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Future Directions for Automated Weed Management in Precision Agriculture

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Abstract

In cropping systems, integrated weed management is based on diversification. Rather than relying solely on one or two herbicides, a multiplicity of weed control strategies is employed. Yet, integrated weed management as currently practiced is far from integrated; every weed is still managed the same regardless of location or season. The recent development of precision application technology is now allowing for smaller treatment units by making applications according to site- specific demands. The automated systems of the future will have sensor and computer technologies that first categorize each and every plant in the field as either weed or crop and then identify the species of weed. Following identification, multiple weed control tools located on a single platform are applied at micro-rates to individual plants based on their biology. For example, if the system identified a weed resistant to Roundup, it could be spritzed with a different herbicide or nipped with an onboard cutter or singed with a burst of flame. This system and others like it will be capable of targeting different weed-killing tools to specific weeds. This chapter will discuss the challenges and tools of the future.

1 Introduction

The population of the world has surpassed seven billion and is expected to reach nine billion by 2050. This presents a global challenge involving the land and resources available. Current estimates indicate 1.2 acres are required to feed a single person (Giampietro and Pimentel 1994). The total land mass of the world is approximately 149 million km^2 where 12–18 % is arable land suitable for crop production. If it takes 1.2 acres to feed one person and there are only 27 million km^2 of arable land, we can only feed 5.5 billion people, which is dreadfully short both now and into the future. From a pragmatic perspective, the conceptual options are reduce the population of the world, increase the amount of arable land, or increase the production efficiency of the number of acres to feed one person. It is obvious that the first two are not likely to occur, so we are left with the last option. To accomplish this in a reasonable period of time will require new planning, funding, research, and outreach. Possible solutions include advances in weed management, improved efficiency in irrigation, progress in genetic research, and the development of better precision crop management. Precision in crop management requires knowing more about plant, soil, and climatic conditions and how to adjust and accommodate changing soil and environmental conditions.

Producers are often faced with challenges from both the environment and the application of technology to various scales and complexity of production that exists locally, nationally, and even globally. In 2012, several regions across the globe (e.g., central USA) were in a drought resulting in extremely challenging conditions for successfully growing crops. Irrigated agriculture did well, while dry land producers realized significant negative economic impacts. Producers also faced challenges with high input costs, such as fuel prices to run tractors and machines, nutrient expenses to improve yield, and pesticide costs to reduce losses, not to mention the associated societal impact.

In the future, it is highly probable that commercial fertilizers (e.g., phosphorous, nitrogen) and water for growing crops will not be as readily available, and, therefore, we will be challenged with how to adequately supply our crops with fertilizers and water. These challenges can be captured under the broad concept of a yield gap (Lobell et al. 2009). The yield gap can be defined as the difference between yield potential that could be achieved under ideal production and the yield obtained under current production. Closing this yield gap will contribute to meeting the food and fiber demand for our increasing global population.

As noted earlier, improved weed management and precision agriculture have the potential to contribute to solving the yield gap challenge. Weeds compete with crops for light, nutrients, and water. Weedy and invasive plants cost the world economy billions of dollars annually in crop damage and lost earnings. In the USA, various states have reported annual weed control costs in the hundreds of millions of dollars. Herbicides account for more than 72% of all pesticides used on agricultural crops. Furthermore, it is estimated that $4 billion was spent on herbicides in the USA in 2006 and 2007 (Grube et al. 2011).

With the increased use of precision crop management comes the need for gathering crop, soil, and environmental information and implementing machine control. The typical paradigm for crop management in Controlled Environment Agriculture (CEA) is to focus on the status and health of individual crop plants. In many ways, the health of field-grown plants is affected by weeds. For example, each individual weed in a field consumes water and nutrients that could be used by crops. Numerous other considerations must be accounted for, and we can now develop the technology to precisely address individual plants, both crop and weed. Unfortunately, the wind, rain, and environmental elements create difficult conditions for easily and quickly making targeted treatments to individual leaf surfaces or small plants. In addition, terrain and spatial distribution of crops and weeds can be nonuniform and difficult conditions to address that are independent of weather and climate. These challenges currently do not have a simple answer, especially with limited funding for perceived high-risk research projects. Therefore, the perception of national and international agricultural policy managers, many in industry, and financial investors that control investment capital needs to change if solutions to the limited world food supply are to be obtained.

