



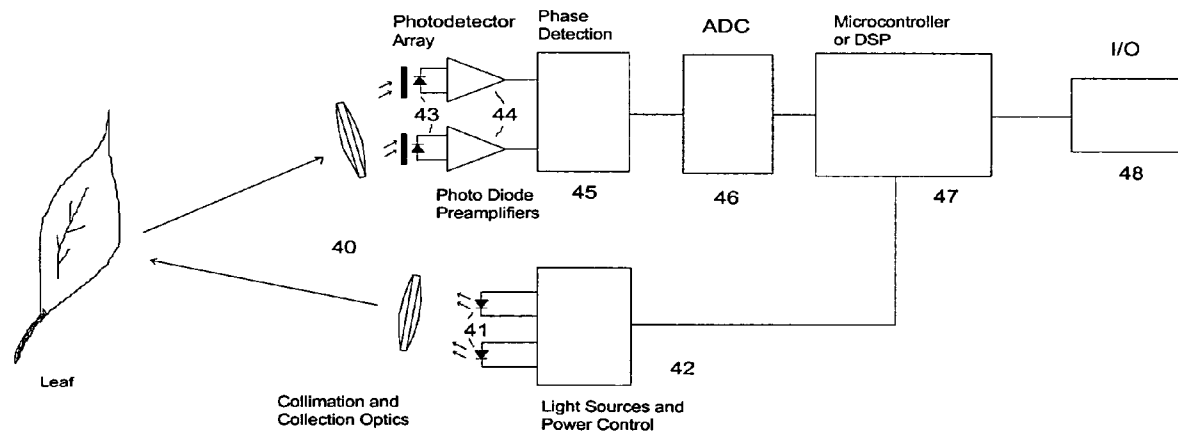
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(19) **United States**(12) **Patent Application Publication**
Holland(10) **Pub. No.: US 2006/0208171 A1**(43) **Pub. Date: Sep. 21, 2006**(54) **LIGHT SENSOR WITH MODULATED
RADIANT POLYCHROMATIC SOURCE**(76) Inventor: **Kyle Holland**, Lincoln, NE (US)

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SUITE 2500****DES MOINES, IA 50309-3993 (US)**(21) Appl. No.: **11/365,110**(22) Filed: **Mar. 1, 2006****Related U.S. Application Data**(63) Continuation-in-part of application No. 10/703,256,
filed on Nov. 7, 2003.**Publication Classification**(51) **Int. Cl.****G06M 7/00** (2006.01)**G01J 3/50** (2006.01)(52) **U.S. Cl.** **250/221; 250/226**(57) **ABSTRACT**

An apparatus is described for assessing plant chlorophyll content remotely sensed by the invention thereby allowing selective monitoring or treatment of individual plants. In one preferred embodiment, a polychromatic emitter provides light beams substantially in the red edge portion of a plant's reflectance spectrum. This light beam illuminates a surface area on the plant, which may be bare ground or plants. The beam of light may be focused, collimated or non-focused. A detector array, usually composed of an array of spectrally sensitive detectors, detects portions of this polychromatic light beam reflected by the surface area and provides a signal indicative of the change in chlorophyll status by determining the wavelength of the red edge inflection point REIP. In another preferred embodiment of the invention, an array of sequentially pulsed monochromatic emitters provides light beams having wavelengths substantially along the red edge portion of a plant's reflectance spectrum. These light beams illuminate a surface area on the plant, which may be bare ground or plants. The beams of light may be focused, collimated or non-focused. A photodetector detects the light reflected by the surface area and provides a signal indicative of the change in chlorophyll status by determining the wavelength of the red edge inflection point REIP. In both embodiments, a controller analyzes the resulting REIP wavelength and responds by activating a device to take some action with respect to the plant or stores the analyzed signal with corresponding DGPS position in the controller's memory for later analysis.

**Block diagram of typical sensor embodiment.**

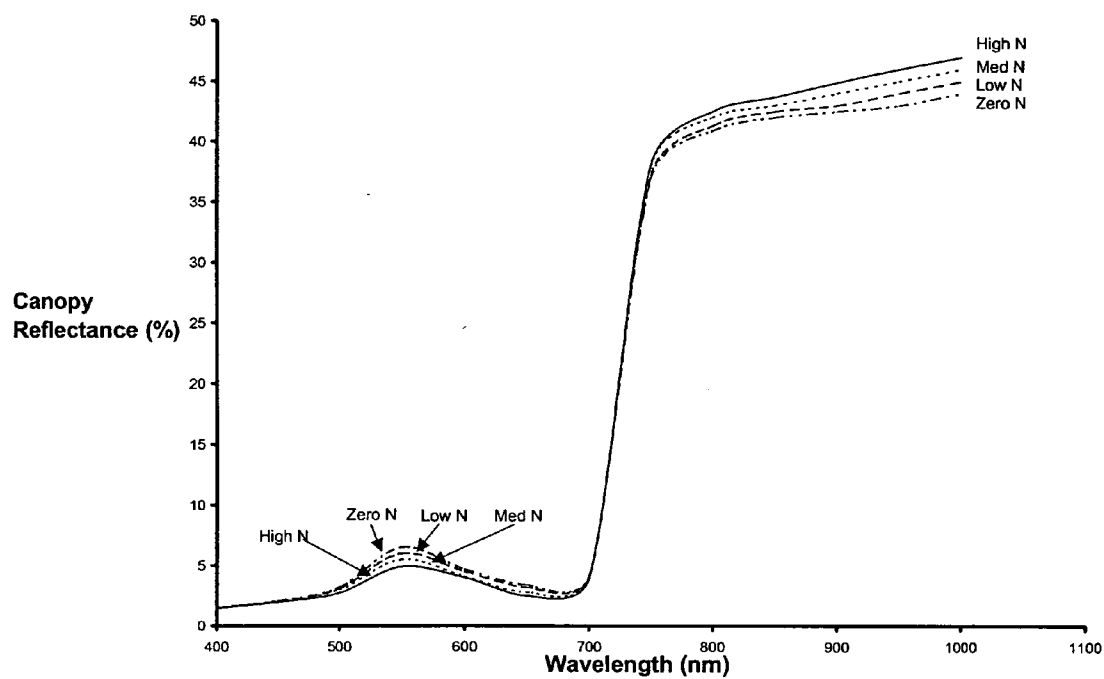


Figure 1. Vegetative reflectance curves for four different N-rates.

