



Hyperspectral Imaging Cameras in Rapid Detection and Potential Diagnosis of Agricultural Crop Threats

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1.0 Abstract

Remote monitoring of crops via satellites using color cameras was the earliest form of spectral imaging in agricultural management. Due to limited capabilities, only basic plant health parameters could be reported. The advent of hyperspectral imaging systems has presented the industry with the potential ability to not only monitor plant health, but also to detect potential plant pathogens. The impact of chemical contaminants and fungal, viral, and bacterial pathogens ranges from moderate to severe but can result in complete crop losses for major commodities such as corn, wheat, and soybean world-wide. Early detection is critical to limiting spread and losses in almost all instances. A new, dynamically adjustable and cost effective hyperspectral imaging technology is introduced as a tool for early identification and prevention of spread of such diseases to mitigate crop losses.

2.0 Hyperspectral Imaging and Precision Agriculture

Hyperspectral imaging cameras generate 'hyper-cubes' of data, whereby the spectrum at each pixel in the image is collected. Subtle reflected color differences that are not observable by the human eye or even by color cameras are immediately identifiable by comparison of spectra between pixels. A variety of spectral imaging technologies exist. Below (**Table 1**) shows some of the most widely used.

Parameter/ Technology	FPI	AOTF	Filter Wheel	Liquid Crystal Tunable/Lyot	Pushbroom Grating	Sagnac Fourier Transform Inter- ferometer	CTIS (Comput- ed Tomogra- phy)
Technique	Fabry-Perot Balon Interfer- ometer	Solid-state non-linear crystal	Mechanical	Solid-state non-linear crystal	Dispersion and mechanical scanning	Interferometric	Dispersion
Spectral Resolution	BP < 4 nm in VIS, scales up in NIR.	Dynamically variable ≥ 1.2 nm (1.2 nm in blue)	Fixed and must be defined by filters selected a priori. Typical- ly 1-10 nm.	Fixed and must be defined by design a priori. Typically 7 nm.	Fixed and must be defined by design a priori. Depends on choice of grat- ing and slit, but fixed. Typically 1 nm.	Fixed but typi- cally high	Fixed but typi- cally ≥ 5 nm.
Data Capture	Fixed sequential band-pass with random access	Variable sequential band-pass with random access	Sequential band-pass	Fixed sequential band-pass with random access	Full spectrum, spatial scan only	Full spectrum only	Full spectrum only
Switching Speed	~ 1-2 ms	100 μ s	~ 50 ms	100-1500 ms	10 ms - minutes	> 10 ms	N/A - Long pro- cessing times
Manufacturers	Hinalea	Brimrose	Sutter, Ocean Optics, SpectroCam	CRi, Meadowlark Optics	Resonon, Specim, Headwall	ASI	J-Y Verdi

TABLE 1: Spectral Imaging Technology Comparison

Push-broom grating systems were the earliest forms of the hyperspectral cameras, initially developed by NASA, mounted on satellites and airborne platforms for research purposes. Over the past decade there has been growing interest in adapting them for use in agriculture. However, these systems must be mounted on a platform that can move at constant velocity, such as a drone or satellite, as they collect images by scanning one line of a field of view at time [1].

Band sequential, front staring or snapshot imagers do not require mechanical scanning. In this technique, a tunable filter that can

sequentially select spectral bands is placed in front of the sensor and generates the hyper-cube by collecting complete images at each spectral band-pass. The acquisition time does not depend on the number of pixels, but rather on the number of spectral bands being acquired. These imagers are especially attractive for applications requiring high spatial and spectral resolutions with tunable spectral ranges and a small form factor.

Fabry-Perot interferometers (FPIs) operate by placing two mirrors parallel to each other. By designing reflectivity and adjusting the spacing of the mirrors, high-finesse spectral filtering can be achieved. See **Figure 1**. Hinalea's hyperspectral cameras all use this FPI technology, which results in small and lightweight systems for field use. The Model 4250 VNIR camera in **Figure 2** captures multi-megapixel images in 300 spectral bands in a few seconds. Moreover, the technology enables real-time processing, so the user does not need to handle the large data sets typically generated by hyperspectral systems. Rather, the camera can identify features of interest, both in the spectral and spatial domains and classify these features in the image [2].

