The present inventors have recognized that various diseases in plants, such as Phytophthora infestans (late blight) and Alternaria solani (early blight), and/or various stages of such diseases in plants, can be reliably detected by applying measurements from electromagnetic reflections detected from a plant in a model to produce an output indicating a probability of the disease and/or stage. In one aspect, coefficients can be applied to each measurement at each wavelength to emphasize identification of a given disease or stage. In another aspect, an imager can capture images comprising spectral pixels in which each pixel comprises measurements from the electromagnetic reflections for application in a model to identify a given disease or stage.

18 Claims, 16 Drawing Sheets
FIG. 6A
FIG. 6B
FIG. 8

1. GENERATE MODELS
2. MEASURE SAMPLE
3. APPLY MEASUREMENTS TO MODELS
4. DISEASE PRESENT?
   - YES: IDENTIFY DISEASE
   - NO: MEASURE NEXT SAMPLE
5. STAGE PRESENT?
   - NO: RECORD/OUTPUT
   - YES: IDENTIFY STAGE
Early Infection

Spectra of Late Blight Infected Plants

Treatment -- Control --- Late Blight Lifestage + Early Infection

FIG. 9
Biotrophic Growth

Spectra of Late Blight Infected Plants

FIG. 10
Sporulation

Spectra of Late Blight Infected Plants

FIG. 12
The present inventors have recognized that various diseases in plants, such as Phytophthora infestans (late blight) and Alternaria solani (early blight), and/or various stages of such diseases in plants, can be reliably detected by applying measurements from electromagnetic reflections detected from a plant in a model to produce an output indicating a probability of the disease and/or stage. In one aspect, coefficients can be applied to each measurement at each wavelength to emphasize identification of a given disease or stage. In another aspect, an imager can capture images comprising spectral pixels in which each pixel comprises measurements from the electromagnetic reflections for application in a model to identify a given disease or stage.
following detailed description and the accompanying drawings. It should be understood, however, that the detailed description and specific examples, while indicating preferred embodiments of the present invention, are given by way of illustration and not of limitation. Many changes and modifications may be made within the scope of the present invention without departing from the spirit thereof, and the invention includes all such modifications.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred exemplary embodiments of the invention are illustrated in the accompanying drawings in which like reference numerals represent like parts throughout, and in which:

FIG. 1 is a diagram of a system for detection of disease in plants in accordance with an aspect of the invention;

FIG. 2 is a diagram of an exemplar plant structure reflecting a spectrum of electromagnetic radiation in the system of FIG. 1;

FIG. 3 is an exemplar plot of waveforms in a spectrum, including for a plant inoculated with a disease and a plant not inoculated with the disease, showing reflections from the plants by varying amounts across the spectrum of electromagnetic radiation indicated by wavelengths;

FIG. 4 is an exemplar plot of spectral values in a “heat map,” which could be Normalized Differential Spectral Index (NDSI) values, calculated from reflections from a plant;

FIG. 5 is a process which can be executed by the system of FIG. 1 for applying spectral values as variables in models indicating stages of infection of disease to produce in accordance with an aspect of the invention;

FIG. 6A is a chart indicating possible ranges for spectral values for indicating various stages of infection of P. infestans with varying percentages of accuracy in accordance with an aspect of the invention;

FIG. 6B is a chart indicating possible ranges for spectral values for indicating a fewer number of stages of infection of P. infestans with varying percentages of accuracy in alternative modes of detection in accordance with another aspect of the invention;

FIG. 7 is a diagram of an alternative system for detection of disease in plants in accordance with an aspect of the invention;

FIG. 8 is a process for detection of disease in plants in accordance with an aspect of the invention;

FIG. 9 is an exemplar plot of waveforms in a spectrum comparing a healthy plant to a plant inoculated with P. infestans at an early infection stage of infection;

FIG. 10 is an exemplar plot of waveforms in a spectrum comparing a healthy plant to a plant inoculated with P. infestans at a biotrophic growth stage of infection;

FIG. 11 is an exemplar plot of waveforms in a spectrum comparing a healthy plant to a plant inoculated with P. infestans at a necrotrophic lesion formation stage of infection;

FIG. 12 is an exemplar plot of waveforms in a spectrum comparing a healthy plant to a plant inoculated with P. infestans at a sporulation stage of infection;

FIG. 13 is a diagram illustrating generation of a model in accordance with an aspect of the invention;

FIG. 14 is a diagram illustrating an application of reflection measurements as variables in a model in accordance with an aspect of the invention;

FIG. 15 is a diagram illustrating an image comprising spectral pixels in accordance with an aspect of the invention; and

FIG. 16 is a diagram illustrating an overhead vehicle capturing an image comprising spectral pixels in accordance with an aspect of the invention.

