatial variability of foliar nitrogen in coffee (*Coffea arabica* L.) plantations with multispectral Sentinel-2 MSI data

Abel Chemura [a,*], Onisimo Mutanga [b], John Odindi [b], Dumisani Kutywayo [c]

[a] *Environmental Science and Technology Department, Chinhoyi University of Technology, P. Bag 7724, Chinhoyi, Zimbabwe*
[b] *University of KwaZulu-Natal, School of Agricultural, Earth & Environmental Sciences, P/Bag X01, Scottsville, Pietermaritzburg 3209, South Africa*
[c] *Department of Research and Specialist Services Head Office, Agricultural Research Centre, Off 5th Street, Harare, Zimbabwe*

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ABSTRACT

Nitrogen (N) is the most limiting factor to coffee development and productivity. Therefore, development of rapid, spatially explicit and temporal remote sensing-based approaches to determine spatial variability of coffee foliar N are imperative for increasing yields, reducing production costs and mitigating environmental impacts associated with excessive N applications. This study sought to assess the value of Sentinel-2 MSI spectral bands and vegetation indices in empirical estimation of coffee foliar N content at landscape level. Results showed that coffee foliar N is related to Sentinel-2 MSI B4 ($R^2 = 0.32$), B6 ($R^2 = 0.49$), B7 ($R^2 = 0.42$), B8 ($R^2 = 0.57$) and B12 ($R^2 = 0.24$) bands. Vegetation indices were more related to coffee foliar N as shown by the Inverted Red-Edge Chlorophyll Index – IRECI ($R^2 = 0.66$), Relative Normalized Difference Index – RNDVI ($R^2 = 0.48$), CIRE1 ($R^2 = 0.28$), and Normalized Difference Infrared Index – NDII ($R^2 = 0.37$). These variables were also identified by the random forest variable optimisation as the most valuable in coffee foliar N prediction. Modelling coffee foliar N using vegetation indices produced better accuracy ($R^2 = 0.71$ with RMSE = 0.27 for all and $R^2 = 0.73$ with RMSE = 0.25 for optimized variables), compared to using spectral bands ($R^2 = 0.57$ with RMSE = 0.32 for all and $R^2 = 0.58$ with RMSE = 0.32 for optimized variables). Combining optimized bands and vegetation indices produced the best results in coffee foliar N modelling ($R^2 = 0.78$, RMSE = 0.23). All the three best performing models (all vegetation indices, optimized vegetation indices and combining optimal bands and optimal vegetation indices) established that 15.2 ha (4.7%) of the total area under investigation had low foliar N levels (<2.5%). This study demonstrates the value of Sentinel-2 MSI data, particularly vegetation indices in modelling coffee foliar N at landscape scale.

1. Introduction

Coffee, a popular non-alcoholic beverage, is a valuable export commodity that contributes significantly to employment, balance of payments and local taxes in many developing countries. Coffee contributes over US$ 20 billion annually to producer countries, with incomes cascading down to millions of smallholder farmers (Waston and Achinelli, 2008). It is estimated that there are between 25 and 30 million coffee farmers in the world, with the majority being smallholder farmers in sub-Saharan Africa, South-East Asia and Central America, supplying over 70% of the world's coffee (Baker et al., 2001). Coffee production is therefore a unique legal source of income for these farmers. In addition to being a source of livelihoods, coffee plantations also contribute to landscape scale ecosystem processes such as carbon sequestration, erosion control and provision of other ecosystem services (Brauman et al., 2007; Soto-Pinto et al., 2010).

Coffee follows the C3 or Calvin cycle photosynthetic pathway, with the plant biomass productivity, growth and yield being dependent on carbohydrates produced through photosynthesis (Wrigley, 1988). The capacity of the plant to produce these carbohydrates depend on nutrient supply with nitrogen (N) being the single most limiting factor to coffee productivity (Coste, 1992). Mature coffee requires a total of 105 kg N ha^{-1} to achieve yield levels of 1 tonne ha^{-1} per year, and yet some coffee farms report up to 6 tonnes clean coffee per ha^{-1} per year (Chemura, 2014). N plays several interconnected roles in coffee plant development and productivity. Firstly, N determines plant establishment and root growth, which in turn influences other aspects of the plant's

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[*] Corresponding author.
E-mail addresses: achemura@gmail.com, achemura@cut.ac.zw (A. Chemura).

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health. Secondly, in addition to enhancing berry productivity in the year of supply, N ensures production of fresh cropping wood frame, valuable for improved productivity in subsequent years (Logan and Biscoe, 1987). Furthermore, N plays a significant role in plant resilience to biotic and abiotic stresses. For example, it has been suggested that bushes with low nitrogen levels are more susceptible to coffee white stem borer attacks (Kutywayo, 2002). In addition, sufficient N helps the coffee plant to tolerate higher levels of manganese by preventing the breakdown of leaf proteins under extremely hot and dry conditions (Logan and Biscoe, 1987). Coffee plants with higher N are also known to have a higher ability to withstand drought due to higher hydraulic conductivity (DaMatta, 2004).

Commonly, N fertilisers are used to supplement soil available nitrogen to increase growth and prevent leaf fall, hence optimise photosynthetic area. On the other hand, excessive or ill-timed N may induce the excessive production of side shoots from the nodes, rather than flower buds, reducing berry yield (Kutywayo et al., 2010). Concerns about leaching and volatilization of N fertilisers from excessive applications have also been raised (Bortolotto et al., 2012; Tully et al., 2012). Although N is essential for coffee plants throughout the year, its demand increases significantly during blossom and berry development (Coste, 1992). Hence, coffee N management decisions are not just about N supply, but about achieving and maintaining a season long balance of nitrogen within the plant.