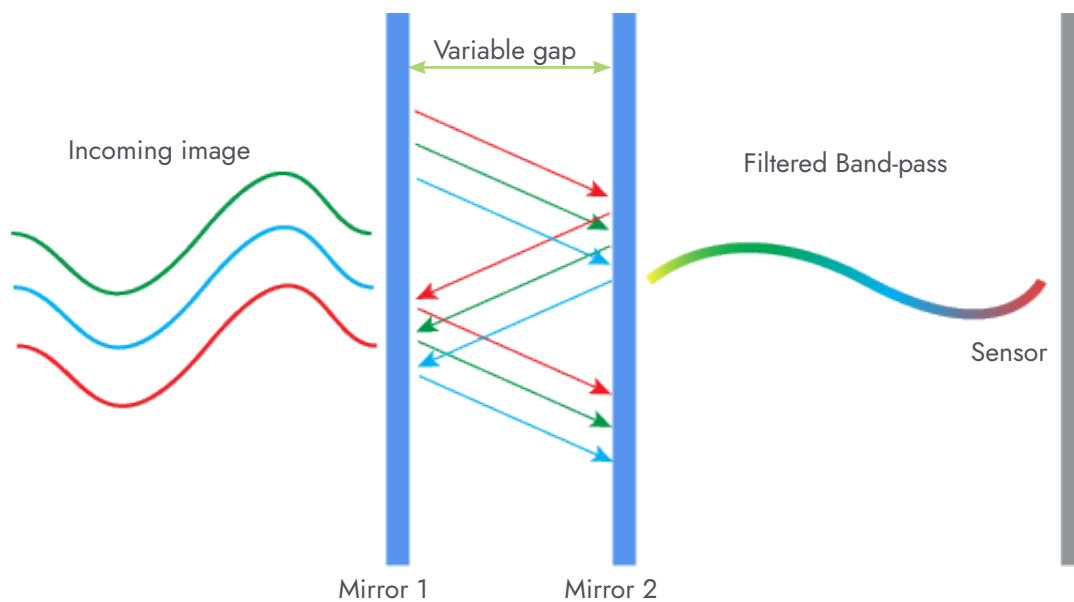


FIGURE 1 Operating Principle Fabry-Perot Filter

The technology can easily be configured into form factors and configurations suitable for laboratory bench-top investigation or production line testing. Such an implementation has not been possible for other band sequential techniques (i.e. AOTFs, liquid crystal tunable filters) due to reproducibility issues, environmental, and power restrictions.

Front staring systems also offer other advantages over line-scanning technologies for agricultural applications, most notably more versatile viewing geometry options. Such systems can not only be used by field operators, but can be mounted on airborne platforms, tractors, and other land vehicles. Moreover, like all automated systems, in contrast to human observers, they are not subject to fatigue, experience, and training. Systems can be configured to quickly assess large samples areas and populations in remote locations at any stage in the plants growth cycle.



FIGURE 2 Model 4250 VNIR (400-1000 nm)