DETAILED DESCRIPTION

Referring now to FIG. 1, a diagram of a system 10 for detection of disease in plants is provided in accordance with an aspect of the invention. The system 10 can include a control system 12 in communication with a controllable light source 14, a spectrometer 16 and/or an I/O interface 18. The control system 12 can include a processor 20 configured to execute a program 22 stored in a non-transient medium 24 to control operation of the light source 14 and/or the spectrometer 16. The processor 20 can also execute to communicate with a user through the I/O interface 18 to receive commands and/or display results as described herein. The I/O interface 18 could include a keyboard and/or monitor connected to the control system 12, and in one aspect, could be implemented by a remote monitoring device, such as a smartphone or tablet.

Under control of the system 12, the light source 14 can project electromagnetic radiation over a continuous spectrum from a radiating portion 15, preferably including visible and infrared spectrums, at various distances and/or angles onto a plant 30, such as an exposed leaf under study. In alternative aspects, ambient lighting and/or other electromagnetic radiation sources could be used. Also, under control of the system 12, the spectrometer 16, through a sensor 26, which could include a lens, in turn, can detect a continuous spectrum of electromagnetic radiation at various distances and/or angles as reflected from the plant 30. In particular, the spectrometer 16 can detect the continuous spectrum of electromagnetic radiation as reflection measurements between lower and upper wavelengths, preferably between at least a lower (longer) wavelength of about 400 nanometers and an upper (shorter) wavelength of about 2500 nanometers.

In one arrangement, the system 10 can be configured as part of portable device carried by a user. In such an arrangement, the sensor 26 and the radiating portion 15 could be integrated into a single handheld contact probe for local testing and monitoring. In another arrangement, the system 10 can be attached to an aerial vehicle, such as a drone, for monitoring larger areas of an agricultural field. In yet another arrangement, the system 10 can be attached to a ground vehicle, such as a tractor or agricultural implement, to interface with a user in a cab, for real-time monitoring of plant conditions during field operations.

With additional reference to FIG. 2, as full portions 32 of electromagnetic radiation projected from the light source 14 come into contact with the plant 30, the full portions 32 are typically divided into reflected portions 34, absorbed portions 36 and transmitted portions 38. The reflected portions 34 are typically further divided into surface reflected portions 34a, which reflect from the plant 30 without penetrating the surface, and internally reflected portions 34b, which penetrate the surface of the plant 30 and reflect from interior structures 40. The absorbed portions 36 most often constitute radiation in the red and blue regions of the visible light spectrum, among other radiation, that is absorbed by chlorophyll during photosynthesis. The transmitted portions 38 constitute radiation at particular wavelengths which are neither reflected nor absorbed by the plant 30.
The present inventors have recognized that various stages of an infection cycle of a disease can induce a different physical, physiological, and/or biochemical response from a plant, thereby causing wavelength reflectance to change. For example, a first portion of the plant not affected by disease reflects the reflected portions in different ways at select wavelengths than a second portion of the plant that is affected by disease. Such reflected portions can therefore be characterized to determine healthy versus diseased plants, and moreover, states of progression of diseased plants, such as early infection, biotrophic growth, transition to necrotrophy, necrotrophic lesion formation, sporulation, and/or disease-induced leaf death, for Phytophthora infestans (P. infestans) in potato or tomato.

With additional reference to FIG. 3, an exemplar plot of waveforms illustrates reflections (p) by varying amounts with respect to a spectrum of electromagnetic radiation at differing wavelengths (λ) between a lower wavelength and an upper wavelength in accordance with an aspect of the invention. Such waveforms could be detected by the spectrometer, displayed to the interface and/or used for calculations by the processor as described herein. The waveforms include, by way of example, a non-inoculated waveform for a plant not affected by disease (“Not Inoculated”), which could include only the first portion of the plant, and an inoculated waveform for a plant that is affected by disease (“Inoculated”), such could include the second portion of the plant.

