DEVELOPMENT OF A BROAD LANDSCAPE MONITORING SYSTEM USING HYPERSPECTRAL IMAGERY TO DETECT PEST INFESTATION

John Glaser¹, Joseph Casas², Kenneth Copenhaver³, Steffen Mueller³

¹US Environmental Protection Agency
National Risk Management Research Laboratory
26 W Martin Luther King Jr Dr, Cincinnati, OH, 45268 USA
513-569-7568 (V), glaser.john@epa.gov

²NASA Marshall Space Flight Center, Huntsville, AL
320 Sparkman Drive, Huntsville, AL 35805 USA
256-961-7717 (V), joseph.c.casas@nasa.gov

³University of Illinois at Chicago Energy Resources Center
1309 S Halsted St, 2nd Floor, Chicago, IL 60607 USA
312-996-4490 (V), kcopenha@uic.edu

ABSTRACT

Comprised of 28 million hectares in 2007, the United States (US) maize agricultural landscape was valued at \$52 billion. Any threat to the continued dependability of this crop, now important as both a food and fuel source, becomes an important economic and ecological resource management factor for the global economy. Many genetically modified maize varieties contain toxins that target insects, reducing insecticide applications with positive ecological and human health consequences. Crop monitoring is required by US law to manage the development of insect resistance. To assess the onset of resistance, a proactive monitoring system must be able to identify maize infestation across the broad agricultural landscape. Non-destructive monitoring tools are necessary at a scale and definition required to discern insect infestation effects. A joint USEPA and NASA hyperspectral imagery and decision support system project has been successfully evaluated for its ability to distinguish insect infestations in several locations.

Index Terms— Genetically modified crops, decision support system, agriculture, bio-fuels, policy

1. INTRODUCTION

Increasing demand for the production of maize emphasizes the economic and ecological importance of the crop in meeting the needs of the emerging biofuels industry while still meeting the requirements of the more traditional food and feed uses and has led to increase plantings and profits. Maize plantings in the United States grew over 3 million hectares from 31.7 million in 2006 to 34.8 million in 2008 [1]. The economic value of the crop also increased from

\$32 billion to \$52 billion in 2006 alone due to increases in yield and prices [2]. The use of genetically modified (GM) maize varieties has been at least partly responsible for the increase in yields in recent years [3]. Many GM maize varieties have genetically inserted toxins (plant incorporated protectants (PIP)) which specifically target and are fatal to certain insect pest orders. Yield increases combined with the reduced use of broad-spectrum pesticides that have ecological and human health consequences are expected to increase the number of hectares planted in GM PIP maize substantially. GM PIP varieties increased from 40% of the total maize plantings in 2006 to 57% in 2008 and are expected to continue to increase with the introduction of new traits and stacking of multiple traits in the same plant [4]. The financial attractiveness, improved yields, and improved insect protection of GM PIP maize is expected to force changes in agronomic practices where the planting of maize on the same field for multiple years could become the operational norm. This practice, combined with the increasing hectares in GM PIP, will significantly increase the likelihood of insect populations developing resistance to the PIP toxins as they could return to the same location each year with the same GM PIP maize plantings. The United States Environmental Protection Agency (USEPA) recognizes preservation and monitoring of GM PIP crops to be in the “public good” because of the overall reduced pesticide use. Registration of all GM PIP crops in the US is required under the Federal Insecticide Fungicide and Rodenticide Act. Part of the registration requirements directs the applicant seed producer to establish a stewardship program to accompany each new crop variety. An element of the stewardship is a monitoring program for pest resistance development.

The increase in production hectares and changes in agronomic practices underscore the need for aggressive monitoring of the GM PIP maize crop to identify the development of insect pest resistance in the shortest time possible. Recent analyses using spatially complex models found that resistance initially evolved in areas with a local high density of GM PIP crop fields [5]. Resistance spread outwards from these centers of insect adaptation. These results emphasize the need for a proactive monitoring approach that must involve the inspection of all 30+ million hectares of the US maize crop. In the massive US landscape devoted to maize cultivation, the only clear solution is the use of remote sensing which can sample large areas in a single space and time to reach the breadth of the maize production landscape.

To improve the ability to detect local changes in insect pest population that is representative of resistance to PIP maize an approach of proxy sampling using remote sensing has been evaluated by the USEPA. USEPA turned to the National Aeronautical and Space Administration (NASA) in these efforts in recognition of NASA's legacy of earth monitoring through the use of remote sensing. The two agencies developed a multi-year project designed to move the research effort to monitor for insect pest resistance to GM PIP crops from a concept to an operational system which could be used by the Office of Pesticide Programs within USEPA. More specifically, the research plan was designed to move from proof of concept (can remote sensing detect insect infestations in maize at the plot level with high resolution hyperspectral imagery) through a proof of principle (can these methods be applied at the production field level) to proof of practice (can the methods developed be used on a portion of the maize production landscape scale) and, finally, to an evaluation of an operational system over the entire maize production landscape (Figure 1).

