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Determination of sufficiency values of canopy reflectance vegetation indices for maximum growth and yield of cucumber

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ABSTRACT

Large nitrogen (N) fertilizer applications are a feature of intensive vegetable production systems, and optimal N management is required to maximize N use efficiency and minimize N losses. Vegetation indices (VIs) of canopy reflectance, measured with proximal sensors, are generally strongly related to crop N status. For practical application, sufficiency values that distinguish between N deficiency and sufficiency are required. In this work, sufficiency values of VIs for maximum crop growth and for yield were determined for two cucumber crops grown in contrasting seasons (Autumn and Spring). Canopy reflectance was measured with a Crop Circle ACS-470 sensor. Sufficiency values for maximum growth were based on the relationships of VIs with the Nitrogen Nutrition Index (NNI), i.e. the ratio between actual and critical crop N contents. Sufficiency values for maximum yield were based on linear-plateau relationships of yield with VIs. Strong relationships were obtained between all VIs and both NNI and yield for most of the weekly measurements during both crops. For NNI, best-fit relationships were linear, quadratic, power or exponential, and had coefficients of determination (R^2) of 0.61–0.98. For yield, most linear-plateau relationships between yield and VIs had R^2 values of 0.47–0.89. VIs based on reflectance in green and red edge had slightly better relationships with NNI and yield than VIs in the red, with the Green Normalized Difference Vegetation Index (GNDVI) and the Green Ratio Vegetation Index (GRVI) being the most sensitive and consistent indices for estimating both crop NNI and yield. Relationships between VIs and NNI and yield for all weekly measurements of each crop, and for the two crops combined, were also analyzed to provide unique sufficiency values for maximum growth and yield that applied to the entire crop cycle of each crop and of both crops considered together. Overall, there were slight differences between sufficiency values for maximum growth and for maximum yield and the unique sufficiency values were generally intermediate to the weekly sufficiency values. This study demonstrated the potential for using VIs for monitoring crop N nutrition and yield in cucumber. The calculated sufficiency values of VIs may facilitate the use of proximal optical sensors in farming practice for optimal N management through periodic monitoring for deviation from sufficiency values.

1. Introduction

Intensive vegetable production systems are generally characterized by large applications of mineral nitrogen (N) fertilizer (Neeteson, 1994; Thompson et al., 2007b). Commonly, the N supply from fertilizer and other sources considerably exceeds the N required for maximum production (Ju et al., 2006; Soto et al., 2015) resulting in substantial nitrate (NO_3^-) leaching loss (Benincasa et al., 2011; Gallardo et al., 2006a; Zotarelli et al., 2007). Optimal N management that meets crop requirements while reducing N loss to the environment is required for intensive vegetable production because of increasing societal pressure to reduce the environmen-

Abbreviations: AIC, akaike information criterion; ANOVA, analysis of variance; CCCI, canopy chlorophyll content index; CNC, critical nitrogen curve; DAT, days after transplanting; GNDVI, green normalized difference vegetation index; GRVI, green ratio vegetation index; MTCI, MERIS terrestrial chlorophyll index; N, nitrogen; NIR, near infra red; NDVI, normalized difference vegetation index; NNI, nitrogen nutrition index; R^2, coefficient of determination; REI, red edge index; RENDVI, red edge normalized difference vegetation index; RRVI, red ratio vegetation index; VI, vegetation index; VI*i*, integrated vegetation index.

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tal problems associated with NO_3^- contamination of water bodies (Andrews et al., 2013; Cameron et al., 2013).

Optimal N management requires that the rate and timing of N supply be matched to crop N demand (Gebbers and Adamchuk, 2010; Meisinger et al., 2008). The frequent application of small amounts of N in intensive vegetable production with the increasing use of combined fertigation and drip irrigation systems requires a N management system that regularly ensures optimal N management throughout the crop (Thompson et al., 2017). Ideally, this requires accurate and rapid on-farm assessment of crop N status. Monitoring of crop N status integrates crop N demand and N supply providing an overall assessment of whether the two are in balance (Schröder et al., 2000). A promising approach for frequent assessment of crop N status is non-destructive crop N monitoring using proximal optical sensors (Samborski et al., 2009; Usha and Singh, 2013). Proximal optical sensors are a form of remote sensing in which the sensors are positioned close to the crop. These sensors do not directly measure N content in crop tissue but provide measurements or indices of optical properties of crops (i.e., canopy reflectance) that are sensitive to crop N status (Fox and Walthall, 2008; Samborski et al., 2009). For N management of vegetable crops, optical sensors have several attractive practical characteristics. Measurements can be made easily, quickly and periodically throughout a crop, and the results are rapidly available. There are no time delays and logistical issues as with methods involving laboratory analysis. Any required adjustments to the N supply can be made very soon after measurement, given the availability of relevant sufficiency values.

During the last 20 years, particularly in the last 10, there has been considerable interest in the use of canopy reflectance sensors for crop N management. These sensors provide information on crop N status by measuring specific wavelengths of light reflected from the canopy (Fox and Walthall, 2008; Hatfield et al., 2008). Proximal canopy reflectance sensors are positioned relatively close to the crop canopy (various centimetres to several meters); most of these sensors have their own light source (Solari et al., 2008). A major advantage of these sensors is that the combination of continuous measurement with a relatively large field of view provides rapid measurement of large areas of crop canopy. Canopy reflectance sensor measurements have been shown to be sensitive to crop N status of cereal crops (Fox and Walthall, 2008; Scotford and Miller, 2005) and to various vegetable crops such as tomato (Gianquinto et al., 2011a; Padilla et al., 2015), muskmelon (Padilla et al., 2014), cucumber (Yang et al., 2010), and broccoli (El-Shikha et al., 2007).