In one aspect, such waveforms could be detected continuously between lower wavelengths of about 400 nanometers to upper wavelengths of about 2500 nanometers. The spectrum could therefore preferably include a visible spectrum (VIS), between 400 and 700 nanometers, and an infrared (IR) spectrum, between 700 and 2500 nanometers. Accordingly, the IR spectrum would also include a near-infrared (NIR) division, between 800 and 1200 nanometers, and a short-wavelength infrared (SWIR) division, approximately between 1300 and 2500 nanometers.

Although the non-inoculated and inoculated waveforms, respectively, follow similar general patterns, the present inventors have recognized that they in fact differ at select wavelengths based on disease states. As a result, such differences can be distinguished in predetermined groups or patterns of spectral values for reliably detecting disease states.

Referring now to FIG. 4, an exemplar plot of a group of spectral values calculated in a “heat map” is provided in accordance with an aspect of the invention. The spectral values are derived from the spectrum of electromagnetic radiation such as from a waveform of FIG. 3, at a particular sampling time. Each spectral value can quantify a relative difference between reflections (p) at differing wavelengths (λ) between the lower and upper wavelengths, respectively. Accordingly, each spectral value can emphasize distinctions between the differing wavelengths, certain ones of which being suitable for detection of stages of infection at particular times.

In one aspect, the spectral values can be Normalized Differential Spectral Index (NDSI) values. Such NDSI values can be calculated as a difference between spectral reflections at first and second wavelengths (or bands) divided by a sum of the spectral reflections at the first and second wavelengths (or bands), respectively, such as according to the equation:

\[
\text{NDSI} = \frac{\text{band}_1 - \text{band}_j}{\text{band}_1 + \text{band}_j}
\]

Referring now to FIG. 5, in accordance with an aspect of the invention, for detection of disease in plants, the processor can execute a process to calculate multiple predetermined groups or patterns of spectral values from reflections of electromagnetic radiation from a plant under study. Each group includes spectral values optimized to most characterize a particular stage of infection of disease for its group when compared to other stages. Accordingly, each group can correspond to a likelihood of presence of that particular stage of infection. In one aspect, for P. infestans in potato or tomato, following a detection of electromagnetic radiation from a plant, the processor can execute to calculate: a first group optimized for detection of early infection (“Stage 1”); a second group optimized for detection of biotrophic growth (“Stage 2”); a third group optimized for detection of transition to necrotrophy (“Stage 3”); a fourth group optimized for detection of necrotrophic lesion formation (“Stage 4”); a fifth group optimized for detection of sporulation (“Stage 5”); and a sixth group optimized for detection of disease-induced leaf death (“Stage 6”).

With additional reference to FIG. 6A, a chart indicates possible ranges for spectral values for indicating the various stages of infection of P. infestans with varying percentages of accuracy. As shown, spectral values for detection of early infection (“Stage 1”) could be optimized in the first group by using reflections at wavelengths in only the SWIR division of the IR spectrum; spectral values for detection of biotrophic growth (“Stage 2”) could be optimized in the second group by using reflections at wavelengths in only the NIR division of the IR spectrum; spectral values for detection of transition to necrotrophy (“Stage 3”) could be optimized in the third group by using reflections at wavelengths in the SWIR and NIR divisions of the IR spectrum; spectral values for detection of necrotrophic lesion formation (“Stage 4”) could be optimized in the fourth group by using reflections at wavelengths in the SWIR and NIR divisions of the IR spectrum; spectral values for detection of sporulation (“Stage 5”) could be optimized in the fifth group by using reflections at wavelengths in only the SWIR division of the IR spectrum; spectral values for detection of disease-induced leaf death (“Stage 6”) could be optimized in the sixth group by using reflections at wavelengths in the visible spectrum and SWIR division of the IR spectrum.