Figure 1. NASA/USEPA research plan and timeline.

At each step, criteria were put into place to end or modify the project if the USEPA/NASA team could not achieve critical objectives. To date, the project is in the proof of practice phase with plans to move into an evaluation of the entire system by 2010. The evaluation phase will include the structured development of CERES (Crop Evaluation Research for Environmental Strategies), a

decision support system within this research project. CERES will combine NASA space-based sensors to provide area wide surveillance with airborne sensors tasked to monitor local conditions and in-field inspection teams to provide the final discernment of insect pest resistance development. USEPA will use the information provided by CERES in developing resistance strategies and required monitoring capabilities. Eventually, CERES can be made available to seed producers, agricultural growers, government and academia to allow each group to monitor and report resistance as it occurs to ensure the continued, effective use of the PIP technologies and the security of the American food and fuel supply.

2. METHODS

The hyperspectral imagery used for the insect pest resistance monitoring project has been collected each year from a fixed wing aircraft equipped with a Zeiss T-AS gyro-stabilized mount at heights of 300 to 3,600 meters with spatial resolutions from 0.5 to 2.0 meters using a digital camera with a spectrograph and lens. The spectral resolution, bandwidths and processing methods have changed from year to year as software and hardware improvements have been implemented and project requirements have changed, but the primary spectral and spatial resolutions and data products developed for analysis have remained consistent (Table 1).

Table 1. Sensor specifications for each study year

Year	Width (Pixels)	Spec. Res.	Spat. Res.	FWHM	Bands
2004	640	470nm 830nm	0.5 meters	1.5 nm	120
2005	640	470nm 830nm	0.5 meters	1.5nm	120
2006	1600	400nm 900nm	1 meter	2.5nm	100
2007	1600	400nm 900nm	1 meter	2.5nm	100
2008	1600	400nm 900nm	1 meter	2.5nm	100

Imagery collected for the project has been corrected for distortion, georectified and calibrated to percent reflectance prior to analysis. Improvements in the methods used to perform these tasks have led to near automated techniques including the use of a global positioning system and inertial navigation system to correct for plane movements and geo-rectify the imagery, and lab calibration of the sensor for automated at-sensor and atmospheric calibration.

Analysis methods have included traditional image classifications, signal processing analyses and statistical analyses all designed to identify insect infestations as accurately and consistently as possible. The goals of the project are to deliver replicable, validated and verified

results. Therefore, the methods have focused on the development of an algorithm or set of algorithms that can be applied to imagery without requiring any additional analyst input such as a threshold value at which a vegetation index is determined to indicate infestation. The project has balanced automation, speed, and accuracy in order to develop a method that can deliver the desired results. Minimum spectral and spatial requirements were also considered to determine if lower resolution satellite imagery would reduce project costs and increase data availability.

Maize small plots (approximately 4 m. by 12 m.) were developed and supervised by the United States Department of Agriculture (USDA) Agricultural Research (ARS) and University researchers. Certain plots were manually infested with insect pests.

3. RESULTS

The project began with basic, plot level research in 2004 and continued in 2005 in the maize producing US states of Iowa, Pennsylvania, and Nebraska. Hyperspectral imagery was collected over the plots. Imagery measurement ratios were developed based on the statistical analysis of the imagery which indicated maximum separability between infested and un-infested maize, derived from an analysis of variance at 650 nm (mid red) and 750 nm (near-infrared). These results were consistent for all three sites and both years (Figure 2).

Figure 2. Analysis of variance results for comparison of infested and un-infested indicate maximum separation at 648nm and 747nm for all three sites (PA, NE and IA) for 2004 and 2005 combined.

As indicated in figure 2, reflectance increased in the red with infestation and decreased in the near-infrared, a ratio of the two bands maximized separability was developed. A threshold ratio was developed based on ground verification of infestation in the plots. Ratio values above the threshold value were classified as infested and those below were classified as un-infested. The results

indicated that hyperspectral imagery could be used to identify infested maize. Classification accuracies improved over the growing season with increasing infestation levels. Accuracies in Nebraska and Iowa were greater than 90% late in the season (Table 2). Accuracies in Pennsylvania were lower as natural infestations confounded the results.