2 Future Patterns

Agricultural land use dropped slightly from 54 to 51 % between 1982 and 2007, labor input declined 30 %, but productivity increased 50 % (O'Donoghue et al. 2011). During the same period, adoption of new technologies increased dramatically. Plant and soil sensors have been a rapidly developing area of technology with widespread adoption in many fields, including agriculture. From Global Positioning Systems (GPS), to guidance, to the potential use of robots for weed management, agriculture has advanced rapidly in recent decades.

In the health and environmental sciences, recent developments have included new sensors at the microscale. At Georgia Tech, scientists are inserting nano-piezoelectronics into the human body to detect early signs of disease in blood, detect minute amounts of poisonous gases in air, and to find trace contaminants in food. These devices are very sensitive, run on low power, some from minuscule generators, but tiny in size. A startup laboratory, BioNanomatrix (now BioNano Genomics), is pursuing the key to personalized medicine, which is based on the rapid computer assessment that can sequence an entire genome in 8 h for a mere $100. With this powerful tool, medical treatment could be tailored to a patient's distinct genetic profile. Perhaps a similar approach can be applied to signature plants within a given field, as an early warning system for biological stress.

Other available or developing technologies that use sensors and embedded computing systems are pill cameras that are remote controlled for movement within the digestive system with muscular contractions. Smaller but still relatively high-resolution cameras result in lighter payloads and smaller energy requirement for robots and other deployment systems to gather plant information.

Figure 1. The light field camera. (Drawing Courtesy of S. A. Smith, Graphics Artist, Biological Systems Engineering, University of Nebraska–Lincoln)

Another type of camera, which was proposed back in 1908 and is receiving recent attention, is the light-field camera (Harris 2012) (Figure 1). Also called a plenoptic camera, it uses a microlens array to capture 4D light-field information about a scene. The plenoptic camera features a matrix of tiny lenses on a sensing chip. These sensors gather light from different sources and directions. Such light-field information can be used to develop a three-dimensional database of the features of complex scenes, such as a canopy. Changing the focal plane would allow one to look deep inside canopies for pests and disease on leaves that are exposed to the sky.

It is obvious that the trends are moving society toward more integration with technology. In cropping systems, a combination of biology and engineering has recently merged to address management tools designed to respond to the dynamics of nature in the land, air, and water.

3 The Need for Change

Current weed control practices lack the precision needed to effectively and safely control weeds without harmful side effects. Organic and conventional producers rank weed control as their number one production cost. For organic producers particularly, weed control has become increasingly important as organic production has increased its market share. In conventional systems, herbicide resistance, off-target movement, and increased regulations have left many growers with few alternatives. Added to this is an increasing demand from the public for a safer and more sustainable supply of food (see Chapter 2). The problems of current mechanized agricultural systems have set the stage for the introduction and adoption of more advanced technology to meet the needs of growers and satisfy the desires of consumers.

Automation and sensor technology continues to expand rapidly with advancements in all fields, including medical, mechanical, and analytical sciences (see Chapter 3). The applications to agriculture have occurred at a slower pace, but new technology is changing this. For the weed scientist, plant biology is one of the most important factors for developing weed control strategies. Without an understanding of the changes that occur during plant growth and development, most weed control practices will be less than satisfactory. Critical to automated control will be an account of weed morphology and the precise periods of when control measures need to be applied (see Chapter 4).

Primarily, weeds are controlled mechanically or chemically in current cropping systems. Mechanical disturbance or destruction is applied to weeds with blades, bars, discs, or other steel instruments that move at a continuous pace through the field following a designated path (see Chapter 7). Similarly, herbicide applications are made indiscriminately to plants, either weeds (e.g., directed spray) or crops and weeds (e.g., herbicide-resistant crops), using broadcast spray equipment (see Chapter 8). Both mechanical and chemical methods of weed control make inputs based on the general or average condition of the field without accounting for the spatial and temporal changes that occur at microscales.

In some parts of the world, there is a pressing need for more precise weed control using advanced technology (see Chapter 10), while in other regions, regulations are less stringent and development is occurring only for select and small market crops (see Chapter 9). Globally, economics are the biggest driver for the adoption of precision weed management technologies (see Chapters 12 and 13). Even in least developed countries, the use of technology for precision weed control has potential but not without support from government programs and cooperation with other nations (see Chapter 14).

4 What Lies Ahead?

Production agriculture is contributing in meeting the needs of a growing population, but our methods for growing food must get better faster or we could face a significant shortfall. One way to do this is by being more precise in our management of pests (e.g., weeds), which will result in increased production, lowered inputs, and reduced environmental contamination, which in many ways moves us closer to more sustainable systems.

