HAND-HELD SENSOR FOR MEASURING CROP REFLECTANCE AND ASSESSING CROP BIOPHYSICAL CHARACTERISTICS

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ABSTRACT

Crop vigor is difficult enough to define, let alone characterize and conveniently quantify. The human eye is particularly sensitive to green light, but quantifying subtle differences in plant greenness is subjective and therefore problematic in terms of making definitive management decisions. Plant greenness is one component of crop vigor and leaf area index or the relative ability of the crop to capture solar energy is another. It is well documented that reflectance of red light is a good way to quantify plant chlorophyll content until the canopy approaches closure. Once the canopy closes, red light reflectance remains very low and thus is no long responsive to changes in plant chlorophyll content. Reflectance in the red-edge region of the spectrum has been shown to be quite sensitive to canopy chlorophyll content over a wide range of biomass conditions. Canopy biomass is best quantified by measuring near infrared (NIR) reflectance. In a practical sense, NIR reflectance quantifies the size of the photosynthetic factory while red and red-edge reflectance collectively characterize how fast the factory can operate. The three-band (red, red-edge, and NIR) hand-held RapidSCAN CS-45 crop canopy sensor was developed to address these needs. The basic optical design was brought forward from the active three-band Holland Scientific Crop Circle ACS-430 sensor. The hand-held version provides a long-life lithium battery, internal GPS, large display and data storage capacity, and convenient data transfer into Microsoft Excel. Additionally, the versatility and autonomy of the RapidSCAN sensor has extended its usefulness to other applications such as unmanned aerial vehicles (UAV). Internally, the software calculates red, red-edge and NIR reflectance, NDVI and NDRE vegetation indices and various statistical values for scanned plant canopies as well as calculating plant biophysical properties or computing nutrient rates based on mathematical models. In practice, the sensor makes it possible for producers and consultants to scan crops to make fertilizer N recommendations, assess forage biomass, estimate yield, estimate crop leaf area and geospatially map agricultural landscapes.

Keywords: Vigor, Active sensor, N recommendation, RapidSCAN, NDVI, NDRE, side-dress, red-edge, chlorophyll, yield estimation, leaf area index, crop mapping, UAV

INTRODUCTION

The challenge facing grain- and oil-crop producers domestically and abroad is how to optimize profitability in their operations while improving sustainability. Nutrient use efficiency and environmental contamination are long-standing concerns of farmers and consumers alike. Algal growth in ponds and lakes and the existence of hypoxic conditions in bays and oceans that receive water from municipal and agricultural sources serve to raise awareness of these problems. Not only does this contamination pose a potential cost to society and fishery-related enterprises, but nutrient losses represent a real cost to producers. Unfortunately, the technologies and management options are not equally available to all producers. Those who can distribute the additional cost of improved management and new technologies over a larger operation can better absorb these costs and even increase profitability. As such, technologies available to large producers to assess crop vigor are not geared for implements used by small and mid-sized operations because of scale and cost. Considering that ~70% of fertilizer nitrogen applied to crops is made by small and mid-sized farming and ranching operations, it is appropriate that this group of producers have access to similar technologies as large producers, but scaled for the size of their implements and fields. New technologies like Holland Scientific's RapidSCAN CS-45 crop sensor and others can provide small and mid-sized producers access to these precision agriculture tools. Tools such as these can provide the small and mid-sized farmer with valuable information regarding crop nutrient and health status needed in order to make informed decisions regarding the management of their agricultural operation. However, data produced by these instruments are generally in the form of simple vegetation indices and require post-processing of data in order to effect a calibration and/or deployment as a canopy diagnostic tool. Users of these technologies have expressed the need for active optical sensor (AOS) instruments (Holland et al., 2012) to provide approximated data calibrated in agronomical units, for example, biomass in tons per hectare, kg N per hectare, approximate yield, leaf area index (LAI) units, etc. plus some basic statistical calculations pertaining to the crop canopy structure. To address this need, a new software ecosystem for the RapidSCAN CS-45 has been developed. The RapidSCAN CS-45 is a small, hand-held instrument that is composed of a polychromatic light source and three spectrally sensitive photo-detectors (670 nm, 730 nm and 780 nm) with an embedded microcontroller that coordinates data collection, geospatial location, data storage, in-situ configuration of an agronomic mathematical model and data transfer. A modular software design approach facilitates configuring the sensor to accommodate user needs. Application operating system (OS) modules have been developed for biomass predication, N rate recommendation, plant vigor assessment, and yield prediction using point and scan data collection procedures; overviews of which will be discussed below as well as the sensor's hardware architecture.