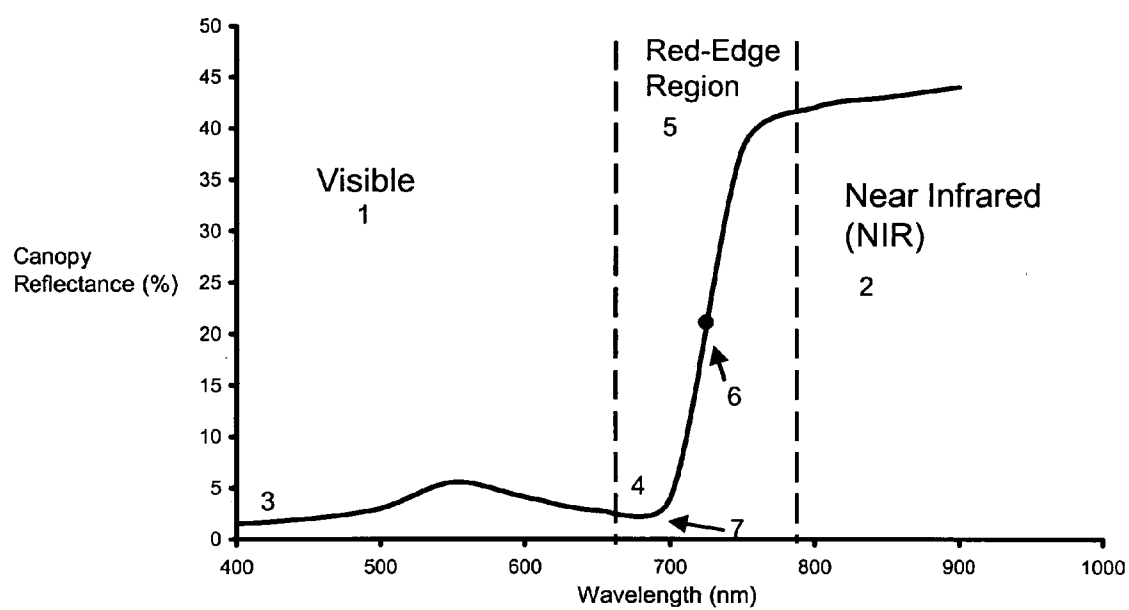


Figure 2. Vegetative reflectance curve.

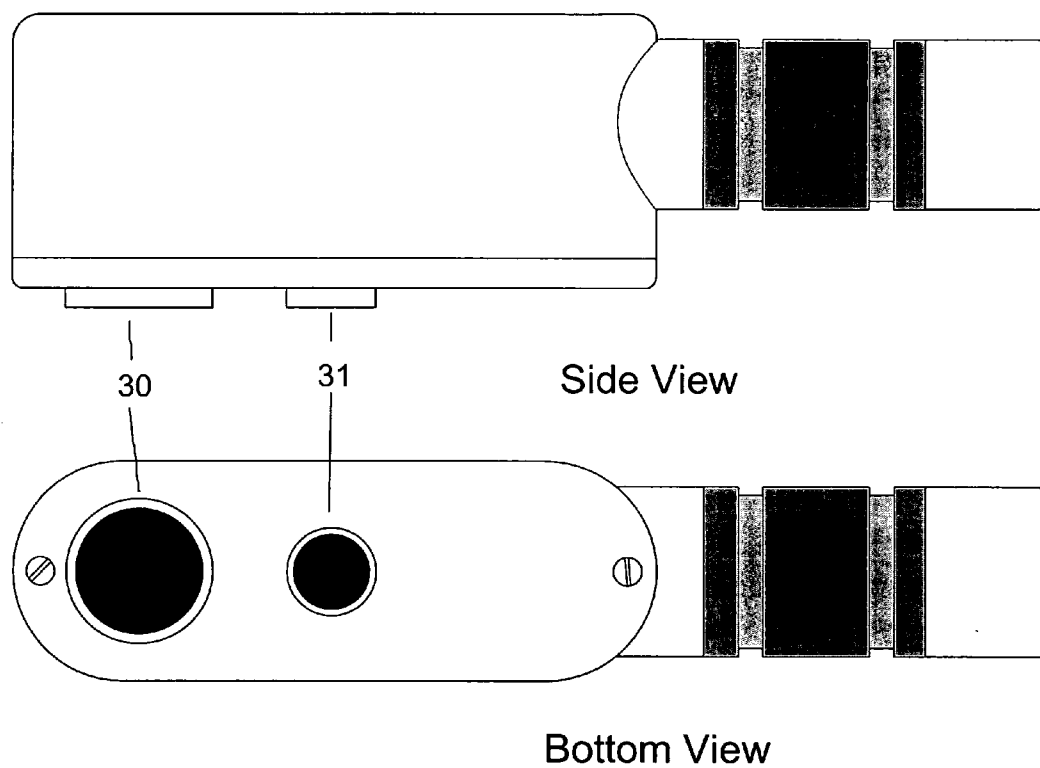


Figure 3. Sensor enclosure diagram.

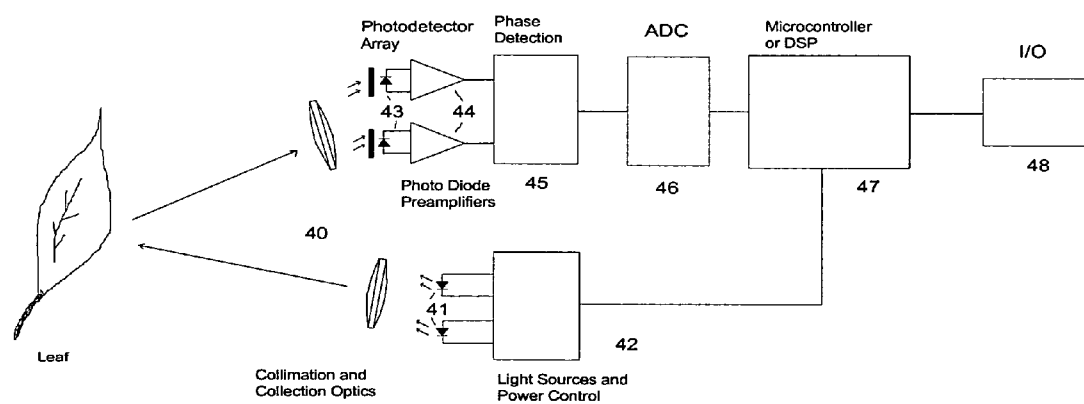


Figure 4. Block diagram of typical sensor embodiment.