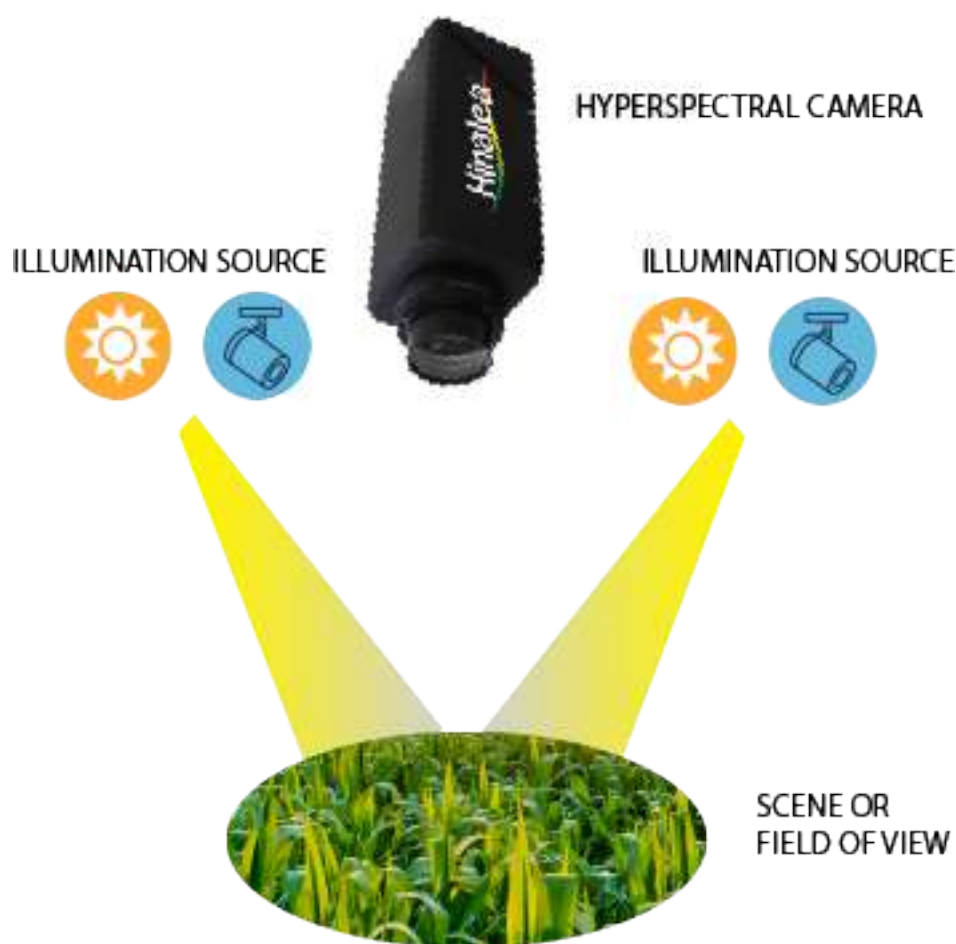


FIGURE 3 Typical Deployment Scenario

Furthermore, hyperspectral imaging allows for detecting unique identifying features that can only be seen in comparison of spectra and are invisible to the eye. More commonly, color (RGB) cameras and multi-spectral imagers with limited band-passes are used on UAV and satellite platforms because of their relatively low price point. The limited ability to identify unique spectral signatures means while these technologies bring the benefits of automating the process, they do not provide enough actionable feedback to recognize returns.

Unlike traditional line-scanning hyperspectral systems used in agricultural applications, Hinalea's technology enables high-spatial

and spectral resolutions and versatile viewing geometries in a real-time, wavelength-programmable package. These systems can be used by field operators, mounted on airborne platforms, masts, tractors, other land vehicles, and in laboratory environments. For outdoor use-cases, solar illumination is sufficient; for indoor automated greenhouses and vertical farming installations, LED and Quartz Tungsten Halogen (QTH) is commonly used (**Figure 3**).

3.0 Monitoring Plant Health

The most popular conventional methods of detection of plant health and diseases are based on ‘scouting’ by human observers. Such visual methods are subject to observer training, varying ability to concentrate on a task for long periods and limited by the human eye’s ability to discern color differences and the time to inspect large areas. Hence, the introduction of remote imaging technology held significant promise for more reliable and accurate reporting of plant health.

Yet, due to the limitation of early satellite and airborne systems in terms of band-passes and spectral resolution, indices based on ‘heuristic models’ or simple ratios of available band-passes were as detailed as was possible at the time. Such parameters provided useful but limited assessments, typically of plant health, growing conditions, coverage, and development. Such information is critical not only to prevent devastating crop losses from conditions such as drought and overexposure but also to assess their quality and nutritional value. See **Table 2**.