Currently, scientific instrument developers and manufacturers supply crop and plant canopy measurement instrumentation that performed fixed or dedicated measurements (e.g., LAI meters, PAR meters, NDVI meters, chlorophyll meters, etc…). While these instruments generally perform accurate measurements relative to their intended purpose, users quickly discover that as the number and type of measurements required increased during the course of a field season, a separate instrument is needed to perform the new measurement and that, subsequently, procurement costs, learning curves and maintenance time increased as well. Often times, the data collected by these instruments can be utilized to estimate other biophysical crop parameters without the need to purchase an additional instrumentation; however, manufacturers of these instruments do not provide a convenient way in which the end-user can readily use these data. As such, a single instrument with the flexibility to change its operational mode could easily perform multiple field measurements for closely related measurements. The authors' intent for this paper is to present a sensing platform concept that can be easily reconfigured via software to provide a number of useful biophysical measurements without the need to procure/acquire additional hardware by the end-user. The design approach utilizes the concept of using a single hardware platform that can re-programmed to make multiple crop-based measurements.

SENSOR PLATFORM ARCHITECTURE

The RapidSCAN CS-45 is shown in Figure 1. The sensor is ergonomically designed for ease-of-use and is light in mass, nominally 0.7 kg. In Figure 2, a block diagram of the RapidSCAN CS-45's instrumentation hardware design is shown. The sensor is composed of a microcontroller that coordinates optical-sensing data collection and storage, a power management controller that performs battery charging and monitoring as well as system voltage conversion, a GPS sensor for geospatial data location and a user interface (display and keypad). The optical component of the RapidSCAN CS-45 has been pulled forward from Holland Scientific's Crop Circle ACS-430 three-channel AOS. The RapidSCAN simultaneously collects spectral reflectance data for the red (670nm), red-edge (730nm) and NIR (780nm) spectral bands. The light source is a polychromatic lamp that simultaneously emits light in each of these spectral bands. Detection is performed synchronously in accordance with light source modulation and measured irradiance values are converted to reflectance values spanning from 0 to 100%. The NDVI and NDRE vegetation indices are computed from these reflectance values. Data are stored in a 32Mb nonvolatile memory. The RapidSCAN CS-45 contains sufficient memory to store over 15,000 canopy scans (NDRE, NDVI and reflectance) including geospatial data and descriptive statistics for each scan.

The RapidSCAN's GPS receiver utilizes a SiRFStar IV core with high sensitivity low noise amplifier (LNA); -160dB, tracking. A ceramic patch antenna (RHCP) is connected to the GPS's core's LNA and provides ~5dBic of gain at zenith with a center frequency of 1581 MHz and a bandwidth of 15 MHz. The GPS core has EGNOS, WAAS, GAGAN and MSAS capability embedded with correction of positional errors due to ionospheric and orbital disturbances. Overall spatial accuracy is typically less than 2.0 meters.

The RapidSCAN's power source is a 4.2-volt lithium, polymer cell. The cell can power the instrument for over 20 hrs of operation. A power management controller supervises cell charging and charge termination. Instrument recharging is performed using either a 5 -voltage USB wall charger or a USB port from an active (powered ON) PC USB port. A typical charge cycle can last up to 5 hours depending on the discharge state of the lithium cell.

Figure 1. RapidSCAN CS-45 handheld crop scanner.