The rationale for using canopy reflectance sensors for N management is that crop N content differentially influences the absorption and reflection of individual wavelengths of light, within the range of visible (390–750 nm) and near infra-red (NIR; 750–1300 nm) (Ollinger, 2011). Plant tissues absorb visible light and reflect NIR (Knipling, 1970); N-deficient crops generally reflect more visible and reflect less NIR than N-sufficient crops (Peñuelas et al., 1994; Schepers et al., 1996). The wavelengths selected for N assessment, using canopy reflectance, are chosen because of their sensitivity to the changes in chlorophyll content, foliage density and biomass that accompany N deficiency (Read et al., 2002; Thenkabail et al., 2002); commonly, reflectance in four bands centered on green (495–570 nm), red (620–710 nm), red edge (light at the extreme red end of the visible spectrum, between red and infra-red light, at 710–750 nm) and NIR are used. In practice, reflectance data of 2–3 wavelengths are combined in mathematical equations to calculate vegetation indices (VIs) (Bannari et al., 1995), of which NDVI (Normalized Difference Vegetation Index; Sellers (1985)) is one of the most commonly-used. A number of N-sensitive VIs have been used; they have been described by Fox and Walthall (2008), Hatfield et al. (2008) and Samborski et al. (2009).

Commonly, the selected indices are interpreted for N management by establishing relationships with yield (Gianquinto et al., 2011a; Morier et al., 2015; Raper and Varco, 2015) or measures of crop N status such as the Nitrogen Nutrition Index (NNI) (Mistele and Schmidhalter, 2008; Padilla et al., 2014). The NNI is the ratio between actual and the critical crop N content (i.e. the minimum content necessary to achieve maximum growth (Greenwood et al., 1990)). Deviations from optimal values of NNI = 1 indicate N deficiency (NNI < 1) or N excess (NNI > 1) (Lemaire and Gastal, 1997). For proximal canopy reflectance sensors to have practical application in farming, the evaluation of the nature, strength and consistency of relationships of VIs with crop yield and/or crop N status is fundamental (Samborski et al., 2009). Frequent measurements of VIs with proximal canopy reflectance sensors can provide on-going assessment of crop N status, enabling subsequent rapid correction of N applied.

A key issue for the adoption of any form of crop N monitoring in farming practice for N management is the development of sufficiency values or ranges that distinguish between deficiency (below the value) and sufficiency (above the value). Sufficiency values of several crop N monitoring techniques have been derived in literature based on yield responses functions (Gianquinto et al., 2004; Ordoñez et al., 2015) or from measurements of crop NNI (Padilla et al., 2015 Peña-Fleitas et al., 2015). Yield-based sufficiency values are derived from linear-plateau segmented regression analysis, which is based on a model that assumes a linear increase in yield with increases in the values of measurements of a crop N monitoring technique until yield is maximized and thereafter remains constant; the breakpoint of this relationship indicates the sufficiency value of the crop N monitoring technique for yield. This regression model has been used to derive sufficiency values of specific leaf N content in corn (DeBruin et al., 2013; Ordoñez et al., 2015) and chlorophyll meter readings in processing tomato (Gianquinto et al., 2004; Gianquinto et al., 2006). NNI-based sufficiency values are derived from mathematical equations of the relationships between the values of measurements of a crop N monitoring technique and NNI, and solving for NNI = 1, which is the value that corresponds to optimal N nutrition for crop growth (Lemaire and Gastal, 1997). This procedure has been used with greenhouse-grown tomato to derive sufficiency values of petiole sap NO_3^- concentration (Peña-Fleitas et al., 2015) and also for VIs of canopy reflectance and of chlorophyll meter readings (Padilla et al., 2015).

Substantial reduction of NO_3^- contamination of water bodies has become a legal obligation in the European Union in areas declared to be Nitrate Vulnerable Zones (Council of the European Communities, 1991, 2000). The intensive vegetable production system in southeastern (SE) Spain is an example (Junta de Andalucía, 2008). The greenhouse-based intensive vegetable production system of SE Spain consists of 38,000 ha of relatively simple plastic greenhouses of which 28,000 ha are concentrated in the province of Almeria (Castilla and Hernández, 2005; Junta de Andalucia, 2013). Nitrate leaching loss from this system has caused considerable NO_3^- contamination of underlying aquifers (Pulido-Bosch et al., 2000; Thompson et al., 2007b). Cucumber is one of the major crops in the greenhouse system of SE Spain, occupying approximately 7000 ha annually (Reche-Mármol, 2011). Proximal canopy reflectance measurements may enable vegetable growers to optimize N management of fertigated cucumber that receive frequent N application.

The objectives of the present work were: (i) to evaluate the use of proximal canopy reflectance measurements to estimate crop N status and yield throughout the crop cycle of two indeterminate cucumber crops, (ii) to assess which VIs better predict crop N status and yield, and (iii) to derive sufficiency values of VIs for maximum growth and yield.