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Estimating Swiss chard foliar macro- and micronutrient concentrations under different irrigation water sources using ground-based hyperspectral data and four partial least squares (PLS)-based (PLS1, PLS2, SPLS1 and SPLS2) regression algorithms

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ABSTRACT

Timely information on crop foliar nutrient content provides a measure of crop nutritional and vitality status. Growers and farm managers use such information for precision crop management such as an appropriate fertilizer application to correct for any crop nutrient deficiencies at identified hotspots. Foliar heavy nutrient content could also be a direct indicator of crops having been polluted from the surroundings, which may be a result of heavy metals absorbed from, among others, contaminated soils and waste water. In the present study, we explored the potential use of four partial least squares (PLS)-based regression algorithms for estimating foliar Swiss chard macro- and micronutrient concentrations using ground-based hyperspectral data under three treatments; i.e. rainwater + fertilizer ('R + F'), tap water + fertilizer ('T + F'), and treated wastewater ('W'). Swiss chard canopy-level hyperspectral measurements under these three treatments were collected using a handheld spectroradiometer 2.5 months after sowing. The reflectance spectra were normalized to their first-order derivatives. The concentrations of three Swiss chard foliar macronutrients (NPK) and three micronutrients (Zn, Cu and Fe) under the three treatments were determined. Regression models for estimating macro- and micronutrient concentrations were then derived using PLS1 and sparse PLS1 methods, while the potential simultaneous estimation of the macronutrient as well as micronutrient concentrations was explored using the PLS2 and SPLS2 regression approaches. Results showed that high variances in the macro- and micronutrient concentrations can be explained by the four regression models under the three treatments (R^2_{train} ranged between 0.73 and 0.99), except when P, Zn and Cu concentrations were estimated using the PLS2-based models under the three treatments (R^2_{train} ranged between 0.08 and 0.68) and Fe concentration using SPLSR1 under 'W' treatment (R^2_{train} = 0.64). Our results further showed that Swiss chard foliar N (RMSE = 1.67%) concentration under 'R + F' treatment and Fe (RMSE = 7.83%) concentration under the 'T + F' treatment most accurately estimated macro- and micronutrients. Our study also showed that the Swiss chard foliar macronutrient concentrations were more accurately estimated compared to micronutrient concentrations and PLS2 outperformed the PLS1 based regression model. The results of the current study pave the way for developing an effective foliar nutrient estimation routine suitable for monitoring Swiss chard nutrient status under different treatments.

1. Introduction

It is projected that the world's population will increase by 38% from 6.9 billion in 2010 to 9.6 billion by 2050 (UN, 2004; FAO, 2014). Recently, studies have focused on identification and implementation of various agricultural systems that sustainably secure

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food for the increasing world's population, with minimal environmental damage. Organic farming is one of the climate-smart agricultural systems that sustainably and efficiently improve crop production and reduces the contribution of greenhouse gases (Badgley et al., 2007; Binta and Barbier, 2015). Organic farming is considered an environmentally friendly production system that avoids the use of harmful chemicals like synthetic inorganic fertilizers (e.g. urea). It has been reported that organically produced agricultural commodities are healthier and more nutritious than those produced under inorganic systems (Annicchiarico et al., 2010). Wastewater irrigation is another innovative and resilient organic production practice that aims to reuse and recycle water that contains liquid wastes generated by urban or peri-urban systems (Banin, 1999). The reuse and recycling of wastewater for irrigation processed through sanitation technologies like decentralized wastewater treatment systems (DEWATS), still poses some challenges. Such problems are (i) direct contact of some useable crop parts with wastewater, (ii) absorption of some noxious compounds like heavy metals by crops from soils under wastewater irrigation, and (iii) the amount of wastewater produced from a sanitation technology system may not fully meet irrigation demand for intensified cropping systems. However, reuse of wastewater offer great potential for small- and medium-scale farmers, particularly those in urban and peri-urban areas (Levine and Asano, 2004). Commonly, vegetable farming (e.g. tomato and Swiss chard) is considered a reliable mode of cyclic farming practiced in urban and rural areas. In addition, World Health Organization (WHO, 2006) noted that some vegetable crops (e.g. Swiss chard and common dry bean) are not eaten raw and hence are not a microbial risk, hence may be irrigated with treated wastewater. It is therefore of interest to investigate the use of treated wastewater generated from DEWATS facilities for usage in growing vegetable crops in urban ecosystems.

In line with global research interest and due to scarcity and high demand for water in South Africa (Turton, 2009), researchers commonly seek for ways to use treated wastewater in irrigating vegetable crops (like Swiss chard) in order to improve the quantity and quality. The hypothesis is that treated wastewater contains considerable amounts of macronutrients (e.g. NPK) and micronutrients (e.g. Zn, Cu and Fe) that are essential for crop growth (Hosetti and Frost, 1995). Wastewater irrigation can also improve some soil physical properties such as the level of organic carbon and enhance crops uptake of these essential nutrients and mediate soil water retention (Abedi-Koupai et al., 2006; Darvishi et al., 2010). It is therefore of importance to monitor leaf nutrient contents in vegetable crops irrigated with treated wastewater in order to test and maximize the aforementioned benefits, as well as manage the associated disadvantages.