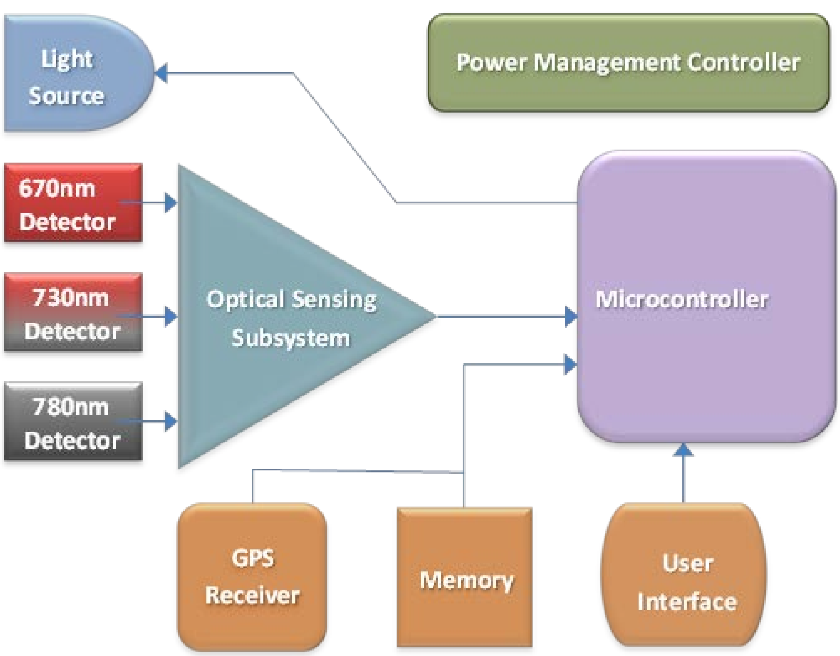

Figure 2. RapidSCAN CS-45 system block diagram.

SOFTWARE APP ECOSYSTEM

The RapidSCAN software application (app) ecosystem consists of seven software apps, see Figure 3. These apps include: Point-and-Scan, N-Rec Split, N-Rec Dose, GeoLog, LAI Estimator, Yield Estimator and Biomass Estimator. Each application is uploadable to the RapidSCAN using an app manager called RapidAPP. RapidAPP negotiates software transfer, configuration parameters and registration codes with the RapidSCAN sensor via a USB serial connection. While all of these potential applications could potentially be integrated into one extensive app, multiple apps were designed so as to maintain ease-of-use by minimizing each app's learning curve and by reducing the degree of complexity of the user interface. Details for each app are described in the following.

Point-and-Scan App

The Point-and-Scan app is the foundational application for the RapidSCAN sensor. It provides a means for scanning plant canopies and computing NDVI and NDRE vegetation indices. The user has the option of enabling the computation of descriptive statistics, reflectance logging and the logging of geospatial information. The statistics that are computed for each scan include: coefficient of variation, standard deviation, maximum, minimum, average and number of samples taken (N). Geospatial data include: latitude, longitude, UTC time, UTC date, horizontal dilution of precision (HDOP), elevation and fix type.

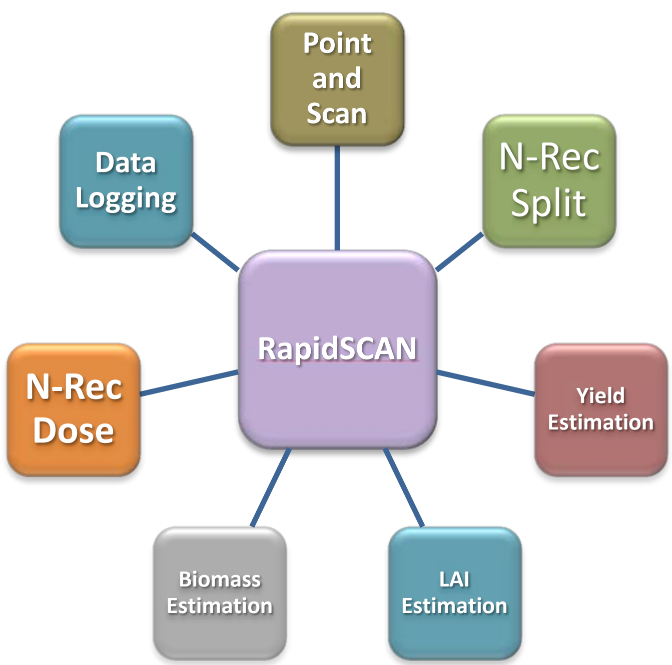

Figure 3. RapidSCAN app ecosystem. The Apps for the RapidSCAN are uploaded to the instrument using RapidTALK communication software.