To achieve the fine N balance in coffee plants, plantation managers supply nitrogen as compound, organic or straight fertilisers applied as basal applications, foliar sprays and/or trickle or drip fertigation. These applications are based on calendar management program or occasional lab-based soil and/or leaf sampling used in conjunction with established diagnostic norms. In extreme cases, nutrient deficiency symptoms such as the characteristic yellowing of leaves for N deficiency are used for reactive decision making. These methods are not only labour intensive, but also commonly adopted once economic damage has already been inflicted on the crop (Chemura et al., 2017a). In the long term, these sampling-based methods are not ideal for balancing the crop nutrient needs, supply of nutrients from natural sources, and the short- and long-term fate of the fertilizer applied, resulting in unsustainable production and yield shortfalls.

Remote sensing methods have been demonstrated to successfully identify distributions of foliar N in natural vegetation and agricultural crops across different biomes. This is enabled by the fact that N is related to factors influencing spectral responses of vegetation across the visible, near-infrared (NIR) and short-wave infra-red (SWIR) regions of the spectrum. Many authors, e.g. Ollinger et al. (2008), Wang et al. (2016) and Lepine et al. (2016) have reported that there are significant correlations between NIR reflectance (800–850 nm) and canopy foliar mass-based nitrogen concentration (%N), which enable remote sensing-based N predictions. Whereas the reason for this correlation is still under speculation (Knyazikhin et al., 2013; Ollinger et al., 2013; Townsend et al., 2013), there is sufficient ground for development of remote-sensing based foliar N prediction and mapping from remotely sensed data at various scales (Baret et al., 2007; Ramoelo et al., 2012; Kalacska et al., 2015; Omer et al., 2017).

Leaf level N vs reflectance dynamics do not necessarily follow canopy level interactions. For instance, Frampton et al. (2013) reported contrasting performance of vegetation indices at leaf and canopy levels in N estimation. Consequently, Wang et al. (2016) suggested that canopy structure confounds the estimation of foliar N when using canopy spectral data because it is the main driver of canopy reflectance variations. This is interesting for application of remote sensing in coffee plantations because coffee plants have a distinct canopy, influenced by their physiology, growth cycle and planting arrangement. Thus, reported interactions between vegetation and reflectance in forests, grasslands, annual crops and other plantations may not hold for coffee. This is because (i) coffee is planted in hedgerows and there is always background effect which reduces potential for saturation, (ii) the function and structure of the canopy that explain reported variation is the same in coffee fields (except where coffee is under shade) and, (iii) each pixel is usually uniform aged plants, with similar height and canopy, which influences adjoining cover reflectance.

Understanding the functional relationships between leaf N and plant growth and development, as well as development of rapid and less expensive diagnostic approaches for spatial and temporal estimation of plant N are necessary for efficient and sustainable management of coffee plantations. However, majority of reported approaches either use hyperspectral data e.g. Moharana and Dutta (2016) and Pullanagari et al. (2016), which is not easily accessible to many coffee producers or field spectroscopy e.g. Ramoelo et al. (2013) and Pompelli et al. (2010), which has similar limitations as aforementioned sampling approaches. To increase applications in vegetation condition assessment, new generation satellite sensors such as WorldView-2 and 3, RapidEye and Sentinel-2 have incorporated new wavebands unavailable in similar predecessor sensors. The Sentinel-2 is particularly attractive due to its free availability, with relatively high spatial resolution, as well as strategically positioned bands, making it useful for many applications that include vegetation characterisation and mapping. It has a huge swath-width of about 290 km with thirteen unique spectral bands (Clevers and Gitelson, 2013). These spectral bands range from the visible and near infrared (VNIR) to the shortwave infrared (SWIR) regions of the spectrum. Of these thirteen bands, four are provided at 10 m spatial resolution, six at 20 m spatial resolution and three at 60 m spatial resolution (Ramoelo et al., 2015). Due to these unique characteristics, the Sentinel-2 multispectral imager is hyped to be capable of providing timely data for the generation of high-level operational products. These include the generation of spatially explicit estimation and monitoring of important plant biophysical and biochemical variables such as chlorophyll, N, LAI, leaf water content and crop health.

Given the uniqueness of coffee as a target and the spectral features of the Sentinel-2 MSI data, the aim of this study was to assess the potential for Sentinel-2 bands and vegetation indices to predict foliar N content in coffee (*Coffea arabica* L.). A secondary objective was to establish the relationships between spectral variables and coffee foliar N at canopy level. The latter objective was aimed at identifying the best performing variables in coffee N prediction for the purposes of quantifying and mapping N levels that can be operationally used to characterise and manage coffee fields to achieve optimum productivity.

2. Materials and methods

2.1. Study area

The study was conducted at Jersey Tea and Coffee Estates in Chipinge district, Zimbabwe. The site is located at longitude 32°41′00E and 32°42′00E, latitude 20°28′00S and 20°31′00S and an average altitude of 900 m above sea level (Fig. 1). The area is characterised by a subtropical climate with two distinct dry and wet seasons, divided almost equally between months of the year i.e. October to March – rainy and April to September – dry seasons. The topography is undulating with a relief difference of over 100 m. The area receives relatively high mean annual rainfall totals for a subtropical area (1200–1300 mm/year) with mostly warm temperatures, around 22.5 °C. With deep red clayey soils formed from mafic rocks, climatic conditions in the area make it suitable