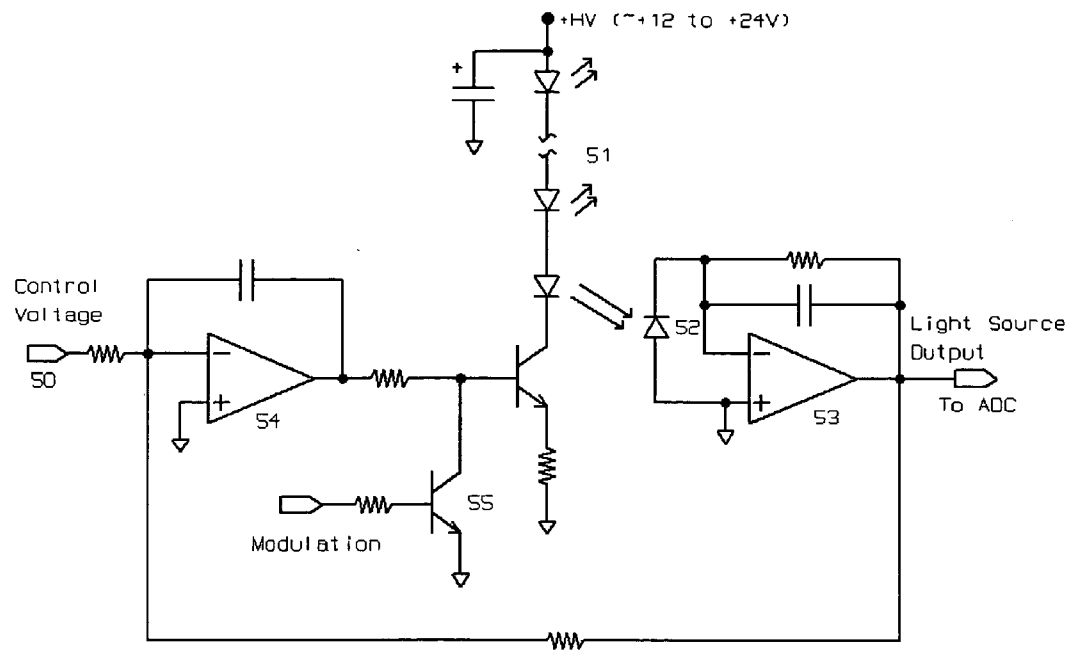


Figure 5

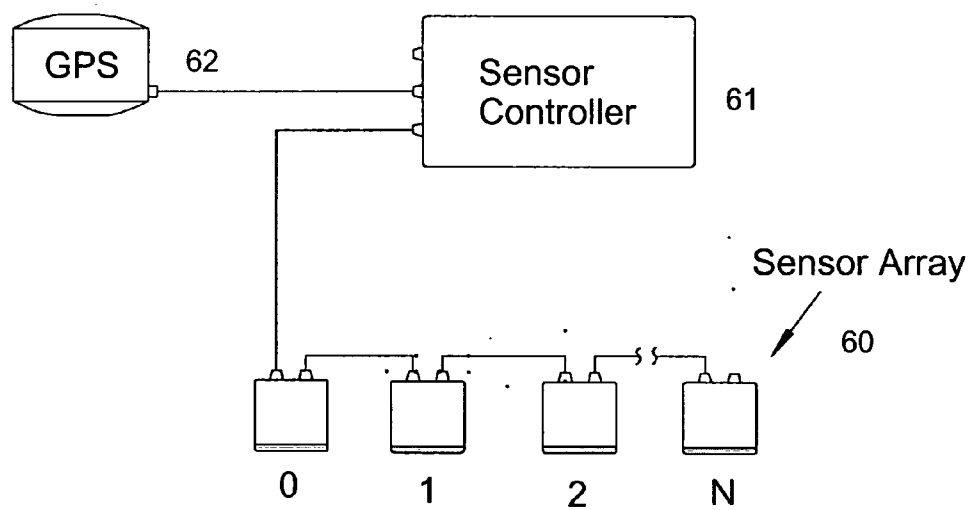


Figure 6. Sensor-based mapping system.

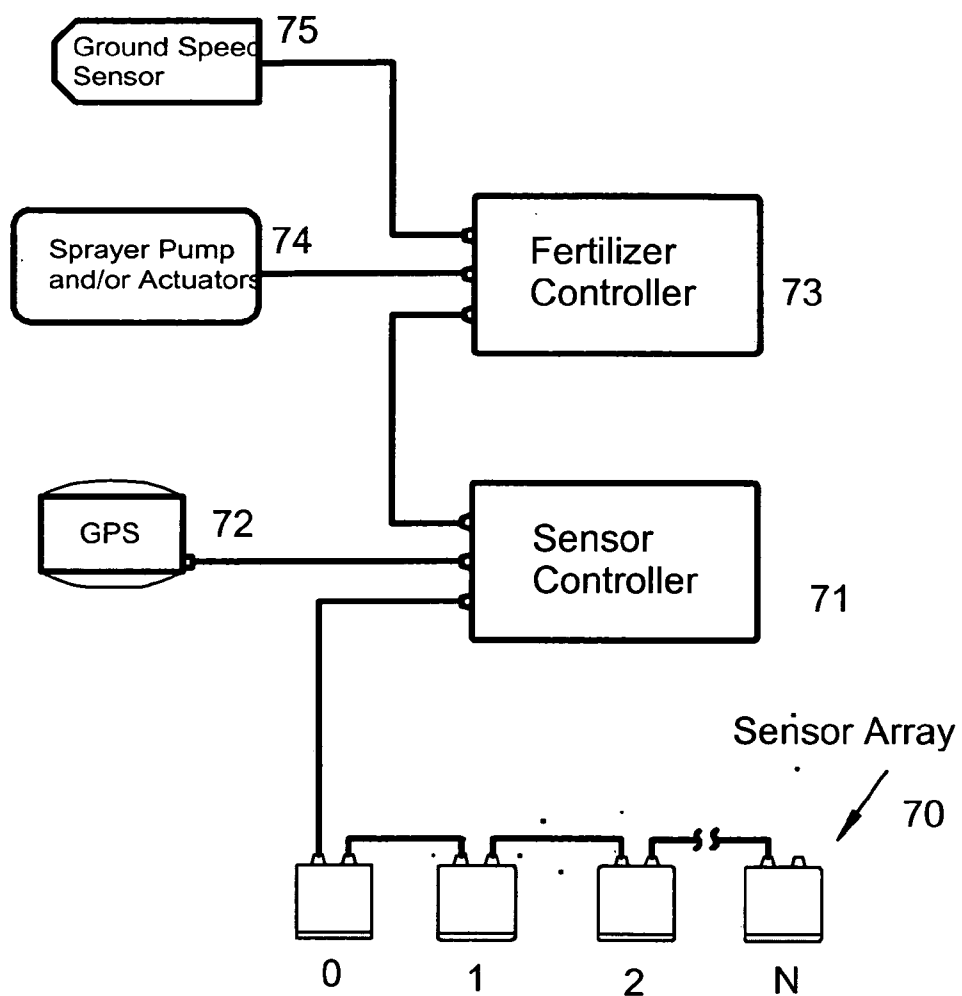


Figure 7. Sensor-based variable-rate applicator system.