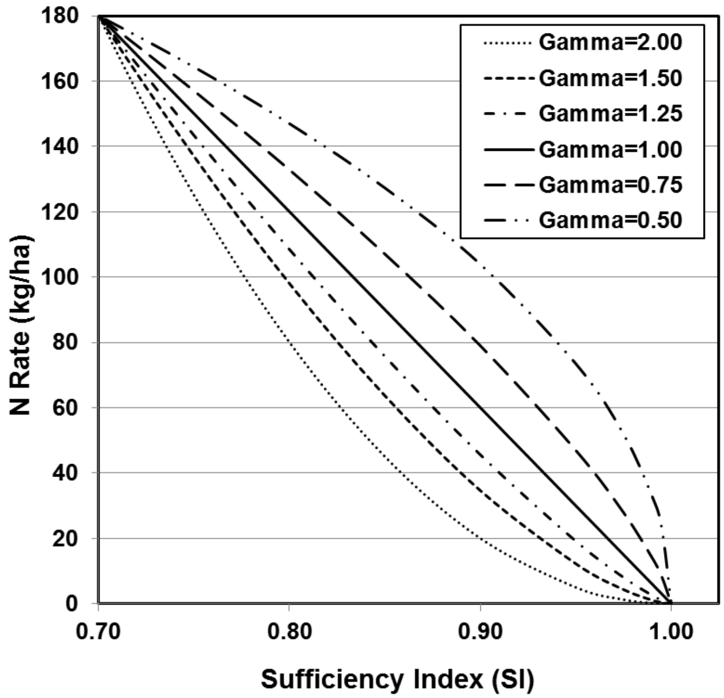

Figure 4. Multiform model response for various values of gamma.

N-Rec Split App

The N-Rec Split app allows a user to estimate the nutrient requirements of a crop for split-N rate applications. This app utilizes the γ-multiform N-rate growth response model to estimate N rate (Holland, 2014). The N rate response curves are shown in Figure 4 for various values of gamma. Calibration is based on the sufficiency index approach where a portion of the crop deemed to have adequate nutrient supply is measured to establish a "reference" for calibration of the nutrient response model. In practice, the N-Rec app makes it possible for producers and consultants to scan the crop and make fertilizer N recommendations without the use of additional computational devices. The procedure is to scan an area that is deemed to have adequate N at that growth stage and use that vegetation index as the reference when evaluating the N status of other parts of the field (Holland, 2007; Holland and Schepers, 2011; Holland and Schepers, 2013). The resulting ratio of sensor readings (managed/reference) describes a parameter called the sufficiency index. Producers provide the minimum and maximum N rate to set the bounds of the algorithm that is used to calculate an N fertilizer rate. The RapidSCAN sensor is not designed to drive a variable flow-rate controller as is possible with the AgLeader OptRx(TM) system, however, data collected by the RapidSCAN is compatible and comparable to data collected by the OptRx(TM) system.

The parameters for the N rate model are:

$$N_{RATE} = f(VI, N_{OPT}, N_{MIN}, N_{CRED}, \gamma, B_{OFF})$$

where VI is the vegetation index used for N-rate calculations, NDVI or NDRE, N_{OPT} is the agronomic or economic optimum N rate in kg/ha or lb/ac, N_{MIN} is the minimum N rate to be recommended via the algorithm in kg N/ha or lb N/ac, N_{CRED} is the N credit for the previous season's crop, nitrate in water, or manure application, γ is the model curvature parameter, $0.33<\gamma<3$ and B_{OFF} is the N-rate application back off scalar for unrecoverable crops, where $B_{OFF} \in$ {None, Low, Medium, High}.

Values for gamma less than unity will produce curves that have downward concavity and gamma values greater than unity will create response curves that have upward concavity. A gamma value of unity results in a linear function. It should be noted, that when the gamma parameter is set to 0.5, the γ-multiform model becomes the Holland-Schepers N-rate model (Holland and Schepers, 2010). With regard to the back-off scalar, this parameter is utilized to reduce applied N for crops that are unable to recover even if adequate N were applied. Selecting the 'None' option turns this function off, whereas a selection of 'High' will cause the calculated N rate to be reduced greatly compared to the normally recommended application rate.

