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Assessment of crop foliar nitrogen using a novel dual-wavelength laser system and implications for conducting laser-based plant physiology

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ABSTRACT

Advanced technologies for improved nitrogen (N) fertilizer management are paramount for sustainably meeting future food demands. Green laser systems that measure pulse return intensity can provide more reliable information about foliar N than can traditional passive remote sensing devices during the critical early crop growth stages (e.g., before canopy closure when vegetation and soil signals are spectrally mixed) when further decisions regarding N management can be made. However, current green laser systems are not designed for agricultural applications and only employ a single green laser wavelength, which may limit applications because many factors that require normalization techniques can affect pulse return intensity. Here, we describe the design of a tractor-mountable, green (532 nm)- and red (658 nm) dual wavelength laser system and evaluate the potential of an additional red reference wavelength to improve laser based estimates of foliar N by calculating laser spectral indices based on ratio combinations of green laser return intensity (GLRI) and red laser return intensity (RLRI). We hypothesized that such laser spectral indices aid in accounting for factors that confound laser based foliar N estimates including variations in leaf angle, measurement distance, soil returns, and mixed edge returns. Leaf level measurements in winter wheat (*Triticum aestivum*) revealed that the two laser spectral indices improved the relationship with foliar N ($r^2 > 0.71$, RMSE < 0.28%) compared to the sole use of GLRI ($r^2 = 0.47$, RMSE = 0.38%). Laboratory measurements also showed that laser spectral indices reduced the effect of measurement distance on laser readings and allowed leaf returns to be better separated from edge returns and soil returns. However, laboratory measurements showed that laser spectral indices did not account for variations in leaf angle, possibly explaining the weak relationships ($r^2 < 0.36$, RMSE = 0.49%) between foliar N and laser spectral indices observed when employing the laser system under field conditions. In fact, the strongest relationship at the field canopy level was shown for GLRI ($r^2 = 0.65$, RMSE = 0.37%) alone. Laboratory measurements suggest that the better performance of GLRI compared to ratio-based laser spectral indices may result from pronounced differences in the leaf-level bidirectional reflectance distribution factor ($BRDF_{leaf}$) between the green and red laser wavelengths, thus confounding leaf angle effects so that they are not cancelled when calculating laser spectral indices. This finding suggests that the small spot size of the laser pulses (⩽5 mm diameter) interacts with $BRDF_{leaf}$ at very fine scales, therefore causing differential, wavelength-specific scattering effects. Additional study of $BRDF_{leaf}$ at the mm scale is therefore warranted, and should be carefully considered in future development and use of multi-wavelength laser systems for remotely sensing foliar biochemistry.

1. Introduction

Improved nitrogen (N) fertilizer management will play an important role to sustainably meet future food demands (Mueller et al., 2012). Inefficient use of N fertilizer not only reduces farmer economic returns, but also adversely affects the environment. Recently, it has been estimated that 11 million tons of N fertilizer could be saved annually while maintaining yields (Mueller et al., 2012). Some of these fertilizer savings could be accomplished with tractor-mountable, optical remote sensors that dynamically sense crop N requirements to inform N management decisions (e.g., Samborski et al., 2009). This commercially available technology

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relies on reflectance readings in the visible and NIR portions of the spectrum to calculate spectral indices that are sensitive to variations in foliar chlorophyll content which, in turn, have been shown to be highly correlated with foliar N content (Evans, 1983; Karele, 2001).

Though foliar N content and spectral indices correlate strongly in dense crop canopies (Hansen and Schjoerring, 2003; Eitel et al., 2008; Hatfield et al., 2008; Vigneau et al., 2011), correlations considerably weaken when examining plants during early crop growth stages when critical decisions regarding N management can be made (e.g., topdressed N) (Eitel et al., 2011a). This is caused by the relatively large field of view (>50 cm^2) of traditionally used hyper- and multispectral sensors that, during early crop growth stages, can be dominated by the soil spectral reflectance. Despite the advent of various soil adjustments in calculating vegetation indices (e.g. Huete, 1988), the mixed spectra make it difficult to isolate the vegetation reflectance signal from the total measured reflectance signal, which are convolved within the sensor field of view.

