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Research Paper

Airborne and ground level sensors for monitoring nitrogen status in a maize crop

Jose L. Gabriel [a], *Pablo J. Zarco-Tejada* [b], *P. Juan López-Herrera* [c], *Enrique Pérez-Martín* [c], *Maria Alonso-Ayuso* [c], *Miguel Quemada* [c,*]

[a] *Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), Ctra de La Coruña Km 7.5, 28040 Madrid, Spain*

[b] *Instituto de Agricultura Sostenible (IAS), Consejo Superior de Investigaciones Científicas (CSIC), Alameda Del Obispo S/n, 14004 Córdoba, Spain*

[c] *School of Agricultural Engineering, Universidad Politécnica de Madrid, Avda. Complutense S/n, 28040 Madrid, Spain*

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Remote sensing could improve fertilisation by monitoring crop nitrogen (N) status using non-invasive methods. The main goal of this experiment was to test the ability of proximal and airborne sensors to identify the nutritional N status of maize. We compared various indices and combination of indices to select those that provided the best estimation. As airborne images were acquired from different sensors and platforms (drone and airplane) we compared the effect of spatial resolution (SR) on the indices calculated. The study was conducted in a field maize experiment in Aranjuez (Madrid, Spain) during 2015. The experiment consisted of a complete randomized design with five fertiliser rates ranging from 0 to 220 kg N ha^{-1} and six replications. Readings at ground level were taken with proximal sensors (SPAD® and Dualex®), and airborne data were acquired by flying a multispectral camera and a hyperspectral sensor at 80 and 330 m above ground level, respectively. The aerial imagery was used to calculate N status indices for each plot. Proximal and airborne sensors provided useful information for the assessment of maize N nutritional status. Higher accuracy was obtained with indices combining chlorophyll estimation with canopy structure or with polyphenol indices. Combined indices improved the estimation compared to an individual index and mitigated its saturation at high N concentration values. Plant N concentration was strongly related with TCARI/OSAVI obtained from airborne imagery but not with NDVI. The SR did not affect the performance of structural indices whereas highly influenced the pigment indices.

1. Introduction

A key factor for improving N fertiliser efficiency and reducing input costs is to adjust N application to crop demand (Arregui & Quemada, 2008). In addition, matching N application and crop requirements decreases deleterious environmental effects of excessive fertilisation, either by nitrate pollution of water (Quemada, Baranski, de Lange, Vallejo, & Cooper, 2013) or by gaseous emissions (Snyder, Bruulsema, Jensen, & Fixen,

* *Corresponding author*. Fax: +34 91 5449 983.
E-mail address: miguel.quemada@upm.es (M. Quemada).

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2009). Some rapid and non-destructive ways to obtain multiple measurements are optical readings that can provide indicators of crop nutritional status. The greenness of plants is strongly related to leaf chlorophyll content and to N status, so it has been used as an indicator of N availability (Fox & Walthall, 2008; Hunt et al., 2013). The best variable to assess crop nutritional status is the N nutrient index, which is based on the critical N concentration (the minimum N concentration in the plant that allows maximizing growth; Greenwood et al., 1990). The strategy of some crops (as *Solanum tuberosum* L.) is to reduce leave development in order to maintain photosynthetic capacity per surface unit (Vos & van der Putten, 1998). However, maize (*Zea maize* L.) does not change leaves appearance rate nor the duration of leaf expansion and it does never reduce leaf area more than 30%. In this case, the leaf N concentration differed by at least a factor of 2 from the lowest to highest N supply, for a large range of N supply, presenting leaf N concentration as a good indicator of N status (Vos, van der Putten, & Birch, 2005). Moreover, along the crop cycle, the N concentration decreases with increasing crop biomass and for a given growth stage and biomass accumulation there is a critical level below which the crop yield would be reduced (Lemaire & Gastal, 1997). Therefore, determination of plant N concentration by destructive techniques (i.e. tissue analysis) is a recommended practice for improving fertiliser management (Plenet & Lemaire, 2000; Tei, Benincasa, & Guiducci, 2002), and a goal for application of remote sensing to improve N fertilisation should be monitoring crop N status by mean of non-invasive methods.