N-Rec Dose App

The N-Rec Dose app allows a user to estimate the nutrient requirements of a crop using multiple N applications (dosing). The algorithm was developed primarily for European wheat and barley production (Holland, 2007; Holland and Schepers, 2011; Holland and Schepers, 2013). The N-rate growth response model is customized to the crop's biomass response to nutrients in that the producer sets a target N rate ($N_{PLANNED}$) that is required to achieve a desired biomass or target LAI. The growth response model modifies this N rate due to changes in crop biomass using sensor readings. The procedure to use this app is to scan an area that is deemed to have average biomass and use the resulting vegetation index as the reference when evaluating the N status of other parts of the field. The resulting ratio of sensor readings (managed/reference) describes a parameter called the median index. Producers provide the planned N rate, number of applications, back-off scalar, trend (defined below) and optimal N rate to set the bounds of the algorithm that is used to calculate an N fertilizer rate.

The parameters for the N rate model are:

$$N_{RATE} = f(VI, N_{Planned}, k, S, N_{OPT}, n, B_{OFF})$$

where VI is the vegetation index used for N-rate calculations; NDVI or NDRE, $N_{PLANNED}$ is the producer rate to be applied to the field, k is the trend scalar; $k \in \{-1,+1\}$, S is the growth/crop sensitivity coefficient; $-3<S<3$, (typically set to 2) N_{OPT} is the season total optimal N rate, n is the number of applications during the field season and B_{OFF} is the N-rate application back off scalar for unrecoverable crops; $B_{OFF} \in$ {None, Low, Medium, High}.

The trend parameter is utilized to set the direction of N application relative to changes in crop biomass. When the trend value is +1, the model applies more N to crops that have low biomass and conversely when the trend is -1. The sensor controlled N rate is set using the N_{OPT} and n parameters (N_{OPT}/n). With regard to the back-off scalar, this parameter is utilized to reduce applied N for crops that are unable to recover even if adequate N were applied. Selecting the 'None' option turns this function off, whereas a selection of 'High' will cause the calculated N rate to be reduced greatly compared to the normally recommended application rate.

GeoLog App

The GeoLog app allows a user to continuously collect real-time data for creating geospatial maps of an agricultural landscape. The GeoLog app can be configured to log data at 2.5 samples per second (sps), 1 sps, 0.5 sps or 0.2 sps. With respect to sensor deployment, the sensor can either be carried by hand or mounted to a vehicle when mapping a field. A unique property of the RapidSCAN also allows it to be utilized in unmanned aerial vehicle (UAV) applications. Because the RapidSCAN is a self-contained measurement system, that is, the sensor contains all the necessary components to measure, log, georeference sensor data and power itself, it is readily adaptable for small UAV applications. Because of its low mass (~0.5 kg, without handle), the sensor can be easily deployed for aerial surveys up to 1 hr depending on the size of the small UAV. Figure 5a shows a photo of the RapidSCAN fitted with a 3-D printed UAV mount and Figure 5b shows deployment of a RapidSCAN on a multi-rotor UAV.

(a) (b)

Figure 5. RapidSCAN modified for UAV use (a). The RapidSCAN handle was replaced with 3-D printed mounting platform. The platform can be easily customized for adaptation to an end-users UAV rigging. RapidSCAN deployed on octocopter (b). The RapidSCAN has an effective sensor-to-target range of 0.5 to 4+ meters.

LAI Estimator App

The LAI Estimator app allows users to estimate the leaf area of a crop using NDRE and NDVI vegetation indices. The leaf area can be estimated based on NDVI measurements using the equation

$$LAI = k \times ln(1 - VI)$$

where LAI is the leaf area index, k is a canopy specific proportionality coefficient ($-6 < k < -2$) and *VI* is the vegetation index, in this case, NDVI.

It should be noted, the above equation was derived from Beer's law for light extinction through a canopy structure (Jones and Vaughan, 2010). Values for coefficient k are highly species and variety dependent. The equation above results in reasonably accurate measurements of LAI up to 3 to 4. For LAIs above 4, other techniques must be utilized to transform sensor data into reasonable estimates for LAI. The RapidSCAN utilizes a proprietary model to extend the usable LAI range past an LAI of 4. Currently, the RapidSCAN has coefficients for estimating the LAI of wheat, corn and soybean. Figure 6 demonstrates the LAI model's performance with respect LAI estimation for wheat canopies having LAIs up to 8. (The model was tested using a Crop Circle ACS-470 versus data collected with a Sunscan LAI meter (Delta-T Devices, Cambridge, UK)