Precision weed management (PWM), which simply stated “places the right amount of inputs on the right target [weeds] at the right time,” is an approach to managing weeds that is better for the environment and better for the producer as it leads to a reduction of inputs without decreasing weed control efficacy. In fact, one of the biggest contributions of PWM is the improved efficacy of controlling virtually all weeds in any cropping system (e.g., conventional, organic) (Figure 2). This shift in approach is based on strong collaborations between biologists, computer scientists, and engineers who are working to harness tools with powerful technology and use them to better manage weeds, which are a major problem in cropping systems throughout the world.

Figure 2. Weed robots of the future will have all of the control tools and a decision support system on a single platform that moves autonomously through the field. Not only that, but also UASs will circle overhead and work directly with on-the-ground robots through wireless communications. (Drawing courtesy of S. L. Young)

4.1 Plant Recognition

Most studies during the last 20 years have addressed the classification of only two crop-weed classes or general cases of broad leaf versus grasses and in other cases, crop row versus between the crop row (Tang et al. 2003). However, to precisely classify a plant species that may be imbedded within other different species of plants in an image is a botanically challenging exercise. Due in large part to advanced sensor and computing technology, it is now possible to put together a complete robust system that essentially mimics the human taxonomic, plant identification keying method. Future studies are needed to determine minimal digital image resolutions needed to maintain the highest species discrimination performance.

Fuzzy logic, cluster algorithms, and cluster reassembly routines mimic human perception and decision-making and tend to work well for extracting convex leaf shapes from plant canopy images (Neto et al. 2006). However, for more botanically diverse leaf shapes, such as species with complex leaves, lobed margins (indented), and trifoliolates, new fitness criteria must be developed to accommodate various leaf shapes. Undoubtedly, integration of specific shape and textural venation feature analyses as a fitness or classification criteria may be a key to improvement for plant species identification (Price et al. 2011). Work has already begun on utilizing digital canopy architecture metrics such as three dimensions, which is important to plant taxonomy.

Table 1. UAS examples and application areas focused on weed management

Examples	Application areas
Precise placement of optical and thermal sensors	Weed control applications
Sensors for natural resource management	Invasive species detection/mapping
Crop scouting opportunities	Infestation detection/mapping
Soil moisture and vegetation type/index	Crop canopy condition/growth stage
Pesticide management and field application	Space/time resolution; crop dusting
Remote sensing with multispectral sensors	FLIR, LIDAR, gas/moisture flux

4.2 Aerial Technology

Collection of very detailed plant canopy and soils production information may be implemented using Unattended Aerial Systems (UASs) equipped with various sensors and extended local wireless data collection capabilities. The UAS offers a unique opportunity to place crop and soil sensors, robotics, and advanced information systems at more timely and desired field locations for increasing production and improving efficiency of agricultural operations. The opening of National Airspace to UAS, currently scheduled for the fall of 2015, has the potential to make a significant contribution to closing the yield gap and could be a "game changer" for the agricultural industry. The potential application of UAS in agricultural and natural resources are wide and varied (Table 1).

The effectiveness of an aerial system as such will depend on its ability to both cover a large expanse of cropland and levitate or focus over desired areas of the crop field. In addition, the UAS will need to carry an appropriate sensor and data storage package, remain on a given target area, and work in tandem with on-the-ground robots via wireless communications. Remote sensing has been traditionally available from satellites and low-flying manned aircraft in the past, however, with variable data quality and high cost. Current trends are that fixed wing UASs have the longest range with flight time measured in miles and hours, compared to multi- propeller helicopters, some with only 20 min of air time. Terrestrial robot systems, especially small ones, may also have short operation times due to energy demands and our current state of energy system density, with lithium polymer batteries being the state of the art. Electro-optical (photonic) sensor technology is quite advanced. Yet another extension of these thoughts includes the concept of a UAS collaboration network, in which multiple UASs work together (perhaps even employ swarm technology), along with an array of terrestrial-based robots, to realize an integrated, collaborative framework that achieves outcomes that are not possible by single robotic systems. The UAS industry has identified precision agricultural applications, including weed control and management, as the single largest market opportunity through year 2025 (Jenkins and Vasigh 2013). Research and development on the deployment of information gathering and subsequent control technology is the current limiting factor (Figure 3).