Conventional monitoring approaches for crop foliar nutrients typically consist of collecting leaf samples, and performing leaf chemical analyses that are costly and time-consuming, particularly when a large number of leaf samples are analyzed for multiple nutrients (e.g. NPK). Furthermore, with traditional methods, relatively fewer sites can be sampled, which may impede site-specific field management practices. Hence, cost-effective, timely and relatively accurate site-driven protocols for monitoring crop foliar nutrient contents are required. In this context, remotely-sensed data are regarded as an attractive source of information for determining crop foliar nutrient contents.

The use of remotely-sensed data in monitoring crop foliar nutrients has been widely documented in the literature. Researchers have utilized multispectral (e.g. Reyniers and Vrindts, 2006; Zhang et al., 2006) and hyperspectral data at leaf (e.g. Read et al., 2002; Zhao et al., 2005; Zhai et al., 2013) and canopy (e.g. Osborne, 2002; Inoue et al., 2012) levels to predict crop foliar nutrients. Multispectral data are captured at relatively fewer spectral bands of wider bandwidths in certain regions of the electromagnetic spectrum (EMS) (Kumar et al., 2003), whereas hyperspectral data are recorded in many narrow, quasi-continuous spectral bands at the visible (400–700 nm), near infrared (NIR: 700–1300 nm), up to the shortwave infrared (SWIR: 1300–2500) regions of the EMS (Lillesand et al., 2004).

A number of studies have used various analytical approaches like partial least squares regression (PLSR) to deal with the problem of small sets of samples and large numbers of estimated parameters associated with models for hyperspectral data (e.g. Nguyen et al., 2006; Inoue et al., 2012; Ramoelo et al., 2013). Also, many wavebands (predictor variables) often correlate with each other to predict a response variable (e.g. crop foliar nutrient content). Hence, if the multidimensionality of hyperspectral data cannot be properly reduced for the large numbers of co-linearity, the predictive models developed using empirical statistical methods can easily be over-fit during the calibration phase (Abdel-Rahman et al., 2014). Over-fitting models perform poorly when validated or are up-scaled when using independent test datasets. Mehmood et al. (2012) noted that PLSR is a multifaceted method that has found widespread use in multivariate data analysis in a wide range of diverse applications like machine learning. In the field of remote sensing, many studies have used PLSR to analyze and mine hyperspectral data for estimating crop nutrient contents (see among others Read et al., 2002; Inoue et al., 2012; Mao et al., 2015). It has been found that PLSR is a suitable method to overcome the over-fitting problem and to reduce the dimensionality of the hyperspectral data as the method transforms the wavelengths in hyperspectral data to a less number of uncorrelated components (Wold, 1995). On the other hand, sparse PLSR is method that uses the principles of PLSR and applies a sparsity solution (Chun and Keleş, 2010; Filzmoser et al., 2012) to select a few relevant wavelengths that contribute to explaining the variability in a crop nutrient content. The continuous development in the linear PLSR algorithm resulted in two linear PLSR methods. PLSR1, or simply PLSR, which is a single response (e.g. a single crop foliar nitrogen content) case and PLSR2 which enables calculations of the eigenvectors (loadings) of the PLS model from many response variables (e.g. multiple crop foliar nutrient contents). In the latter, multiple responses can be estimated simultaneously in one model (Manne, 1987). In the present study, we tested the use of four PLS-based regression algorithms; i.e. PLSR1, PLSR2, SPLR1 and SPLR2 for estimating Swiss chard foliar macro- and micronutrient concentrations using canopy-level hyperspectral data. Specifically, our aim was to estimate Swiss chard foliar nutrient concentrations under three different treatments; viz., rainwater + fertilizer ('R + F'), tap water + fertilizer ('T + F'), and treated wastewater ('W').

2. Crop description and experimental site

Whereas there are numerous different types of vegetables that can be farmed in a cyclic manner, we grew Swiss chard (*Beta vulgaris*) as a test crop because it is a leafy vegetable that is cooked before consumption. Therefore, the crop is not a source of a microbial contamination risk when irrigated with treated wastewater. Ultimately, part of treated wastewater irrigation strategy is to ensure that there are no pathogenic risks. Swiss chard has moderately deep hard root system and fleshy stem with fan-like large crisp dark green leaves. It is a cool-season vegetable that favours sunny days and well-drained and fertile soils (Rehm and Espig, 1991). Like other leafy vegetables, Swiss chard requires fairly frequent irrigation that keeps the soil at more than 50% available water under South African environmental conditions (Department of Agriculture, Forestry and Fisheries, 2010). Swiss chard is nutritious vegetable and excellent source of vitamins,