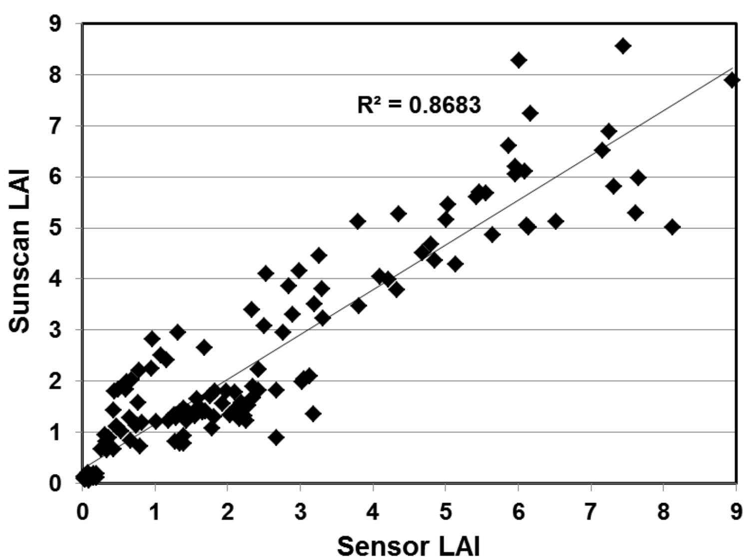

Figure 6. LAI model performance for wheat canopies. The data were collected using a Holland Scientific Crop Circle ACS-470 sensor fitted with 670 nm, 730 nm and 780 nm filters.

Yield Estimator App

The Yield Estimator app allows a user to estimate maize yield over the growth stages spanning from V5 to V14. The app uses a generalized yield estimation model based on the sufficiency index concept. Although the model was developed primarily for maize, it is anticipated that this model can be used for all crops that have strong yield dependence to applied nutrient. The yield model implemented in this app may potentially provide powerful in-season estimations of a crop's future performance. This data can be used for logistical estimations or for estimating crop losses due to natural disasters such as hail, drought, etc… It may also be utilized by government authorities or financial markets to predict potential surplus or deficits of grain.

The parameters for the yield estimation model are:

$$Y_{Estimated} = f(VI, Y_{MAX}, \alpha, B_{OFF})$$

where VI is the vegetation index used for N-rate calculations; NDVI or NDRE, Y_{MAX} is the estimated maximum yield for the crop, α is the estimated ratio of minimum yield to maximum yield; typically $0.2<\alpha<0.7$ and B_{OFF} is the yield back-off scalar for poor performing crop; $B_{OFF} \in$ {None, Low, Medium, High}.