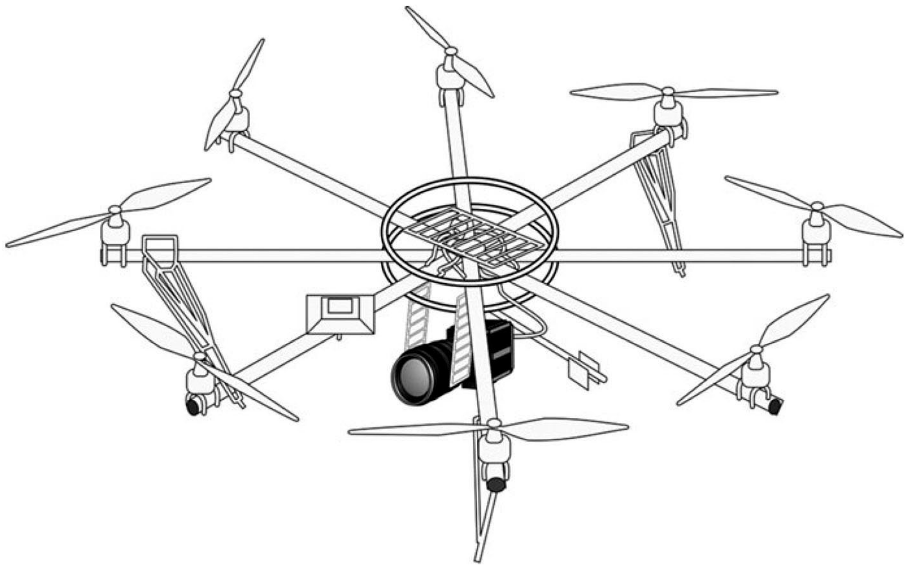

Figure 3. Multi-rotor Unmanned Aircraft System (UAS). (Drawing courtesy of S. A. Smith, Graphics Artist, Biological Systems Engineering, University of Nebraska)

5 What Do We Need to Do?

Success on PWM is based on the integration of expertise from multiple fields of study that can address a problem that has plagued agriculture from its very start: weeds. Even before the introduction of the first herbicides, researchers had been developing biological methods and engineering approaches to control weeds. Since then and more recently, a reliance on herbicides eliminated the need for real advancement in weed management, and subsequently engineers and biologists tended to work separately.

Today, the broadcast application of herbicides is impacting our ecosystems (e.g., runoff, drift, ground water contamination) and causing entire cropping systems to fail (e.g., herbicide-resistant weeds), signaling the need for renewed collaboration between biologists and engineers. Considering the increasing number of people on this planet and the little amount of time to reconcile how to feed them all, we cannot afford to have our current systems fail, let alone ignore what is needed for the future.

In an effort to address this need, a paradigm shift is needed by those involved in weed control in cropping systems from the grower to the consultant to the researcher. If we expect to continue to maintain current yields and also increase production in the future, we will have to think more broadly in incorporating alternative approaches in our management strategies. A possible starting point is the model by Zijlstra et al. (2011) for a crop protection system of the future that is

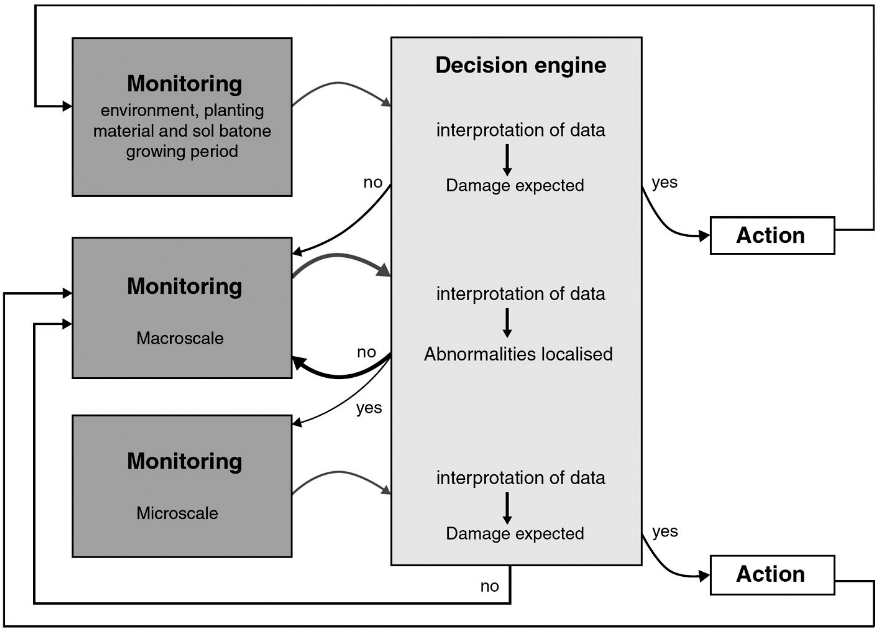

Figure 4. