History of Crop Canopy Sensors

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A patent search indicated that optical sensor technologies were developed by Ferte in 1939 for automatic weeding and thinning of crops like celery and sugar beets. In 1946, Marihart developed a more sophisticated optical sensor system that he attachment to a cultivator for plant thinning and weed removal. In 1954, he patented a pulse sprayer system that was triggered by an optical sensor. This system was intended for plant-specific application of herbicides to kill weeds or to selectively fertilize plants. Computers brought on an advanced generation of sensor technologies. This patented approach (1969) used a power-take-off (PTO) generator to power an on-board mini-computer that controlled an optical sensor that detected individual weeds and then synchronized a burst of spray onto the vegetation.

A major advancement in optical sensing was made in the late 1980s when an electronics engineer (James Beck) thought to be with National Semiconductors developed a unique phase-shift device and circuit to control the modulation of two synchronized circuits for red and NIR waveband reflectance measurements. The dual-modulated light source and single detector system, along with related microcircuits, was designed to detect vegetation that was out-of-place (weeds) and trigger directed spray of herbicide onto the vegetation. Beck formed the Patchen company and marketed the integrated device as the WeedSeeker. In mid-1995 the Patchen technology was purchased by Deere and Company.

Somewhat concurrently, a soil scientist (Bill Raun) at Oklahoma State University (OSU) was concerned about over-fertilization of wheat in cases where poor germination in the fall or winter-kill reduced plant density when it was time to fertilize the crop. Uniform fertilizer application in the spring was typical even when plant density was reduced. He enlisted the expertise of colleagues (engineers John Solie and Marvin Stone) along with support from the lawn and garden division of Deere and Company to develop a passive light sensor system to only apply fertilizer where there were living plants and at the proper amount to better utilize the fertilizer. Their sensor alternately monitored green and red wavebands with a single detector plus it included an ultrasound detector. Details of the sensor were published in 1996. Problems with variable cloud cover, shadows, and time-of-day issues limited this approach to quantify plant density.

In October of 1998, Deere and Company sold the Patchen technology to a regional John Deere dealer in Ukiah, CA. Concerned with ongoing sensor studies by the OSU research team to develop a crop sensor, the new owner of the Patchen patents and related technologies was concerned about competition by groups in Oklahoma and Australia. When confronted with the thought of potential patent infringement, Marvin Stone at OSU agreed to repackage the WeedSeeker technology into a machine-mounted sensor known as the GreenSeeker. This device was manufactured by NTech Industries, a subsidiary of the John Deere dealer, and commercially introduced and actively marketed by them beginning in 2001.

The resulting dual waveband / single detector plant canopy sensor (GreenSeeker) used modulated red and NIR light sources. The operation of the sensor is based on the phase-shift circuit patented by Patchen in 1994. Analysis and interpretation of sensor reflectance data were based on the normalized difference vegetation index (NDVI) that was developed in 1974 using red and NIR wavebands to quantify living biomass in forests. Scientists and graduate students at OSU conceptualized and developed a series of algorithms for making in-season N recommendations for a variety of crops. They patented four inventions in 2003-04. Over the next decade (roughly 2000-10), graduate students at OSU and other universities conducted a variety of studies to characterize the use of the GreenSeeker with different crops and test the conceptualized OSU algorithm. The strong association between red and NIR reflectance led to the popularity and success of the GreenSeeker in the marketplace but eventually led to its demise as will be discussed later.

Sensor development efforts in Nebraska originated with the need to address nitrate contamination of shallow groundwater. Previously (1984), the late Dr. Richard Hageman (a premier plant physiologist) commented to Jim Schepers that the best way to quantify crop vigor and manage nitrogen (N) was to measure plant chlorophyll content. Subsequent N-rate research with leaf punches to collect and measure leaf N concentration and chlorophyll content led to development of the ***sufficiency index*** concept that used N-rich plants as a reference. This approach for assessing crop N status worked well for scheduling fertigation of maize based on Minolta SPAD meter readings.

Efforts to mobilize chlorophyll measurements began in 1993 with testing of various optical devices. In 1995, Li-Cor agreed to modify an existing sensor to individually measure reflectance in the red, green, blue and NIR wavebands. These wavebands were combined into a single passive sensor that had limited application because of clouds, shadows, time-of-day, etc. In 1999, Kyle Holland, a former Li-Cor engineer, began to develop an active sensor that would be functional any time of the day. His design used modulated light from a single light source (amber LEDs) and multiple filters and detectors to monitor reflectance in desired wavebands. The first two-band sensor called the Crop Circle monitored amber and NIR reflectance. A later version used newly developed white LEDs to generate the light which made it possible to monitor red, red-edge and NIR reflectance.