By way of example, the inventors have found that spectral values for detection of early infection (“Stage 1”), at about 24 hours post inoculation, could be optimized in the first group by using NDSI values based on any of the following combinations of wavelengths (formatted as X_first_wavelength, second_wavelength, in nanometers, where the NDSI value is calculated by subtracting the reflectance at the second wavelength from the reflectance at the first wavelength over the sum of the two reflectance at the specified wavelengths) (corresponding classification accuracies for each combination, derived from 500 iterations of a 70-30 training-testing dataset split, are also provided): a. X2034.2029+X2051.2030—about 78% accuracy;
The following combinations of wavelengths:

b. X2032.2029+X2032.2031+X2031.2029+X897.887+X2032.2030+X2033.2029+X1948.1944+X827.826+X2034.2029—about 74% accuracy;

c. X2032.2029+X2032.2031+X2031.2029+X897.887+X2032.2030+X2033.2029+X1948.1944+X827.826—about 75% accuracy;

d. X2032.2029+X2032.2031+X2031.2029+X897.887+X2032.2030+X2033.2029+X1948.1944—about 72% accuracy;

e. X2032.2029—about 78% accuracy;

The following combination of wavelengths:

b. X2284.2276—about 70% accuracy;

c. X2284.2276+X1932.1922+X1931.1922+X1948.1944+X558.552+X564.552—about 75% accuracy;

d. X2284.2276+X2285.2276—about 78% accuracy.

The NDSI value based on the following wavelengths:

b. X1932.1922+X564.552—about 79% accuracy.

c. X1130.1015+X1130.1015+X139.965+X138.965+X1084.1080+X557.556—about 75% accuracy.

d. X2284.2276+X2285.2276+X1931.1929—about 78% accuracy.

e. X2284.2276+X564.552—about 78% accuracy.

Referring again to FIG. 5, the processor 20 can further execute the process 73 to apply the multiple groups 70 of spectral values 72 as variables in models 74 for indicating stages of infection of disease to produce outputs 76 indicating likelihoods of presence of the respective stages of infection in the plant. Each model 74 can execute a multivariate logistic regression using particular spectral values 72 to produce a probability for providing the output 76. Each model 74 could execute simultaneously or sequentially. The output 76 could be expressed as probability or percent likelihood of presence of the particular stage of disease. For *P. infestans* in potato or tomato, the first group 70a of spectral values 72 ("Stage 1") can be applied in a model 74a to produce an output 76a indicating a likelihood of presence of early infection; the second group 70b of spectral values 72 ("Stage 2") can be applied in a model 74b to produce an output 76b indicating a likelihood of presence of biotrophic growth; the third group 70c of spectral values 72 ("Stage 3") can be applied in a model 74c to produce an output 76c indicating a likelihood of presence of transition to necrotrophy; the fourth group 70d of spectral values 72 ("Stage 4") can be applied in a model 74d to produce an output 76d indicating a likelihood of presence of necrotrophic lesion formation; the fifth group 70e of spectral values 72 ("Stage 5") can be applied in a model 74e to produce an output 76e indicating a likelihood of presence of sporulation; and the sixth group 70f of spectral values 72 ("Stage 6") can be applied in a model 74f to produce an output 76f indicating a likelihood of presence of disease-induced leaf death.

In one aspect, the outputs 76 could be collectively sent to the I/O interface 18 for graphic display to a user. The user could then interpret the results to determine presence or absence of disease, and moreover, a stage of infection of the disease, if present. However, in another aspect, each of the outputs 76 could be sent to an analyzer 78 for producing a selection 79 indicating presence or absence of disease, and moreover, stage of infection of the disease, if present. The analyzer 78 could be a program executing to reference a library comprising historical test results and apply statistical analysis and/or machine learning to produce the selection 79. The selection 79, in turn, could be sent to the I/O interface 18 for graphic display to the user to provide a simplified result.

Referring now to FIG. 7, an alternative system 100 can be provided for detection of disease in plants in accordance with an aspect of the invention. The system 100 can include a combined control system 102, including a processor, data store, spectrometer and/or I/O interface, in communication with an enclosure 104, through a cable 106 providing I/O control and/or a waveguide. The enclosure 104 can include a door 107 having a clip or other mechanism for retaining a plant material 108, such as a leaf, under study. The plant material 108 can be held by the clip and, as shown in detail view 112, the door 107 can be closed to contain at least a portion of the plant material 108 inside the enclosure 104 for testing.

With the plant material 108 held inside the enclosure 104 and the door 107 closed, the control system 102 can be triggered to initiate testing. When initiated, as shown in detail view 112, the control system 102 can trigger the enclosure 104 to project a spectrum of electromagnetic radiation, directed toward the plant material 108, from a radiating source 114, preferably including visible and infrared spectra. A lens 116 could then direct reflections from the
plant material 108 to the spectrometer. The control system 102, with results from the spectrometer, can then calculate the predetermined groups 70 of spectral values 72, and apply the groups 70 of spectral values 72 as variables in a model 74 to produce outputs 76 indicating likelihoods of presence of stages of infection in the plant material 108 and/or the selection 79 for graphic display.

Referring now to FIG. 6B, in another aspect of the invention, a chart 80b indicates possible ranges 82b for spectral values 72 for indicating the various stages 84b of infection of P. infestans with varying percentages of accuracy 86b. In this aspect, a fewer number of stages 84b can be detected, in this case four, with different percentages of accuracy for each stage by using different NDVI values, similarly as described above with respect to FIG. 5.

In addition, in an alternative aspect of the invention, the fewer number of stages 84b can be detected, with varying percentages of accuracy 86c, using an application of coefficients as described herein. Referring now to FIG. 8, in such a system, the processor 20 can execute the process 200 to obtain reflection measurements from the spectrometer 16 and apply such measurements as variables in a model configured to indicate a likelihood of presence or absence of a disease in a plant. Beginning at step 202, the process can begin by generating models used for determining plant healthiness, presence of disease, such as P. infestans (late blight) and/or A. solani (early blight), and/or presence of stages of infection of a disease. By way of example, with additional reference to FIGS. 9-12, waveforms are provided illustrating reflection measurements versus wavelengths for plants inoculated with optimally identifiable stages of infection of P. infestans as determined by the inventors, including early infection (FIG. 9), biotrophic growth (FIG. 10), necrotrophic lesion formation (FIG. 11), and sporulation (FIG. 12), each in comparison with a healthy or “control” plant. The models can be generated and re-generated with adjustments as often as desired.

With additional reference to FIG. 13, in one aspect, to generate a given model, first and second spectrums of electromagnetic radiation 222 and 224, respectively, can be detected by the spectrometer 16. Each spectrum can represent an array of reflection measurements corresponding to wavelengths between lower and upper wavelengths, such as between 400 and 2400 nanometers, in given increments, such as every 1 nanometer. For example, each spectrum could have a first reflection measurement at 400 nanometers, a second reflection measurement at 401 nanometers, a third reflection measurement at 402 nanometers, and so forth. The first spectrum 222 (“M1”) can be a control or reference data set captured with respect to a healthy plant (such as control curve 242 of FIG. 9). However, the second spectrum 224 (“M2”) can be a captured data set for a given disease or stage of infection being targeted by the model (such as inoculated curve 244 of FIG. 9). The first and second spectrums 222 and 224, respectively, can then be applied to a function 226 to produce an array of coefficients 228 (“X”) or multiplier values corresponding to the wavelengths between the lower and upper wavelengths. The function 226 is applied to produce coefficients 228 that are configured to emphasize identification of the given disease or stage (exhibited by the second spectrum 224). That is, the coefficients are determined to maximize contributions of reflection measurements at particular wavelengths which are most indicative of the given disease or stage.

Referring again to FIGS. 9-12, wavelengths which may maximize contributions of reflection measurements for the various stages of P. infestans are identified by bands 240. By way of example, for identifying the early infection stage of P. infestans, a reflection measurement at 1000 nanometers may provide a greater predictor of presence of this stage of infection than a reflection measurement at 500 nanometers (see FIG. 9). As a result, a coefficient corresponding to 1000 nanometers can be emphasized by the function 226 by configuring a greater value coefficient at 1000 nanometers and a lesser value coefficient at 400 nanometers. In one aspect, the function 226 can apply a partial least squares discriminant analysis with respect to the first and second spectrums 222 and 224, respectively, to generate the coefficients 228.

With additional reference to FIG. 14, coefficients 228 can be prepared for each given disease or stage of disease being targeted by the process for analysis. For example, first coefficients 228a (“X1”) can correspond to an A. solani model comparing the reference data set M1 captured with respect to a healthy plant to a data set M2 for a plant inoculated with A. solani; second coefficients 228b (“X2”) can correspond to a first stage P. infestans model (early infection) comparing the reference data set M1 captured with respect to a healthy plant to a data set M2 for a plant inoculated with first stage P. infestans; third coefficients 228c (“X3”) can correspond to a second stage P. infestans model (biotrophic growth) comparing the reference data set M1 captured with respect to a healthy plant to a data set M2 for a plant inoculated with second stage P. infestans; fourth coefficients 228d (“X4”) can correspond to a third stage P. infestans model (necrotrophic lesion formation) comparing the reference data set M1 captured with respect to a healthy plant to a data set M2 for a plant inoculated with third stage P. infestans; fifth coefficients 228e (“X5”) can correspond to a fourth stage P. infestans model (sporulation) comparing the reference data set M1 captured with respect to a healthy plant to a data set M2 for a plant inoculated with fourth stage P. infestans; and so forth. In addition, sixth coefficients 228f (“X6”) can correspond to a model indicating a likelihood of presence of one or more data sets M2 for a plant inoculated with a given disease or stage. Accordingly, such models can be configured to indicate a likelihood of presence of diseases and/or stages in a plant.

Referring back to FIG. 8, after generating the models, the process can continue to step 204 in which a given plant sample can be measured by the spectrometer 16. Referring also to FIG. 14, the plant can be measured to produce a sample spectrum 230 (“MO”) representing an array of reflection measurements corresponding to wavelengths between the lower and upper wavelengths, in increments corresponding to the models, such as every 1 nanometer. Reflection measurements of the sample spectrum 230 can then be applied as variables for indicating a likelihood of presence of diseases and/or stages in the plant. In particular, at step 206, each reflection measurement of the sample spectrum 230 can be multiplied by a coefficient for a given wavelength, for each of the models produced. An analyzer 232, in turn, can receive the products of the sample spectrum 230 separately multiplied by each set of coefficients 228 in separate paths. With these calculated values, the analyzer 232 can analyze the results of each path to determine a likelihood or probability of a disease being present, an identification of the disease if present, and/or an identification of a stage of infection of a given disease if present. In one aspect, the analyzer 232 can apply stages of multivariate regression to produce an output.

Still referring to FIG. 8, at decision step 208, the process can determine a likelihood of presence of a disease. If a
A. solani
measurements corresponding to wavelengths in a spectrum.
the sample spectrum
the analyzer
to the one or more models.
Then, at decision step 216, the process can
come to whether the identified disease is comprised of
stages of infection. For example, P. infestans could be
comprised of four identifiable stages of infection based on
targeted models, such as early infection, biotrophic growth,
necrotrophic lesion formation, and/or sporulation. However,
A. solani might not be comprised of any further identifiable
stage of infection, aside from the disease itself. If the
identified disease is not comprised of stages of infection
(“No”), the process can proceed to step 210 to record and
output the results of the disease itself, then step 212 to
measure a next sample spectrum 230, and then step 206 to
apply the new reflection measurements as variables again
with respect to the one or more models. However, if the
identified disease is comprised of multiple stages of
infection (“Yes”), the process can proceed to step 218 to identify
the stage of infection to a given probability.
Then, the process can proceed to step 210 to record and output
the results of the disease and stage, then step 212 to measure
a next sample spectrum 230, and then step 206 to apply
the new reflection measurements as variables again with respect
to the one or more models.

Referring again to FIG. 14, in one aspect, output 234 from
the analyzer 322 could comprise a ranking (“Z”) of the
likelihood of presence of each disease and/or stage of
infection of disease with probabilities, corresponding to the
paths produced by the different models of coefficients 228.
For example, when analyzing a sample spectrum 230 with
respect to six different models X1-X6, the results of each can be
ranked from most probable to least probable. Moreover,
in some aspects, the first ranked result can be provided to an
output, such as a graphic display implemented on a com­
puter screen or mobile device.

Referring now to FIG. 15, in another aspect of the
invention, a spectrometric imager can be used to capture
images 250 comprising spectral pixels 252 in which each
spectral pixel comprises reflection measurements corres­
dponding to wavelengths in a spectrum. For example, an
imager can capture the image 250 of a plant leaf comprising
in rows and columns of spectral pixels 252. Each spectral
pixel can comprise an individual sample spectrum M0, like
the sample spectrum 230, which could be modeled and
analyzed in the system of FIG. 14. Depending on distance
from the plant being measured, and resolution of the imager,
greater or lesser numbers of sample spectrums M0, covering
greater or lesser areas of plants, can be captured and
analyzed in varying degrees. Accordingly, such analysis can
be carried on a micro level, such as with respect to leaves
and plants, and/or on a macro level, such as with respect to
fields and terrains.