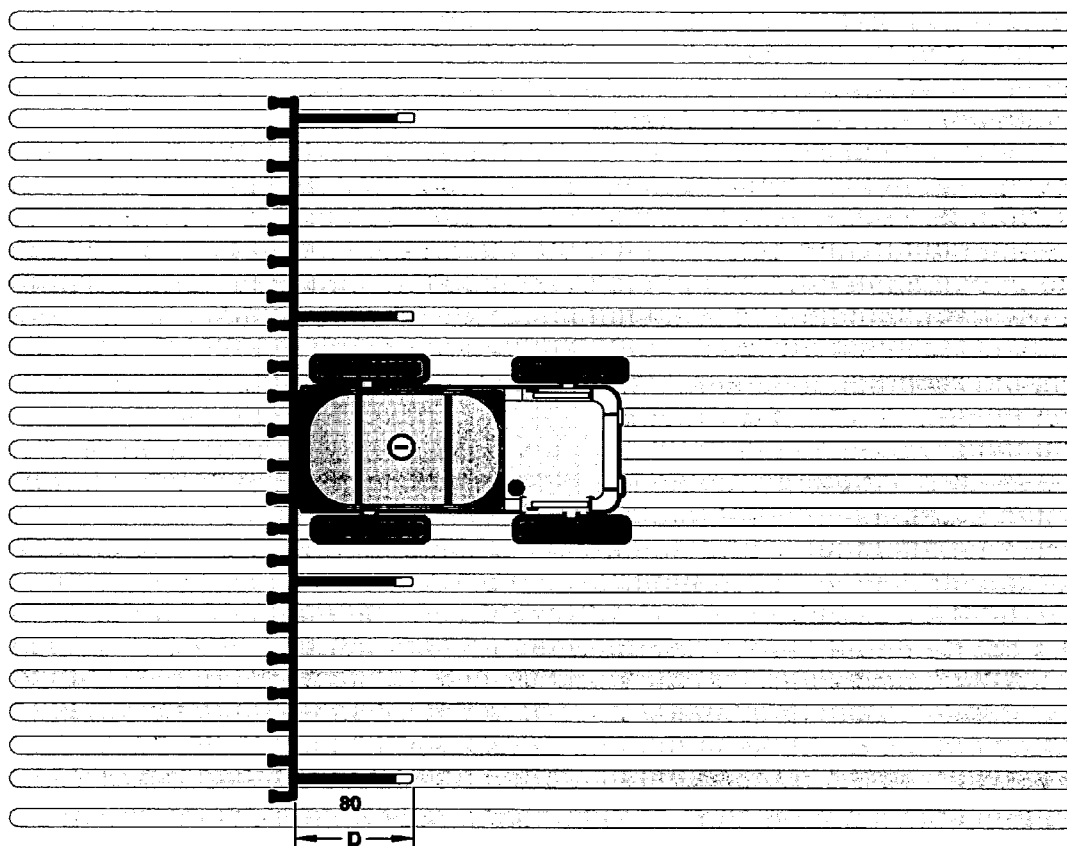


Figure 8. Variable rate applicator implementation depicting sensor-to-nozzle distance D needed to average plant canopy periodicity and leaf orientation.

LIGHT SENSOR WITH MODULATED RADIANT POLYCHROMATIC SOURCE

[0001] This invention is a continuation in part to U.S. patent application Ser. No. 10/703,256

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates to a structure and a method for determining changes in the chlorophyll status of a plant via remote sensing of the plant's reflectance spectrum spanning from approximately 650 nm to 800 nm.

[0004] 2. Description of Related Art

[0005] In order to manage our natural resources in an efficient and cost-effective manner, producers and turf professionals need a way in which to measure and assess the health and performance of their landscapes. For example, the need to know when and how much fertilizer (nitrogen) and other nutrients to apply to a plant to elicit the appropriate growth response is primarily guess work to the producer. Because nitrogen is required by the plant in the greatest quantities and because nitrogen is rather mobile in soils, producers have practiced a one time application of nitrogen to cover the crops need for the entire growing season. However, over application of nitrogen on agricultural and commercial landscapes has resulted in the contamination of ground and surface waters. The primary vectors for water contamination are run-off and leaching. Nitrate-nitrogen is the most common contaminant found in U.S. groundwater. Nitrate contamination is increasing both in area and concentration, particularly beneath landscapes dominated by corn production. It is estimated that 1.8×10^9 kilograms of nitrates wash into the Gulf of Mexico from the Mississippi River basin each year. Of this amount, 55% of the nitrogen released into the basin can be attributed to agricultural fertilizers with only a 3% contribution attributable to non-agricultural fertilizer application primarily on turf for lawns and recreational land (CAST, 1999).

[0006] Techniques to remotely measure crop status include the use of a spectroradiometer and other instruments (Bausch et al. 1994; Chappelle et al. 1992; Maas and Dunlap, 1989), aerial photography (Benton et al, 1976), and satellite imagery.

[0007] The techniques listed above are not without their limitations. For example, early research by Resource21™ determined that during the optimal fly over times between 10 a.m. and 11 a.m. for satellite imaging, cloud cover had adverse affects on visibility. It was found that during the 10 am to 11 am time frame, fields in Colorado were visible approximately 80% of the time while eastern Nebraska fields were visible approximately 50% of the time. This trend in decreased visibility continued the farther east that data was collected. Also, spatial resolution for satellite imagery is poor (Landsat, 20 meter and panchromatic, 10 meter). Similar problems plague aerial photographic methods as well. While aerial imagery has better spatial resolution (typically less than 3 meters) than satellite imaging, partial cloud cover can shade sections of fields giving biased or incorrect reflectance measurements. Both techniques, however, suffer from the need for extensive data processing (performed by third party providers at high cost and long lead time) and geo-referencing issues. Even with spectroradi-

ometric methods using sunlight as the ambient light source, cloud cover and time of day (8 a.m. to 8 p.m.) demands limit the mainstream acceptance of the technology for addressing the nitrogen rate over-loading problem. What is needed is an on-the-go type sensor that overcomes the time of day and fair-weather issues surrounding the aforementioned measurement techniques.

[0008] In certain crops or plant varieties, nutrient deficiencies constitute only part of the management problem. In particular, the basic problem of determining or monitoring plant status with respect to stress whether it stems from nutrient, water, pest, disease, or otherwise is of primary concern. For instance, turf stress determination is of major concern for the turf manager. Earlier detection can protect the health of the grass but also reduce the cost of restoring the badly damaged turf to good health. Turf stress can be due to many causes such as water, pest, nutrient, heat, disease, and the like. By detecting changes in the turf landscape early, turf quality can be maintained and costly restoration operations can be reduced or eliminated. On the other hand, being able to control the degree of stress is important for some producers. Grape producers, for example, like to control the degree of water stress prior to harvesting in order to control disease and increase the sugar content of the grape.

SUMMARY OF THE INVENTION

[0009] The new sensor of the present invention overcomes the time-of-day and fair weather limitations of passive technologies by incorporating its own radiant source and by rejecting the influence of ambient light on the measured canopy reflectance. Unlike passive sensor technology, this sensor will be able to operate under completely dark or full sun conditions. Additionally, the new sensor apparatus is an improvement both in performance and cost over competing active-sensor technologies commercially available.

[0010] As discussed above, the invention presented here will be advantageous in a number of commercial applications. For site-specific agricultural applications, the developed sensor would allow the producer to reduce the amount of nitrogen fertilizer applied to a crop or facilitate spoon-feeding the crop during the growing season, thus having the potential for lowering production costs and enhancing environmental quality. Also, by being able to determine the appropriate fertilizer needs of the crop at any given location in the field, the producer can apply only the fertilizer needed to prevent yield loss or degradation of product quality (i.e., protein content in wheat and barley or sugar content in sugar beets). Subsequently, decreased fertilizer rates will substantially lower nitrogen runoff and leaching losses, which will improve the health of our watersheds, waterways, lakes, and oceans. In addition, data produced by the sensor may be used to produce relative yield maps for forecasting crop production. As for turf grass applications, the sensor technology would allow turf managers to map changes occurring on turf landscapes or for monitoring the status of turf quality.

[0011] In accordance with the present invention, structures and methods are provided for assessing plant status using the chlorophyll status changes and/or biomass properties of the plant remotely sensed, in the red-edge portion of the vegetative reflectance spectrum (~650 nm to ~800 nm), thereby allowing selective monitoring or treatment of individual plants.

[0012] When incorporated into variable rate applicator and/or sprayers systems, the present invention significantly reduces the use of fertilizers by precisely applying agricultural products to individual plants to be treated or eliminated. Moreover, the present invention is operable under a wide variety of conditions including cloudy conditions, bright sunlight, artificial illumination, or even total darkness. The advantage to the producer is that field operations do not have to be timed to daytime sunlight hours for operation.

[0013] All embodiments of the invention can be used in two primary ways. The first method of use includes the application of the invention to handheld instrumentation. Here the invention is utilized to measure plant canopies held in hand by a producer, turf manager, researcher, and the like. The invention includes the use of GPS for geo-referencing data collected by the invention. A second method of use includes applications where the sensor is mounted a moving object such as a tractor, mower, center pivot/linear irrigator, or the like. Again, data may be geo-referenced using GPS for mapping and data layer (GPS maps, soil maps, etc.) integration. Problem areas can be logged and reviewed later by the producer or land manager for analysis and site management decisions.

[0014] An object of the invention is to provide a sensor for remotely sensing plant status using biophysical and biochemical properties of the plant thereby allowing selective monitoring, elimination, or treatment of individual plants.

[0015] This and other objects of the invention will be made apparent to those skilled in the art upon a review of this specification, the associated drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] **FIG. 1** is a graphical representation of the effect of nitrogen rate on the plant reflectance curve over the visible and near infrared portion of the spectrum.

[0017] **FIG. 2** is a graphical representation of plant reflectance curves over the visible and near infrared portion of the spectrum with the red-edge portion of the spectrum emphasized.

[0018] **FIG. 3** is a side and bottom view of a sensor of the present invention.

[0019] **FIG. 4** is a functional block diagram of a preferred embodiment of the present invention.

[0020] **FIG. 5** is a diagram of a circuit used to generate a light source of the present invention.

[0021] **FIG. 6** shows diagrammatically a sensor based mapping system of the present invention.

[0022] **FIG. 7** shows diagrammatically a sensor based variable-rate applicator system of the present invention.

[0023] **FIG. 8** illustrates preferred sensor-to-spray nozzle separation for compensating for plant canopy periodicity and random leaf orientation.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0024] The following contains a description for a sensor that remotely measures plant canopy chlorophyll content

independent of soil reflectance and ambient illumination levels. The sensor can be used in stand-alone instrumentation configurations or in a network of sensors mounted to a vehicle or moving apparatus for on-the-go remote sensing applications. The following description of the invention is meant to be illustrative and not limiting. Other embodiments will be obvious in view of this invention.

[0025] The positive relationship between leaf greenness and crop nitrogen (N) status means it should be possible to determine crop N requirements based on reflectance data collected from the crop canopy (Walberg et al., 1982; Girardin et al., 1985; Hinzman et al., 1986; Dwyer et al., 1991) and leaves (McMurtrey et al., 1994), see **FIG. 2**. Plants with increased levels of N typically have more chlorophyll (Inada, 1965; Rodolfo and Peregrina, 1962; Al-Abbas et al., 1974; Wolfe et al., 1988) and greater rates of photosynthesis (Sinclair and Horie, 1989). Hence, plants that appear a darker green are perceived to be healthier than N deficient plants and as such healthier plants reflectance less light in the visible portion of the spectrum (400 to 700 nm) and reflect more light in the near infrared (>700 nm), see **FIG. 1**. Chlorophyll in leaves absorbs strongly in the blue **3** and red **4** regions of the spectrum (460 nm and 670 nm) and as the wavelengths increase past 670 nm the leaves begin to strongly reflect infrared light, see **FIG. 2**. The transition region between the photosynthetic portion **1** (400 nm to 670 nm) and the biomass portion **2** (>780 nm) of a plant's reflectance spectrum is sometimes referred to as the red-edge region **5**. It has been reported in literature that the wavelength where the maxima of the derivative **6** for the red-edge band occurs is strongly correlated to changes in the chlorophyll status of a plant. Guyot and Baret (1988) developed an algebraic relationship expressing the wavelength of the red-edge inflection point (REIP) **6**, sometimes referred to as the red edge position (REP), using four reflectance bands spanning from 670 nm to 780 nm. The usefulness of measuring red-edge reflectance spectra, and subsequently determining the inflection point's wavelength position, is that the chlorophyll status of the plant can be measured independently of soil background interference. That is, the chlorophyll status as denoted by shifts in the red-edge inflection point is independent of the slope of the vegetative reflectance curve and has reduced sensitivity to soil and biomass reflectance characteristics. Shifts in the value of the inflection point are directly related to the chlorophyll status (and water content) of the plant with chlorophyll content being closely related to nutrient status. Another useful red edge parameter is the red well position **7** (RWP). This is the point on the vegetation reflectance curve that represents the plants minimum reflectance, i.e., the wavelength of maximum chlorophyll absorption. This parameter, like the REIP, is also useful in determining changes in a plant's chlorophyll status.

[0026] There are two general embodiments of the invention that can be utilized to measure red-edge reflectance. In the first embodiment of this invention, discrete monochromatic emitters providing coincident light beams; the beams are substantially in the red-edge portion of the vegetative reflectance spectrum (650 nm to 880 nm) and are sequenced on and off with respect to each other. The light source may be composed most preferably from two or more emitter banks having different wavelengths. The light beams illuminate a surface area on the plant's canopy, which may include bare ground and desired plants. The reflected light

signals are then detected by a single photodetector. In a second embodiment, a chromatic or polychromatic emitter (a light source made up of multiple monochromatic emitters pulsed on/off in synchrony) and a spectrally sensitive detector array (e.g. four photodiodes fitted with 10 nm bandwidth interference filters having center wavelengths of 670 nm, 700 nm, 740 nm and 780 nm). As in the previous embodiment, the light beam illuminates a surface area on the plant's canopy, which may include bare ground and desired plants. Each embodiment utilizes a controller for analyzing reflectance signals measured by the instruments and, assuming a plant is detected, responds by activating a device to take some action with respect to the plant or stores the analyzed signal with corresponding DGPS position in the controller's memory for later analysis. A number of actions may be taken by the controller. If the plant is a crop that is determined to be lacking in nutrient, the desired action may be to apply fertilizer. Additionally, if the plant under test is a turf landscape, such as found on golf courses and sporting fields, plant chlorophyll and/or biomass may be mapped and geo-located using GPS for later, comparative analysis.

[0027] In an improvement on the first embodiment of this invention, three or more light emitters (preferably four) provide selectively modulated monochromatic light beams of different wavelengths. The light beams would preferably have the emission wavelengths of along the red-edge portion of the plant's vegetative reflectance spectrum. The preferable wavelengths for the embodiment utilizing four monochromatic light sources include the following wavelengths: 670 nm, 700 nm 740 nm and 780 nm. For example, one could fabricate a light source composed of discrete LED light sources having wavelengths of 660 nm, 700 nm, 740 nm and 780 nm. It will be apparent to one skilled in the art that other wavelengths along the red edge may be utilized in place of the four aforementioned wavelengths and that similar results will be obtained. Each of these light sources would preferably have a spectral-line half-widths of less than 15 nm. Each monochromatic light source is modulated such that each of the beams illumination time is non-overlapping with the other light beams or partially overlapping as occurs when the beams are staggered by a slight phase shift or modulated at harmonic frequencies. These light beams illuminate a small surface area on the ground, which, again, may be bare ground, desired plants or undesired weeds. A single detector senses portions of the monochromatic light beams reflected by the surface area and provides a quantitative signal indicative of the chlorophyll content of the plant. The signal produced can be integrated into a controller and processed as in the previous embodiment in order to determine plant chlorophyll content.