Sensor development in Germany lead by Hermann Heege and Stefan Reusch was based on the shift in red-edge reflectance as crop vigor changes with concurrent increases in plant N and chlorophyll content. In about 2000, they developed the red-edge inflection point (REIP) concept for data analysis to quantify crop biomass and N status. They compared many of the standard vegetation indices and found that REIP was the most highly correlated with N supply. Their instrumentation used an elaborate system of spectrometers to monitor reflectance in visible and NIR wavelengths. They identified four wavebands in the red to NIR region of the spectrum for the REIP analysis. These data made it possible to characterize the shape and position (shift) in the red-edge region of the spectrum. They subsequently found that the simple NIR to red-edge ratio was superior to REIP to quantify the N uptake of wheat. These ratios (R730 / R780 or R760 / R730) are quite similar to those proposed by Anatoly Gitelson used in the chlorophyll index [(NIR/red-edge) – 1] The German sensor (N-Sensor) was mounted on the cab of a tractor and viewed obliquely to both sides. This sensor had the same passive light limitations as those developed in the U.S. but their work identified that red-edge reflectance effectively complimented NIR reflectance to quantify crop N status.

Hyperspectral sensors led to the development of many vegetation indices that were calibrated to individual data sets. Gitelson and colleagues suggested that green reflectance was highly correlated with red-edge reflectance. This information prompted NTech to replace the red LEDs in the GreenSeeker with green ones to generate a proxy for red-edge reflectance. The green LEDs had to be filed down to fit on the circuit board and the extra power requirement over-heated the circuitry and so the green version of the GreenSeeker was non-functional.

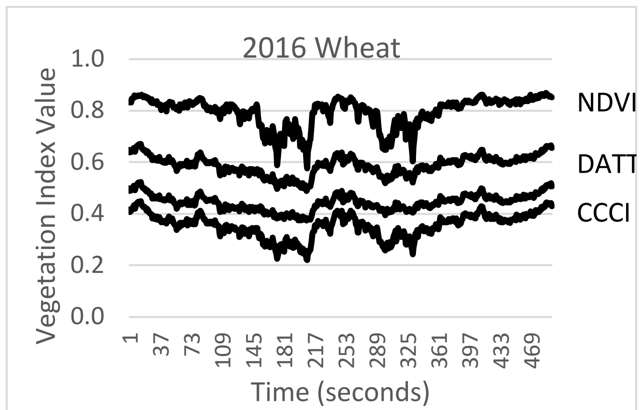
Holland Scientific introduced a commercial Crop Circle three-waveband sensor (red, red-edge, and NIR) in 2008. Somewhat before that time, NTech sued Holland Scientific for patent infringement to discourage competition. A basic review of the mechanical and optical sketches presented in the patents made it obvious that the two sensors were significantly different. Holland Scientific prevailed which was the beginning of the end for the GreenSeeker sensor. NTech tried to sell the patents and technology to sprayer, seed, and implement companies without success and ended up selling the technology to Trimble for the reported cost of the legal fees. Trimble redesigned some of the components and circuitry, modified the name (GreenSeeker2), and tested a prototype but abandoned the project because the new sensor would not effectively compete with the Holland Scientific sensors.

Orientation and position of sensors relative to the vegetation has a bearing on performance and sensitivity of sensors. The Crop Circle and GreenSeeker sensors modulate the light at `40,000 Hz and compile the reflectance values at 1 sec intervals, or more frequently. Each of these sensors was designed to have a unique footprint to accommodate the intended application. The footprint of the GreenSeeker is about 1.5 x 60 cm regardless of the distance above the crop target. The Crop Circle's footprint is variable depending on the distance from the target but has a ratio of about 1:5 (width to length). Both sensors are intended to be positioned about 60 cm above the crop (nadir) and oriented with the footprint transverse to the row direction. Crop Circle sensors are capable of collecting reliable reflectance data at various heights. This feature was demonstrated when Holland sensors were mounted on a drone and sprayer plane. At a height of 10 m when attached beneath a drone, the footprint is about 10 m wide to accommodate the width of a 12-row implement. The N-Sensor developed in Germany has a unique oval-shaped footprint on each side of the implement. The size of the footprint changes as the crop height increases. In contrast, the active sensors are positioned nadir to the canopy.