Table 2. Classification accuracies for identification of insect infested plots

Year	Location	Accuracies
2004	Iowa	97%
2004	Nebraska	99%
2004	Pennsylvania	72%
2005	Iowa	88%
2005	Nebraska	97%
2005	Pennsylvania	78%

The positive results at the plot-level from 2004 and 2005 encouraged the project to move closer to an operational environment in 2006. Collection of the hyperspectral imagery and ground verification of infestation locations was extended to production maize fields in Illinois. East-central Illinois has a history of infestation with the western corn root worm (CRW) which is an insect targeted by many of the PIP maize toxins. Imagery was collected over the fields and within 24 hours a potential infestation map was generated using the project-developed ratio and other algorithm techniques. Using global positioning system (GPS) guidance, scouts were sent to locations within fields identified as potential infestations in the image products. Using these methods, a field was identified as potentially infested in 2006. Upon visiting the field, scouts found damage from CRW feeding. Assay testing, however, indicated no GM PIP toxins in the maize. Discussions with the grower determined that the portions of the field with infestation had mistakenly not been treated with insecticide. Natural infestations in the production environment are expected to be rare events as PIP toxins and insecticides are intended to minimize the events. Finding an infestation using the imagery as a guide was a positive indication that imagery can identify infestations and potential resistance to GM PIP toxins in the production environment.

In 2007 and 2008, the project moved more toward operational implementation. Techniques were developed to automate image processing for the rapid development of maps for the fields. Larger numbers of fields were covered by ground verification scouts with the goal of finding as many infestations in the production environment as possible. In 2007, project scouts discovered infestations of CRW in production fields containing GM PIP maize (Figure 3). The cooperating grower had alerted the project team to CRW issues in the field. When a ratio image product from August

17 was analyzed, mottled patterns of stress were evident. Further field investigation and crop assays identified a continuous pattern of CRW infestation in areas where a GM PIP variety was planted. This maize was seed insecticide treated but did not have the PIP CRW toxin. A more interesting pattern was revealed in the southern half of the field where linear groups of healthy maize were followed by linear groups of stressed maize. The field work revealed that one CRW PIP variety was being affected by CRW infestations while a second (planted in a split planter) was not. The grower indicated that the hybrid that was not being affected was a newer hybrid and probably better able to handle the infestations.

Figure 3. Mottled grey patterns in image indicate infestation from CRW. First image is one infested variety. Second image shows two varieties (one infested) planted side by side.

Results from 2008 also produced a 32 hectare field with CRW infestations in PIP maize. The infestations were previously unknown by the grower and were first identified from the hyperspectral imagery. Locations of special interest within the field were tagged for the scouts to visit who identified damaged maize in these locations. Representative samples of maize stalks were removed and the roots assessed. Results for the root ratings indicated that root worm pressure was experienced well above the allowable tolerance in GM PIP maize. The evidence of CRW pressure in the 2007 and 2008 imagery (each in PIP maize) is strong evidence of the usefulness of the imagery.

4. FUTURE WORK

The project plans to begin the system evaluation phase in 2009 while continuing proof of practice in the production environment in eastern Central Illinois. System evaluation will include a set of procedures that specify all critical components for a decision support system including spatial, spectral and temporal resolution requirements. As part of system evaluation, the CERES monitoring tool will be further developed, examining the production maize landscape at four different spatial perspectives. The regional perspective will use NASA MODIS imagery to examine overall crop vigor; the landscape perspective will

determine locations of maize fields, contiguous maize fields and locations at which maize has been planted in continuous years as well as the vigor and changes in the maize fields. High resolution imagery will identify potential infestations and possible GM status and field scouts will examine locations with the greatest likelihood of infestation.

5. CONCLUSIONS

Results from the 2004 and 2005 analysis indicated that insect pest infestations could be readily identified. Statistical analysis identified a simple ratio that could be applied to two bands of imagery to consistently identified infestations. Once the concept was proven at the plot level, a proof of principle at the production field level in Illinois and Minnesota was initiated in 2006. Again, hyperspectral imagery collected at one meter resolution was able to detect infestations. During proof of practice in 2007 and 2008, the hyperspectral imagery collection was expanded over production maize fields in Illinois and automated techniques were applied to rapidly produce image products taken to the field for verification. The methods resulted in the identification of infestations in PIP corn in two separate years indicating the imagery could be used in the larger production environment. The project still must develop and evaluate methods that will allow for the assessment of the entire 30+ million hectare production maize environment which will include the development of methods to monitor at multiple resolutions using multiple sensors.

6. REFERENCES

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