In the past decades, a tremendous progress on sensor technology for assessment of plant N status has been achieved. At the leave level, there are various commercial sensors to that estimate chlorophyll content and can be used to provide N fertilizer recommendations for farmers (Arregui et al., 2006; Piekielek, Fox, Toth, & Macneal, 1995). These chlorophyll leaf clip sensors ensure a good contact with the plant and show good relationships with N status, but may present some limitations as readings can be affected by water content, leaf structure, thickness changes or nutrient deficiencies other than N. Complementing chlorophyll measurements with polyphenol concentration in the leaf epidermis is a mean to overcome such constraints (Cerovic et al., 2002). The chlorophyll to polyphenol ratio has been reported to be more stable than the non-uniform leaf chlorophyll distribution (Cartelat et al., 2005).

On the other hand, remote sensing can cover large areas and reflect spatial variability of crop canopies. Remote sensors have being mounted in different platforms as: tractors, drones, airplanes and satellites, to provide information for precision farming (Fox & Walthall, 2008). There are several indices based on remote sensors that characterize plant canopy structure, soil cover, above-ground biomass, yield or water and nutrient-deficiency. The indices are calculated by combining reflectance on the wavelengths located in the visual, red-edge and near infrared range. The most commonly-used is the Normalized Difference Vegetation Index (NDVI) developed to identify areas covered by natural vegetation (Rouse, Haas, Schell, Deering, & Harlan, 1974). The NDVI and its variants (i.e. RDVI, Renormalized Difference Vegetation Index (Rougean & Breon, 1995)) characterize plant canopy structure and have been frequently used to analyze crop N performance and for fertiliser recommendation (Elazab, Ordóñez, Savin, Slafer, & Araus, 2016). More recently, researchers proposed other indices related to plants pigment concentration as a more accurate mean to estimate crop N status while minimizing the impact of canopy structure. Stroppiana, Boschetti, Brivio, and Bocchi (2009) showed that the optimal Normalized Difference Index (NDI_{opt}), based on the blue/green reflectance region, was less affected by leaf area index (LAI) and canopy structure of rice than NDVI, and was more sensitive to changes in plant N concentration. Chen et al. (2010) developed the Double-peak Canopy Nitrogen Index (DCNI) to estimate crop N status of wheat and maize and minimized the effect of canopy structure.

In field-scale images, the canopy reflectance spectrum is affected by both, canopy structure and N concentration. Remote sensors are carried at different altitudes above the ground level depending on specific application and the platform used. Sensors spatial resolution (SR) depends on the altitude and the sensor specifications. The SR at which the image is captured might affect the relative weight of canopy structure on the actual value of a particular index due to the angular effects of shadows and background at each specific resolution. Therefore, there is a need to evaluate the effect of image SR on the indices designed to estimate crop N status.

Nitrogen only constitutes 2–4% of the maize dry matter but is considered the most important factor in grain maize production together with water availability (Elazab et al., 2016). In addition, when low crop growth is attained, the canopy only covers the ground partially. During this period, the N deficiency may be affected by both, canopy structure and pigment concentration. The FAO (United Nations Food and Agriculture Organization) has identified the maize as the second most cultivated cereal worldwide in terms of land area and the first in production (FAO, 2016). The world production in 2014 was over a thousand million Mg and is continuously increasing.

The main goal of this experiment was to test the ability of proximal and airborne sensors to identify the nutritional N status of maize. We specifically compared various indices or combination of indices to select those that provided the best estimation. As airborne images were acquired from different sensors and platforms (drone and airplane) we compared the effect of SR on the indices calculated.

2. Material and methods

2.1. *Experimental site and crop management*

The study was conducted at La Chimenea field station (40°03′N, 03°31′W, 550 m a.s.l.), which is located in the central Tajo river basin near Aranjuez (Madrid, Spain) during 2015. The soil at the field site is a *Typic Calcixerept* (Soil Survey Staff, 2014), alkaline, rich in organic matter, silty clay loam texture and low stone content throughout the soil profile. The soil mineral N at planting in the first 1 m depth was 25 kg N ha^{-1}. The climatic conditions in the area are Mediterranean semi-arid. Mean annual temperature is 14.2 °C with an average annual rainfall of 350 mm, most of it during autumn and spring. Details on soil and climate conditions are described in