[0028] In both of the above embodiments, the red visible wave bands (660 nm to 680 nm) and the long wave near infrared bands (760 nm to 880 nm) may be utilized to calculate classic biomass vegetative indexes such as normalized difference vegetative index (NDVI), simple ratio index (SRI), etc... Additionally other unique vegetative indices, sensitive to chlorophyll can be formulated utilizing the wavebands along the red edge. For example, one could use a 730 nm LED and a 780 nm LED to illuminate the canopy in order to measure the a plant's chlorophyll content. The reflectance ratio of these two wavebands is proportional to the chlorophyll status of the plant. Albeit, this ratio may be somewhat sensitive to soil background interference, it

will produce good data for canopies with LAI's greater than 2, that is, canopies that have more complete closure.

[0029] Prior art cited in U.S. Pat. No. 3,910,701 teaches the use of multiple LED wavelengths for plant status determination. And the use of wavelength differentials (slopes) for comparative determination of plant status. This art, however, makes no distinction on the use the red-edge portion of a plant's reflectance spectrum for qualitative chlorophyll assessment. Prior art cited in U.S. Pat. No. 5,789,741 make no distinction with respect to chlorophyll content measurement but rather refer to changes in the slope of the vegetative reflectance spectrum as being indicative of the presence or absence of plant material as compared with soil background reflectivity. The resultant measurement made by the invention of '741 will be heavily influenced by soil background interference. Furthermore, this invention does not incorporate the spectral reflectances around the red-edge vegetative reflectance curve but rather detects slope changes as they deviate from the soil background line (but still heavily influenced by soil background interference); one slope calculated from 600 nm to 670 nm and the other from 670 nm to 780 nm. As such, one trained in the art will note that data produced by this method (U.S. Pat. No. 5,789,741) offers little benefit over biomass calculation methodologies via data produced by prior art referenced in U.S. Pat. Nos. 5,296,702, 5,389,781, 5,585,626 and 6,596,996

[0030] While each of the two embodiments previously discussed have different modes of operation, the fundamental electronic instrumentation required to realize the two devices share many common features and in many ways are essentially the same. A discussion electro-optic elements required to realize each of the embodiments follows.

[0031] FIG. 3 shows a diagram of the sensor enclosure. The enclosure facilitates the protection of the electronic circuitry while providing optical emission and reception ports for the light source and the light detector components, respectively, of the sensor. Port 30 in FIG. 3 is the emitter port of the sensor while port 31 is the detector port of the sensor. Port 30 and port 31 can facilitate various types of optical components to concentrate and collect optical energy. The type of optics used by the sensor can include lens, mirrors, optical flats, filters, and diffusers. The type of optics selected for the emitter and detector optics depends on the application; that is, the required field of view, the height the sensor will be operated above the plant canopy, the required cost of the sensor all may play a part in the design of the sensor's optical arrangement. The sensor can operate at a distance of 1 foot and up to 10 s of feet from the plant canopy or surface of interest but is not limited to this specific range. To those skilled in the art it should be readily apparent that fore optics on the emission side and the detection side can take on many forms.

[0032] For example, a useful optically adaptation on the detector side of the optical arrangement would be to encapsulate the detector optics (filters and detectors). The outer optical surface would have a convex surface spaced from the plane of the photodiode so as to create an afocal or nearly afocal optical arrangement. This preferred mode of construction improves the optical energy collection performance of the filter/diode combination while sealing the optical path from dust and water vapor condensation.

[0033] On the emission side of the sensor, there are a number of ways in which to shape and direct the light beam emitting from the sensor body. For instance, if one wishes to generate a line pattern from the sensors light source, preferably a bank of LEDs, one could place a cylindrical lens in front of this light source spaced appropriately so as to image a line of illumination in the field of view of the detection optics.

[0034] Alternately, a circular or ellipsoidal area of irradiance can be produced using only the encapsulation optics of an array of LEDs. In this instance, the beam pattern produced by the source is defined by the spatial irradiance distribution of each individual LED. No additional collimation or focusing optics is incorporated. Encapsulated LEDs can be purchased commercially that have spatial distribution angles of 4 degrees to almost 180 degrees. Most preferably, it is best to collimate the light emitted from an LED in order to maintain a light beam with relatively constant irradiance over distance. In this case the LED or LED array would be spaced an appropriate distance from a convex lens (or concave mirror) to form an afocal or nearly afocal optical system. The resulting optical system will produce a light beam that will be collimated along the optical axis of the light source resulting in areas of illumination with high radiance.

[0035] FIG. 4 shows a system diagram typical for the many embodiments of the invention. The sensor is composed of optics to facilitate optical energy collimation and collection, a modulated light source 41 comprised of one or many banks of polychromatic LEDs and/or monochromatic LEDs with associated modulated driver and power control electronics 42, single or multichannel photodetector array 43, high-speed preamplifier(s) with ambient light cancellation 44, a phase sensitive signal conditioning 45 and data acquisition circuitry 46, and a microcontrol unit (MCU) or digital signal processor (DSP) 47 and an input/output interface 48 to communicate sensor data to an operator or controller. These system elements will be discussed in the following.

[0036] The light source for the invention is most preferably composed of light emitting diodes. LEDs are convenient light sources for this type of invention for a number of reasons. First, LEDs are available in a number of colors useful for making plant biomass and pigment measurements. LEDs are readily available in colors spanning from deep violet (395 nm) to mid infrared (>4 um). Second, LEDs are extremely easy to use and can be modulated to megahertz frequencies. Relatively simple electronic driver circuits can be implemented and easily controlled by sensor controller electronics. Last, LEDs have long lifetimes and are rugged. The typical LED will operate between 80,000 and 100,000 hours depending on the quiescent device power and operating temperature range.

[0037] LEDs are crystalline materials composed of various transition elements and dopants that include gallium, arsenic, phosphorous, aluminum, nitrogen and indium. Common material chemistries for LEDs are Gallium Arsenide (GaAs), Gallium Arsenide Phosphide (GaAsP), Gallium Aluminum Arsenide (GaAlAs), Indium Gallium Nitride (InGaN), Gallium nitride (GaN), Indium Gallium Aluminum Phosphide (InGaAlP), and Gallium Phosphide (GaP). Material chemistries that include GaN and InGaN are

typically utilized to produce LEDs that emit blue (400 nm) and green (570 nm) light. InGaAlP chemistries emit light in the green (560 nm) to red (680 nm) region of the spectrum while GaAs and GaAlAs emit light in the red (660 nm) to near infrared (950 nm) region of the spectrum. LEDs can be purchased in encapsulated packages or in die form. Encapsulated packages have the benefit of providing mechanical robustness while reducing Fresnel losses associated with a die/air interface.