Hyperspectral imaging cameras enable measurement of multiple indices within a single instrument while also obtaining additional information not discernible from such representative data. For example, **Figure 4** shows data from Hinalea’s camera, measuring the top leaf, facing east with contact imaging of a 10x16 mm measurement area of Swiss chard crops at Urban Farm (Berkeley, CA). From these measurements, the level of betalain content (used as red pigment and phytonutrient which provides significant antioxidant, anti-inflammatory and detoxification support) can be determined. The figure also illustrates the collection of the data and the normalized reflectance spectra and relative reflectance spectra.

TARGET	SPECTRAL RANGE (nm)
Chlorophyll Absorption; Anthocyanins	VIS (400-700)
Chlorosis	VIS (550-650)
Chlorophyll Concentration (Red Edge Shift)	VIS (~680) 705-745
Crop Growth/Leaf Area Index (LAI)	VIS (705-745)
Vegetation Health and Biomass Content, Stressed Vegetation	NIR (760-900)
Normalized Difference Vegetation Index (NDVI)	NIR (760-900)
Vegetation Health and Biomass Content	NIR (860-1040)
Moisture	SWIR (1.57 - 1.65 μ m)

TABLE 2: Major Agricultural Parameters Measured by Remote Sensing (Solar Reflectance) [3]