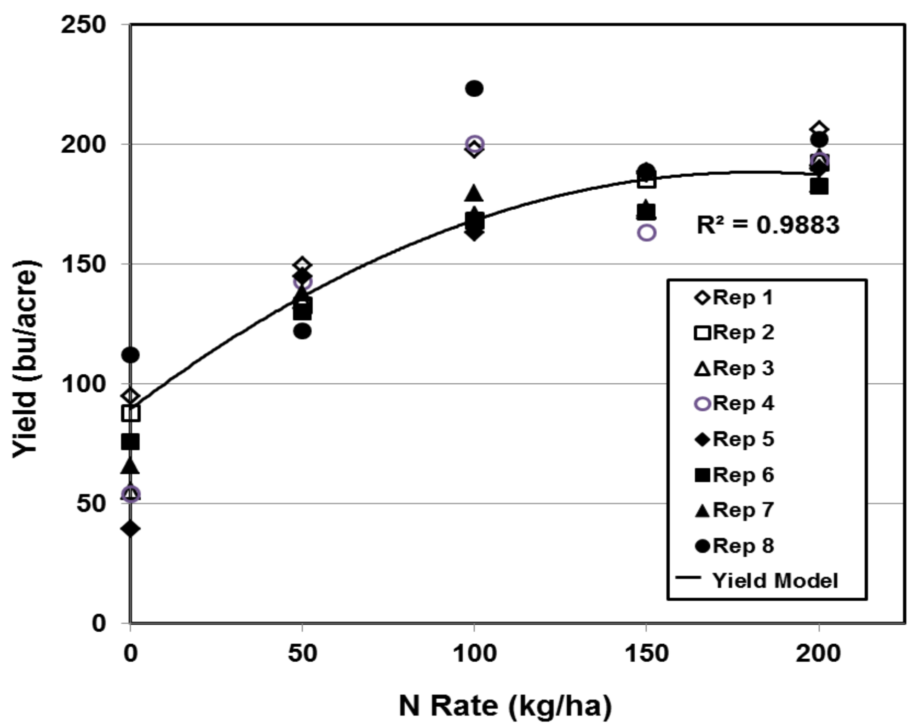

Figure 7. Yield rate model compared against maize N rate study with eight replications. Data were collected using a Holland Scientific Crop Circle ACS-470 sensor. The irrigated maize was at the V9 growth stage. The coefficient of determination was determined using the mean of the eight replications.

Figure 7 shows the performance of the yield model for data collected using an NDRE vegetation index, an α equal to 0.5, B_{OFF} set to 'Medium' and Y_{MAX} equal to 190 bushels per acre. The model was compared to a study with eight N-rate maize replications. Note, when Y_{MAX} is set equal to unity, the yield estimation model computes a relative yield or what might be considered an estimate of crop vigor.

Biomass Estimator App

The Biomass Estimator app allows the user to make calibrated forage ($F_{Estimated}$) biomass estimations. The model was developed using European wheat canopies. Fresh weight biomasses for the model ranged from 1 to 37 t/ha.

The parameters for the biomass estimation model are:

$$F_{Estimated} = f(T_{MAX}, S_{TRIM})$$

where T_{MAX} is the estimated maximum fresh weight biomass for the forage in t/ha and S_{TRIM} is the low biomass calibration adjustment value.

Figure 8 shows the performance of the model on wheat. Of the models that were developed for the RapidSCAN, the biomass estimator proved to be the most difficult to develop. This is, in part, due to the fact that estimations for mass were done by proxy via canopy chlorophyll content and LAI estimations. More testing is required for other types of forage crops in order to establish the effectiveness of this model.

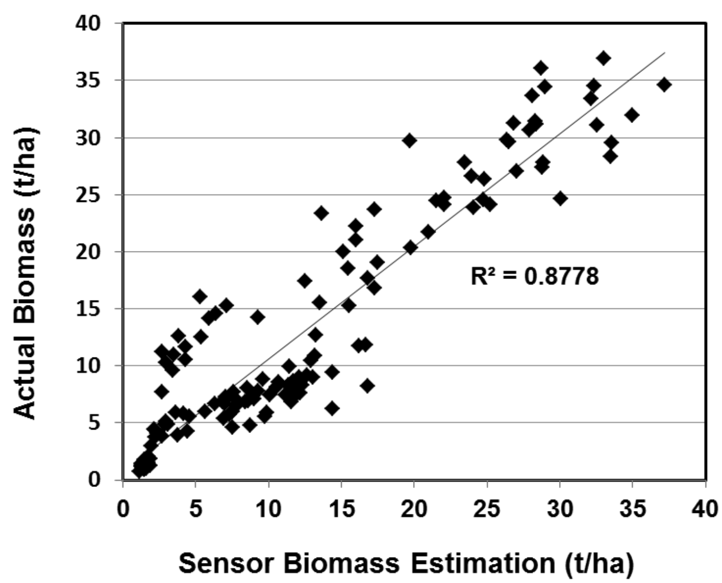

Figure 8. Sensor biomass estimation versus actual fresh weight (FW) biomass. Sensor model utilizes red, red-edge and NIR spectral bands.

CONCLUSION

A new type of multi-measurement remote sensing platform has been presented in this paper that allows a user to reconfigure the sensor's measurement mode by uploading specialized software apps that are dedicated to particular types of measurements. What enables a single instrument to make varied plant physiological and agronomical measurements and estimates, without modifications to the instrument's hardware, is that each measured/estimated biophysical property is fundamentally related to the spectral reflectance characteristics of the crop canopy. Apps for the sensing platform developed thus far include estimators for LAI, biomass, nutrient and yield/vigor. Two other apps pertain to data acquisition of plant canopy reflectance, one for point-and-scan measurements and the other for real-time data logging.

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