With additional reference to FIG. 16, in one aspect, an
overhead vehicle 258, such as an aircraft, drone or satellite,
could include such an imager used to capture images 260 of
a large terrain, such as swath of the Earth’s surface, in which
spectral pixels 262 of the image each comprise reflection
measurements corresponding to wavelengths in a spectrum.
At this macro level, an image 260 could capture large areas
of plants and vegetation, such as a first spectral pixel 262
capturing densely populated trees. However, the image 260
could also capture significant areas of non-plant material,
Phytophthora infestans (P. infestans)
tification of the disease.

value quantifying a relative difference between reflection measurements are transformed into spectral values, each spectral measurements are applied to indicate a likelihood of presence of one or more stages of infection of disease.

ments correspond to wavelengths between 400 and 2400 nanometers.

The system of claim 1, wherein the reflection measurements correspond to wavelengths between 400 and 2400 nanometers.

4. The system of claim 3, wherein the reflection measurements are provided in increments of at least 1 nanometer.

5. The system of claim 1, wherein the reflection measurements are applied to indicate a likelihood of presence of Phytophthora infestans (P. infestans) or Alternaria solani (A. solani).

6. The system of claim 1, wherein the reflection measurements are applied to indicate a likelihood of presence of one or more stages of infection of P. infestans.

7. The system of claim 6, wherein the stages of infection comprise: early infection; biotrophic growth; necrotrophic lesion formation; and sporulation.

8. The system of claim 6, wherein the model produces an output ranking the likelihood of presence of each stage of infection.

9. The system of claim 1, wherein the reflection measurements are transformed into spectral values, each spectral value quantifying a relative difference between reflection measurements at differing wavelengths to emphasize identification of the disease.

10. The system of claim 9, wherein the spectral values are Normalized Differential Spectral Index (NDSI) values, each NDSI value being calculated as a difference between reflection measurements at differing wavelengths divided by a sum of the reflection measurements at the differing wavelengths.

11. The system of claim 10, wherein the model applies no more than ten NDSI values for indicating the likelihood of presence of the disease or stage of infection of disease.

12. The system of claim 1, wherein the processor further executes to send the likelihood of presence of the disease or stage of infection of disease to a graphic display.

13. The system of claim 1, wherein the spectrometer is attached to a contact probe, an agricultural implement or an aerial vehicle.

14. A system for detection of disease in plants, comprising:

an imager configured to capture an image comprising a plurality of spectral pixels, each spectral pixel corresponding to a spectrum of electromagnetic radiation reflected at a plurality of wavelengths, the spectrum comprising reflection measurements corresponding to wavelengths; and

a processor executing a program stored in a non-transient medium to apply reflection measurements at each spectral pixel as variables in a predetermined model configured to indicate a likelihood of presence of a disease in a plant at the spectral pixel and output the likelihood of presence of the disease in the plant.

wherein the model provides an array of coefficients multiplied by each reflection measurement, wherein each coefficient corresponds to a given wavelength and emphasizes identification of a disease or stage of infection of disease.

5. The system of claim 1, wherein the reflection measurements at differing wavelengths divided by a sum of the reflection measurements at the differing wavelengths.

11. The system of claim 10, wherein the model applies no more than ten NDSI values for indicating the likelihood of presence of the disease or stage of infection of disease.

12. The system of claim 1, wherein the processor further executes to send the likelihood of presence of the disease or stage of infection of disease to a graphic display.

13. The system of claim 1, wherein the spectrometer is attached to a contact probe, an agricultural implement or an aerial vehicle.

14. A system for detection of disease in plants, comprising:

an imager configured to capture an image comprising a plurality of spectral pixels, each spectral pixel corresponding to a spectrum of electromagnetic radiation reflected at a plurality of wavelengths, the spectrum comprising reflection measurements corresponding to wavelengths; and

a processor executing a program stored in a non-transient medium to apply reflection measurements at each spectral pixel as variables in a predetermined model configured to indicate a likelihood of presence of a disease in a plant at the spectral pixel and output the likelihood of presence of the disease in the plant.

wherein the model provides an array of coefficients multiplied by each reflection measurement, wherein each coefficient corresponds to a given wavelength and emphasizes identification of a disease or stage of infection of disease.

5. The system of claim 1, wherein the reflection measurements at differing wavelengths divided by a sum of the reflection measurements at the differing wavelengths.