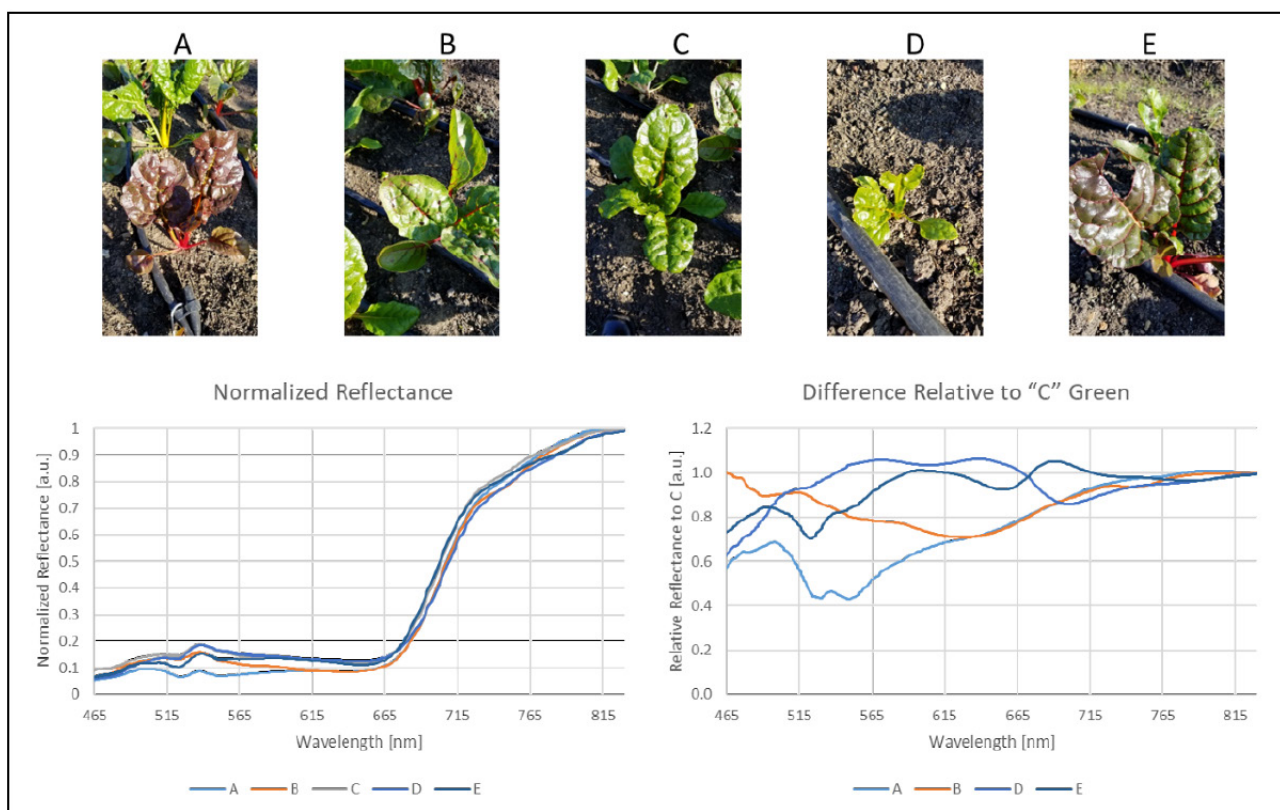


FIGURE 4: Hyperspectral image captures of Swiss chard crops at Urban Farm (Berkeley, CA). Spectral reflectance data of red chard row

Similarly, plant stresses can also be easily monitored by a benchtop configuration of the Hinalea hyperspectral camera. **Figures 5 and 6** show the effects of plant stress over time. A common green weed is imaged by a system with a larger field of view system (80mm x 130mm). Note that the reflectance spectra change over time as an indication of plant stress (i.e. loss of moisture). The raw, normalized, and difference spectra shown in subsequent graphs.