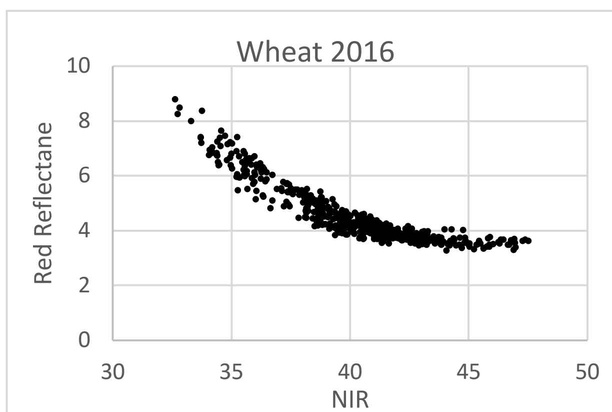
In defense of the GreenSeeker sensor, it satisfied Dr. Raun's objective to quantify plant density (vegetative cover) and his colleagues developed an impressive sprayer control systems for making variable rate fertilizer applications to wheat, especially for plot research and producer demonstrations. Their algorithm is linked to NDVI and predicts the difference in yield potential between an N-rich area and the area of the field in question. The amount of N contained in the yield difference plus a fertilizer inefficiency factor becomes the N recommendation. Their algorithms trend to under-apply fertilizer because they do not compensate for the extra N needed to build plant structure that must occur before the extra grain can be produced. The GreenSeeker strategy is also criticized because the crop's response to N fertilizer is based on previous cropping experiences (***response index*** vs. yield) from a variety of fields, locations, and undocumented weather conditions rather than being calibrated within the field in question and at the time of application. The ***response index*** is a non-linear coefficient that is the inverse of the linear ***sufficiency index*** developed for maize. A critical limitation of the GreenSeeker became obvious when NTech aggressively marketed the sensor system to maize producers without acknowledging that NDVI significantly loses insensitive after the crop canopy closes. Disillusioned maize producers contributed to the negative feeling about sensors in general. As an alternative, Holland and Schepers developed a universal algorithm that uses the ***sufficiency index*** concept and virtual reference approach to calibrate the algorithm to the producer's field situation rather than a designated N-rich area. This field specific calibration approach demonstrated that yield is highly dependent on soil N supply and fertilizer rate within a given field. In contrast, the OSU algorithm uses regional historic data (sensor and yield) to develop a general crop response function that is used to transform the sensor data into an N-rate recommendation. This regional dataset led them to conclude that yield is independent of fertilizer N rate, but should be expected unless soil properties, cultural practices, and weather conditions are documented and considered.

Researchers continue to use crop canopy sensors, hyperspectral scanners, cameras and multiband sensors attached to drones, high resolution cameras in aircraft, and satellite imagery to characterize and evaluate various aspects of vegetation. Over 100 vegetation indices have been developed around the world but only a few prevail for commercial agricultural applications because the readily available wavebands (blue, green, red, red-edge, and NIR) usually limit the vegetation indices to NDVI, NDRE, CI, DATT, MTCI, CCCI, and a few more. These two or three waveband indices are well documented in the literature and most use NIR reflectance as the primary component because it is indicative of living biomass and yield potential. Much of the initial research data used to develop and test these indices was generated from relatively small areas. Extending these indices to field strips where they can be compared side-by-side throughout the field illustrates the relative sensitivity of the indices to biomass changes and perhaps soil and landscape features that affect soil fertility status or water holding capacity.

The data in the adjacent figure was collected with a pair of Holland Scientific.430 active sensors while driving through a wheat field in the spring during tillering. It is commonly known that NDVI begins to saturate for values > 0.6 and the canopy is considered closed at 0.8. The trends were similar for these vegetation indices except for NDVI when values were <0.8. The red to NIR relationship at low NDVI is especially sensitive because as red reflectance decreases there would be a concurrent increase in NIR reflectance.



The scatter in the relationship shown in the figure on to right at low NDVI values (high red values) is because of variable ground cover. Perhaps the weakness in the relationship is also because young leaves at the top of the canopy contain juvenile chlorophyll that is not fully functional in terms of capturing red light, but is sufficiently viable to reflect NIR radiation. Bidirectional reflectance and a combination of leaf orientation and position could help account for this weak relationship. Having immature leaves at the top a plant canopy before the reproductive growth stages is a fact of life and needs to be considered with any type of remote sensing. SPAD meter users avoid this problem by sampling leaves that are fully matured (formed a collar around the stem in the case of maize) to avoid being misguided.



Numerous protypes of low-cost proximal sensors that mimic the output of commercial passive sensors have been developed and tested over the past decade, but low-cost facsimiles of active sensors are not yet commercially available because of the sophisticated electronics.