[0038] LEDs are noncoherent light sources and their emission characteristic classified as being mostly monochromatic or quasi-monochromatic, that is, the frequencies composing the light are strongly peaked about a certain frequency. The spectral characteristic of an LED is defined by an emission band having a center wavelength (CWL) and a spectral-line half-width. The center wavelength defines the peak emission wavelength of the LED and the spectral-line half-width defines the spectral bandwidth of the LED. Two other types of LED emitters can be classified as either having polychromatic or chromatic emission characteristics. Polychromatic LED's have a spectral signatures that are defined by having two or more distinct emission peaks. An example of an LED having this characteristic is the TLYH160 manufactured by Toshiba Corporation (Tokyo, Japan). This device emits simultaneously at 595 nm and 880 nm. Another example would include the True White LED manufactured by American Opto Plus (Pomona, Calif.). This particular device is an RGB LED that produces white light from the simultaneous emission of three different LED structures (red, green and blue) on the same LED die. As noted above, LED's can also have chromatic emissions that produce a broad spectral emission signature. LED's of this type utilize a phosphor that is applied over an LED die and then encapsulated with a transparent epoxy resin. A blue light LED is utilized to stimulate the phosphor to emit a white or colored broadband light. The emitted light has a broad emission spectrum similar to that of fluorescent light. Both of the aforementioned LED types can be rapidly modulated to produce highly effective illumination signals for active light sensors.

[0039] In order to achieve good output stability with respect to thermal and aging effects, the LED sources should be adequately driven and monitored. The output intensity of LEDs is very temperature dependent. Depending on the material type, an LED's output can drift between 0.4 %/C and 1 %/C. A decrease in output intensity, even if it is being monitored and corrected via calculation, can result in diminished signal to noise performance of the measurement.

[0040] FIG. 5 shows schematically a circuit that provides active power control for the light source and an output intensity signal for monitoring and calibration. Control voltage 50 sets the output power of light source 51. Photodiode 52, an Infineon SFH203 (Munich, Germany), samples part of the output intensity of light source 51 and feeds this signal via amplifier 53 to servo amplifier 54. Modulation of the output signal is performed using transistor 55. Furthermore, the output of amplifier 53 can be utilized to monitor the light source intensity for purposes of calibration and diagnostics. The performance of this circuit has provided output intensity control of approximately 0.05%/C over the operating range of the invention. Many techniques have been discussed in literature detailing methods on maintaining and stabilizing light sources for photometric type measurements including the method presented here. As those

skilled in the will note, there are numerous techniques and methodologies for light source power monitor/stabilization for photometric measurements discussed in engineering and scientific literature.

[0041] The detectors used in the invention are most preferably silicon photodiodes however other detector technologies such as GaAsP and the like, may be utilized as well. Silicon detectors have a typical photosensitivity spanning from 200 nm (blue enhanced) to 1200 nm. Band shaping of the detectors is performed using filtering materials such as colored filter glass, interference filters or dichroic filters. Combinations of the aforementioned filter techniques can be combined in order to band-shape the radiation impinging on the photodetector surface. For example, an interference filter can be used to select a narrow bandwidth of light. In this situation, one could choose to use a 10 nm interference filters to select a band of interest along the red-edge portion of the vegetative reflectance spectrum. Utilizing an array of photodetectors fitted with interference filters would provide the wavelength selection needed to realize the invention of embodiment two that utilizes a polychromatic source for illumination. In the case of embodiment one that uses only a single photodetector, the incorporation of an long pass edge filter can be utilized to trim the photodiode response by blocking short wave light and subsequently improving the ambient light rejection of the associated preamplifier electronics. As one trained in the art will see, there are numerous ways in which various optical filters can be utilized to shape and control the light impinging on a photodetector or photodetector array. A unique configuration pertaining to embodiment two involves the use of linear diode array detector and diffraction grating (or linear variable filter (LVF) technology). The diffraction grating (or LVF) separates incoming, modulated light in to many wavelengths. By configuring embodiment one with a diffraction grating (or LVF)/linear array combination sensitive to the red edge region of the vegetative reflectance curve, plant chlorophyll concentrations can be measured independent of soil background interference.

[0042] Referring once again to FIG. 4, both embodiments of the invention utilize a phase sensitive detector subsystem (PSD) 45 and analog-to-digital converter 46 (ADC) after each photodetector. The PSDs, sometimes referred to as lock-in amplifiers, are utilized by the invention to extract and further amplify the very small signals detected and amplified by the photodetector preamplifier(s). PSDs are often used in applications where the signal to be measured is very small in amplitude and buried in noise. Detection is carried out synchronously with modulation of the light sources. Phase sensitive detection is one of many types of band narrowing techniques that can be utilized to measure small signals. As will be apparent to those skilled in the art, other methods include the use of averaging techniques, discriminators and direct digital conversion/processing. With respect to direct digital conversion/processing, the phase sensitive acquisition component can be performed internally to a MCU or DSP by directly sampling the output of the photodiode amplifiers and performing the band pass and PSD functions digitally. By performing these operations in the digital domain, the temperature drift of the phase detector, common to analog techniques, can be eliminated. The invention performs the synchronous modulation/demodulation at a carrier frequency of 250 kHz. It should be noted that the operation of the invention is not limited to this

particular modulation rate and can operate at other modulation frequencies as well with as much effectiveness. Additionally, this rate can be increased or decreased as dictated by the application. The MCU or DSP samples the output of a PSD 45 utilizing ADC 46. The resolution of the ADC is most preferably 12 bits. Each channel can sampled using a dedicated ADC or one ADC can be utilized to sample all channels via a multiplexer.

[0043] Once the detected optical signals are amplified, demodulated and quantified, the MCU or DSP 47 can calculate chlorophyll content and/or a vegetative relationship based on the reflectance values sensed. Calculations for plant chlorophyll status based multiple red-edge reflectance spectra can be performed a number ways. For the situation where the instrumentation has been designed to measure four or more reflectance values along the red edge, polynomial fitting may be used to fit the curve represented by the reflectance points. Subsequently, the resulting polynomial may be differentiated to find the red-edge inflection point value. The resulting wavelength will be proportional to relative shifts in the chlorophyll status of the plant. When four reflectance values are measured, the four reflectances having the center wavelengths of 670 nm, 700 nm, 740 nm and 780 nm, a preferred method is the four-point interpolation method. This method has the following mathematical for

$$\rho_i = \frac{\rho_1 + \rho_4}{2}$$

$$\lambda_i = \lambda_2 + (\lambda_3 - \lambda_2) \cdot \frac{\rho_i - \rho_2}{\rho_3 - \rho_2}$$

Where λ_1 , λ_2 , λ_3 and λ_4 are wavelengths 670 nm, 700 nm, 740 nm and 780 nm, respectively, and ρ_1 , ρ_2 , ρ_3 and ρ_4 are reflectances at the corresponding wavelengths, respectively. Additionally, another red edge parameter, the red well position RWP, may be calculated using these same wavebands. The RWP interpolation has the following mathematical form

$$\lambda_0 = \lambda_1 + (\lambda_2 - \lambda_1) \cdot \frac{\rho_1 - \rho_2}{\rho_3 - \rho_2}$$

The RWP represent the wavelength position of a plants minimum reflectance in the red, or rather the position of maximum chlorophyll absorption. The RWP functions in a similar fashion as the REIP for predicting relative changes in plan chlorophyll status.

[0044] Other mathematical techniques for determining the REIP and RWP include Lagrangian interpolation, inverted-Gaussian modeling, regression modeling, etc. . . . As will be apparent to one skilled in the art, the list of the aforementioned methods is not exhaustive and other common approaches to determining the REIP and RWP wavelength positions may be formulated or found in literature.