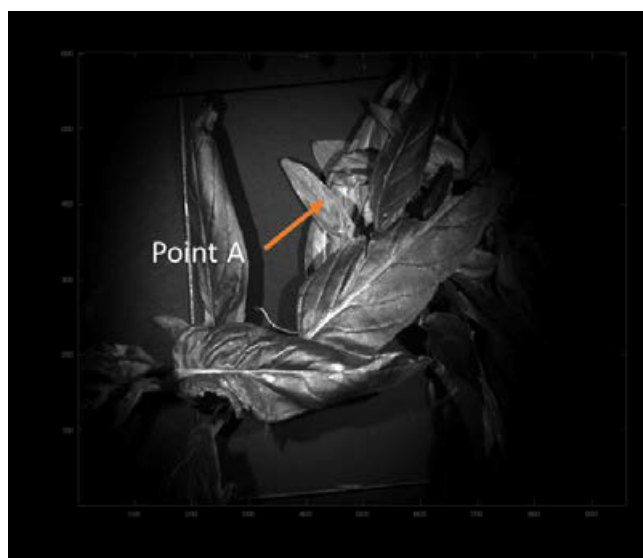


Figure 5: Stressed Weed Image at T=0

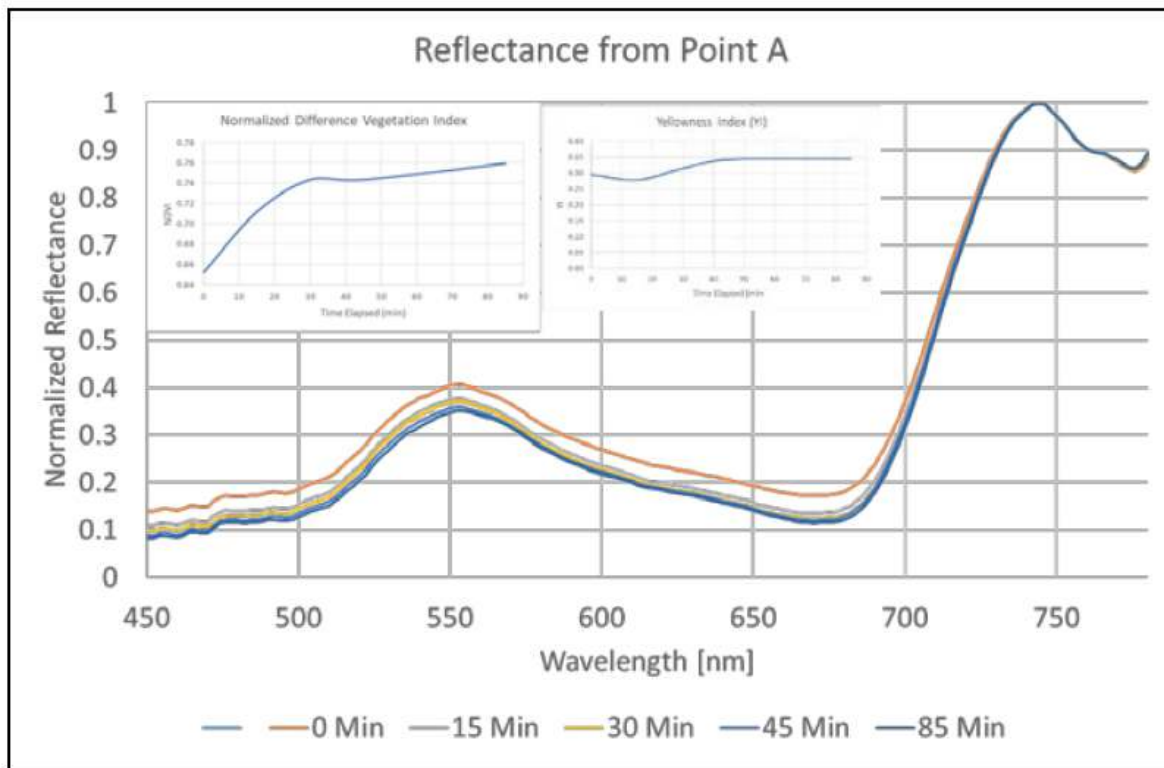


Figure 6: Spectral reflectance over time at 'Point A' on stressed weed

4.0 Pathogen Crop Threats

Detection and mitigation of losses due to pathogens is a strong economic motivator for adoption of hyperspectral imaging in industrial agriculture. Wheat (\$10B), soybean (\$40B) and corn (\$50B) are major crops in the United States [4] and susceptible to specific plant diseases which can have critical impacts on their yields.

4.1. Brown Rust

Most pathogens exhibit distinct physical symptoms. For example, wheat leaf rust is a disease that affects the stems, leaves and grains of not only wheat but also barley, rye and other major cereal crops. Also known as 'brown rust', it is caused by the fungus *Puccinia triticina* and spread via spores.

The disease occurs worldwide and is spread by wind and water. It is most severe when mild and humid conditions are present during the flowering stage in the spring. In southern states the pathogen can survive over the winter. The disease is identifiable by its fruiting spores or 'uredinia'. These typically appear on the leaf surface but can also be present in the sheath. They appear as brown circular spots which do not penetrate the leaf itself. See **Figure 7**.



Figure 7: Wheat Leaf Rust Symptoms [5]

Crop losses range from moderate 20%, to severe, from 50% to even 100%. The disease has the greatest impact prior to flowering when the spots cover leaves prior to flowering. The disease parasitically robs the plant of its nutrients resulting in premature loss of leaves and a reduced period for grains to populate as well as smaller, often shriveled kernels.

Treatment options range from application of fungicides to seed and variety selection to field application of fungicides. However, the fungus has shown an ability to adapt quickly to resistant strains. Hence, early identification is critical to mitigating impact. This is currently done by human 'scouting' of fields for indications of the disease and taking samples to an expert (i.e. local county extension at a university or college) for confirmation [6,7].

4.2 Frogeye leaf spot

Frogeye leaf spot is a common soybean pathogen caused by the fungus *Cercospora sojina*. The fungus infects leaves, stems and pods. The disease occurs worldwide and is most severe in warm regions or during periods of warm, humid weather. Domestically, it occurs mainly in southeastern soybean growing areas but recently have increased in the mid-west to levels comparable to those in the south due to favorable weather conditions in the past five years.

The most commonly identifiable symptom are small, yellow spots on the leaves which can be as large as ¼" with gray-reddish brown and purple margins. Stems and pods also exhibit reddish-brown lesions and seeds may appear dark, shriveled and have a cracked coat. See **Figure 8**.