The utility of laser sensors has been recently demonstrated to circumvent the spectral mixture problem in plant canopies (Eitel et al., 2011a; Eitel et al., 2014). Lasers have a small target instantaneous field of view (i.e., 'footprint' on the order of several mm^2 to a few cm^2) and are capable of acquiring thousands of measurements per second. The small footprint increases the likelihood that a laser pulse either hits only vegetation or soil. The pure vegetation return signals can then be separated from soil return signals by using simple thresholds (Eitel et al., 2011a; Höfle, 2014). Strong correlations have been observed between the return intensity of a green (532 nm) scanning laser and foliar chlorophyll concentration ($r^2 = 0.77$) of tree saplings (Eitel et al., 2010). Foliar N concentration of wheat has also shown strong correlation ($r^2 = 0.68$, RMSE = 0.30 $\mu g\ g^{-1}$) with the return intensity of a green scanning laser (Eitel et al., 2011a). Recent findings further show that the return intensity of a green scanning laser provides useful information about plant photoprotective mechanisms across a range of species (Magney et al., 2014). Obtaining information about photosynthetic performance at the fine, 3-dimensional scales afforded by laser instruments could ultimately help to diagnose photosynthetic downregulation as a function of different environmental stressors across a wide range of plant canopy conditions because damage to the photosystem often occurs during early stages of stress (Maxwell and Johnson, 2000). Besides relatively recent findings indicating the usefulness of lasers for mapping foliar biochemistry (e.g., Eitel et al., 2011a, 2011b; Gaulton et al., 2013; Danson et al., 2014), laser technology is routinely used to obtain plant structural information (e.g., Lovell et al., 2003; Clawges et al., 2007; Ehlert et al., 2009; Hosoi and Omasa, 2009; Long and McCallum 2013; Zheng et al., 2013).

Though the above findings for conducting laser-based plant physiology are promising, the laser sensor used for the aforementioned studies is not designed to be operated from a moving platform or under harsh field conditions. Consequently, the system could not be operationally used in precision agriculture where dynamic sensing of crop fertilizer requirements is required on a tractor to dispense the appropriate amount of fertilizer in real time. Another major limitation of the sensor technology used by the above studies is that the laser sensor only employed a single, green laser wavelength. As a result, the laser return intensity is strongly affected by the distance between the laser and the measured object. With increasing distance, the laser return intensity decreases in accordance with the inverse distance square law of light, complicating interpretation of the laser return signal. Interpretation of the laser return signal intensity is further hampered by variations in leaf angle that affect the angle of incidence. Even for the same leaf, varying amounts of light can be reflected back to the laser instrument depending on the incidence angle (Eitel et al., 2010). Another complicating factor that confounds the laser return intensity signal occurs if the laser pulse is split at the edge of a leaf so it may strike two or more objects (Hebert and Krotkov, 1992; Tuley et al., 2004). In such cases, the returned laser return signal integrates the reflectance signal of the fore- and background object(s). The resulting returns are known as "mixed edge returns" (also known as mixed pixel, ghost return, or air return) where the recorded intensity signals derive from two or more surfaces at different distances away from the sensor. The confounding effects caused by the inverse distance square law of light, mixed edge returns, and angle of incidence could potentially be reduced by using a two-wavelength laser system (Eitel et al., 2011a; Gaulton et al., 2013; Eitel et al., 2014).

The availability of two or more lasers with different wavelengths that simultaneously measure a given point allow the calculation of return intensity ratios, where complicating effects can be partially (or completely) cancelled if the return intensity of both wavelengths is similarly influenced by the given effect (Gaulton et al., 2013). For example, with increasing distance between the sensor and the object, the laser return intensity of both laser wavelengths theoretically decrease in a similar fashion and hence would not affect their ratio. Further, the use of two or more wavelengths might increase the spectral separability of vegetation laser returns from soil returns and mixed-edge returns.

Recently, several prototypes of multi-wavelength (Rall and Knox, 2004; Tan et al., 2005; Wei et al., 2012; Gaulton et al., 2013; Danson et al., 2014) and hyperspectral (e.g., Chen et al., 2010; Hakala et al. 2012) laser systems have been developed for monitoring vegetation and their promise for remotely sensing foliar biochemistry has been demonstrated by laboratory (Gaulton et al., 2013) and modeling studies (Morsdorf et al., 2009, 2010; Woodhouse et al., 2011).

To date, however, we are not aware of a rugged, tractor mountable, multi-wavelength laser system designed for the remote sensing of foliar N to support N management decisions. Our objective is thus to describe the design of a tractor-mountable, green (532 nm) and red (658 nm) laser system and conduct initial tests to evaluate its ability to remotely estimate foliar N. For the latter, we tested the following 4 hypothesis:

When compared to a single wavelength system, laser indices derived from green and red laser return intensity will

(1) provide crop foliar N predictions that are more accurate than single-wavelength laser techniques, by
(2) improving the spectral separablity of ground vs. vegetation returns,
(3) reducing confounding effects caused by the inverse distance effect of light, and
(4) reducing confounding effects caused by the variations in the angle of laser incidence.

Given that lasers are routinely used to obtain information about plant structure, this study only focuses on the novel use of the beam return intensity of multi-wavelength laser systems for mapping foliar biochemistry.

2. Sensor design and methods

2.1. Sensor design

The Green Economic Chlorophyll Observation (GECO) sensor (GECO – the Project, Germany; Patent DE 10,010,034 603) employs two, eye-safe laser diodes (Laser class 2); a green (532 nm) laser (Flexpoint FP-53/10AAF, Laser Components GmbH, 82133 Olchingen, Germany) and a red (658 nm) laser (Flexpoint FP-66/20AAF,