[0045] In another useful red-edge sensor embodiment, a red polychromatic LED, such as the one utilized in U.S. patent application Ser. No. 10/703256, and a monochromatic LED, with an emission wavelength in the red edge portion

of a plant's vegetation reflectance spectra (680 nm to 760 nm), are utilized in a sensor that can distinguish between both plant nutrient and water stresses via the Canopy Chlorophyll Content Index (CCCI). The sensor utilizes two particular vegetation indexes. They are a Normalized Difference Red-Edge (NDRE) index which has the following mathematical form:

$$NDRE = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2}$$

and a standard Normalized Difference Vegetation Index (NDVI) which has the form:

$$NDVI = \frac{\rho_3 - \rho_1}{\rho_3 + \rho_1}$$

Where ρ_1 , ρ_2 and ρ_3 are reflectances at wavelengths 650 nm, 720 nm and 880 nm. The NDVI as an estimate of percent plant cover and the NDRE as an indicator of plant chlorophyll content. The CCCI formula utilizes both the NDVI and NDRE indexes to calculate the impact of water and nutrient on a crop or plant. The benefits of utilizing the polychromatic and monochromatic LED combination are many. First, the use of the polychromatic LED reduces the number of LED banks from three to two. Second, because the number of LED banks have been reduced, the number of LEDs in a particular bank can be increased which subsequently enhancing the sensor's signal-to-noise performance. Third, because there are fewer banks to modulate, the modulation rate can be higher for the LED banks that are incorporated and subsequently enhancing the sensor's signal-to-noise performance. Last, easier temperature control and compensation can be performed with fewer LED banks.

[0046] Data calculated by the sensor's processing component is communicated to an operator or system controller via input/output interface 48. In the case of a handheld instrument, the I/O interface may take the form of a keypad and display. If the invention is incorporated into a sprayer or mapping system having several sensors networked together, the I/O interface will most preferably be a networkable serial port such as RS485 port or CAN 2.0b port.

Applications of Use-Methods

[0047] FIG. 6 show a block diagram of the invention incorporated into a system that is used to map plant status. Elements of the system include sensor array 60, sensor controller 61, and GPS 62.

[0048] The role of the sensor in this system is to measure the chlorophyll status and/or biomass properties of the plant being mapped. Data produced by the sensor are collected by the system controller for storage and later analysis. Each sensor point is geo-referenced using the GPS connected to the system controller. There are two primary ways in which mapping can be performed by the system. First, the map collected by the system can be all-inclusive, that is, every data point measured by the sensor can be stored away in the controller's memory for later retrieval and analysis. Second, the sensor/controller can be programmed with a defined set of rules so as to distinguish poor performing regions of a

landscape from good or healthy regions and vice versa and store only the poor performing regions. This mode of operation saves storage space in the controller and reduces the amount of data processing that has to be performed. As an example, the mapping systems could be mounted to the mower machinery for a golf course. When the course personnel perform their weekly mowing operations, the mapping systems would scout for problem areas of the turf. For turf management operations, this mode would be most useful because regions of turf that are suffering from stress (disease, water, nutrient, and so forth) or are beginning to suffer. The mapping systems would flag affected areas for the turf manager to scout out visually.

[0049] FIG. 7 show a block diagram of the invention incorporated into a system that is used for applying an agricultural product. Elements of the system include sensor array 70, sensor controller 71, GPS 72, fertilizer controller 73, sprayer pumps/actuators 74 and ground speed sensor 75.

[0050] The agricultural product may be either in liquid or solid form and may be, but not limited to, a nutrient, mineral, herbicide or fungicide or a combination of the aforementioned materials. The variable rate control system can be mounted to a commercial sprayer or tractor mounted sprayer system. GPS can be incorporated in the system when a map is required of plant canopy characteristics for later analysis. In addition, to mapping plant characteristics, material dispensation rates can be mapped as well. GPS is also required when applying fertilizer referenced to an N sufficient reference strip. In this situation, a region of the field is given an N-rate that totally meets the needs of the crop to grow without loss of yield and apply a lower amount of pre-emergent fertilizer (only the amount to initially cause the crop to grow) to the remainder of the field. At a time later in the growing season, the producer will apply a second treatment to the remainder of the field using the sensor readings for the N sufficient region of the field. Readings from the N insufficient parts of the field will be compared with readings from the N sufficient regions of the field. The controller will use the sensor measurements to calculate the appropriate rate of fertilizer to apply to the N insufficient portion of the field in order to prevent yield loss. FIG. 8 shows an applicator example with the sensor stood-off from the spray nozzles. When designing variable rate application system, the obvious approach is to physically locate the sensor close or next to the sprayer nozzle. However, because of the random orientation of most plant canopies the sensor should be separated from the sprayer nozzles by a distance D 80. This allows the sensing instrument to collect data on a portion of the crop, so as to average the spatial variability, before applying an agricultural product. The separation distance D between the sensor and sprayer nozzles should most preferably be greater than 3 feet. In operation, the variable rate system will collect data for D feet and apply an agricultural product over D feet while sensing the next D separation distance. Another strength of a red-edge measurement sensor, as disclosed above, is that the measurement made by the instrument is relatively invariant with respect to varying plant population. This is critical for making N fertilizer recommendations on fields that have had crops planted utilizing variable rate seeding techniques. With a biomass sensor, a seed rate map would have to be utilized in conjunction with the variable rate application algorithm in order to compensate for changes in plant biomass resulting from the seeding operation.

[0051] The benefits of a system such as the one just described are both economic and environmental. By using

less fertilizer and only applying it where the crop needs it, the producer can lower his use of fertilizer and thus lower his production cost. Additionally, by using less fertilizer and only applying it where the crop needs it, reduced run-off and leaching into our watershed occurs. Because the present invention produces its own source of light, the measurements that it makes is not influenced by ambient light conditions. Applicator equipment fitted with sensors of this type can be operated around the clock at night and under full sun.

[0052] Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the embodiments given without materially departing from the novel teachings and advantages of this invention. Accordingly, various modifications, adaptations, and combinations or various features of the described embodiments can be practiced without departing from the scope of the invention as set forth in the claims.

What is claimed is:

1. Apparatus for assessing the status of plants in a plant canopy, comprising:

- (a) a light source having an emission spectrum substantially in the red-edge portion of the plant's reflectance spectrum for illuminating the plant canopy;
- (b) a detector for detecting portions of the emission spectrum reflected off of the plant canopy; and

- (c) a processor for determining the wavelength of the red edge inflection point of the light collected by the detector.

2. Apparatus as defined in claim 1, further comprising a processor for determining the chlorophyll content of the plant from the red edge inflection point.

3. Apparatus as defined in claim 1, wherein the light source consists of a plurality of monochromatic light sources.

4. Apparatus as defined in claim 1, wherein the light source consists of one or more polychromatic light sources.

5. Apparatus as defined in claim 1, further comprising a mapping system for generating a map of the assessed plant status over a selected area.

6. Apparatus as defined in claim 1, further comprising an applicator responsive to the processor to apply a horticultural material to the plant canopy in response to the assessed plant status.

7. Apparatus as defined in claim 6, wherein the horticultural material is selected from the group consisting of fertilizer, herbicide, insecticide, fungicide, and combinations of such materials.

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