Figure 8: Frogeye Leaf Spot Symptoms [6]

Domestic crop losses can be as high 30% annually on susceptible varieties with severe blighting and reduction in leaf area. As a polycyclic disease, the damage and disease will continue to increase if the weather is favorable for infection. If the infection persists until late in the season, the fungus will infect pods and seeds where it can survive in residues, affecting future crops. Although disease resistant varieties have been identified, each of these new crop breeds tends to be resistant to only a specific strain of the disease. Therefore, early detection and preventing future infection are critical to mitigating losses. Treatment in the form of blanket spraying of fungicides can lessen the severity, but not eliminate, the infection and are most effective either at the seed or pod development (R3) stage [8,9,10,11].

4.3 Maize streak disease

Maize streak disease is caused by a viral pathogen, the maize streak virus (MSV, Mastrevirus of the family Geminiviridae), transmitted by insects, predominantly the maize leafhopper (*Cicadulina mbila* Naude). It is known to cause epidemics with crop losses as high as 100% throughout sub-Saharan Africa and parts of Asia.

Symptoms appear 3 to 7 days after infection, typically initially on young tender leaves, as uniform chlorotic and yellow streaks of varying width centered on the leaf veins. The disease results in stunting of the plants and underdevelopment of the ears. Prevalence increases under favorable conditions of high rainfall and elevated temperatures. MSV is often easily confused with other pathogens with similar symptoms. See **Figure 9**.



Figure 9: MSV Symptoms [9]

Diagnosis is currently performed by human inspection and confirmation through ELISA (Enzyme-Linked Immunosorbent Assay) or similar laboratory testing methods, whereby detection often occurs after damage can be mitigated through treatment. Although resistant varieties of maize exist, many are not accessible to farmers in the region affected and conflict with their open pollination practices. Pesticide treatments pose significant risk to humans and are controversial. For example, the recent introduction by Dow Chemical of a maize variety and pesticide combination sparked protest when it was revealed that it shared a common chemical component with the Agent Orange herbicide used by the US Military in the Vietnam War [12,13,14, 15,16,17].

The Hinalea hyperspectral imaging system, with its combination of a high resolution spatial image with the spectral information contained within each pixel may be, for example, used for a reliable detection and diagnosis of such plant diseases. Such an instrument would be capable of not only detecting a pathogen such as Maize Streak Virus but also able to distinguish it from similar pathogens such as Bacterial Maize Streak disease allowing for appropriate measures to be applied and avoiding misdiagnosis and lost time, opportunity, and crops [18].

4.4 Herbicide drift

Finally, the drift of herbicides such as dicamba into non-target crops can result in serious losses (60%-70%) even at low treatment rates (0.05X). In 2017 alone, farmers reported 3.6 million acres of damage from dicamba and complaints of off target exposure are expected to rise. Symptoms include 'leaf cupping' and stunting of the plant. There is supporting data showing that drift can be detected early, regardless of concentration, prior to symptoms using spectral techniques in the VNIR range (325-1075 nm) and that higher spectral resolution than that used in common vegetation indices is required. See **Figure 10**. In such instances, hyperspectral imaging can not only provide information on exposure but also coverage, potentially continuously as in a pole mounted configuration. Earlier work on glyphosate and paraquat support the hypothesis that the technique can be used to detect other herbicide and pesticide exposure on off target crops [19,20,21].



Figure 10: Dicamba Drift Symptoms [20]

5.0 Dynamically Adaptable Solutions for Crop Management

The earliest stage at which diseases can be detected is at the seed stage. The visual indicators for contamination or infection are somewhat ambiguous to the human eye, but a unique spectral profile or signature can likely be identified. A seed inspection station using a bench-top hyperspectral inspection tool based on the Hinalea technology with a wide field of view lens is ideal for this sorting task. With appropriate application software, images are spectrally classified with false color labels using machine learning algorithms. This is not possible with non-imaging tools. See **Figure 11**. These images are easily interpreted by operators without the need for sophisticated or extensive training. Moreover, when combined with automated handling systems, the hyperspectral imager can rapidly segregate infected specimens from healthy ones.

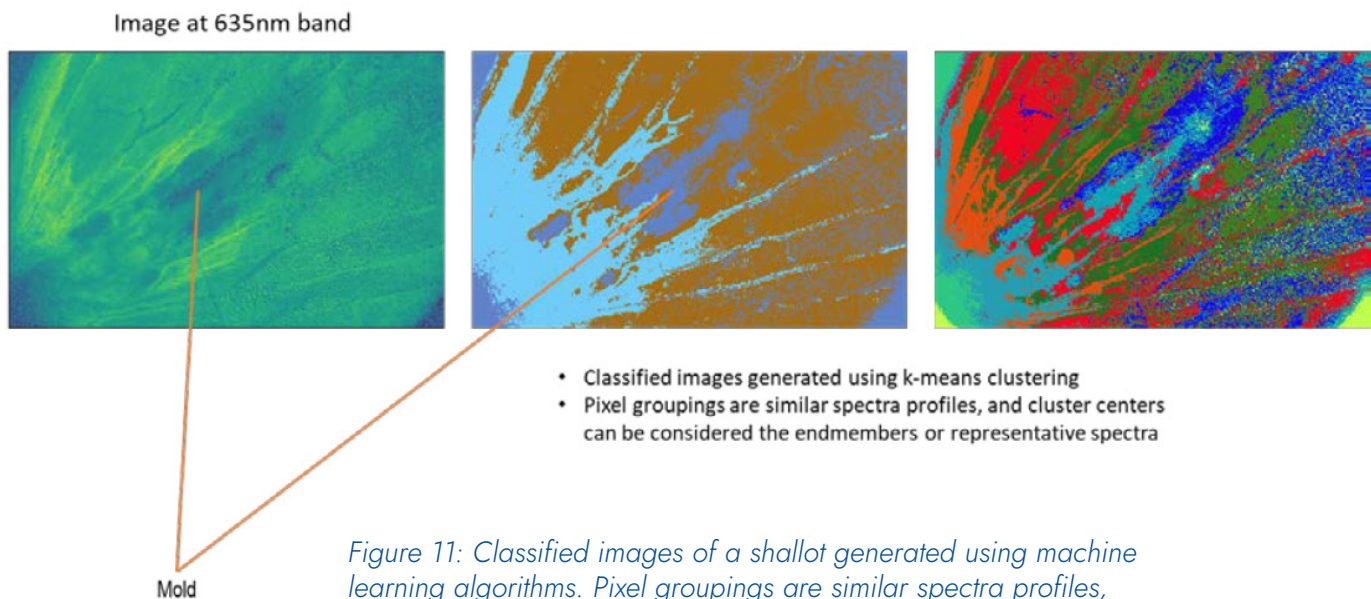


Figure 11: Classified images of a shallot generated using machine learning algorithms. Pixel groupings are similar spectra profiles, and cluster centers can be considered the endmembers or representative spectra

In the field, leaf inspection using a compact tool which provides microscope-level high resolution with a processed output showing infected areas in the field with similar labels at early stages would allow operators to quickly and rapidly take actions and apply treatments such as fungicidal spraying to counter spread of the disease. Tractors or other vehicles are also ideal platforms for automating and expediting the process in the field, combining identification and treatment into a single step.

6.0 Conclusion

By identifying indicators in plants invisible to the eye, color cameras, and multi-spectral imagers commonly used on UAV and satellite platforms, Hinalea's camera can increase the reliability of early specific detection to save farmers money and ensure the quality of food on our tables.

Moreover, the ability to dynamically change spectral range and band-pass capability of the Hinalea technology means the same instrument can be configured within a single campaign or mission. For example, a drone mounted system can be set up to capture the critical band-passes for an overpass of a given crop and then changed by data from on board GPS to another en route.

However, threat determination and mitigation is only one aspect of the many agricultural applications of hyperspectral imaging in the near IR. For example, it has been shown to be effective in seed variety classification to determine variety purity and increasing crop yield [22]. Such unprecedented versatility confers significant savings not only in capital equipment investments but also in operating costs.

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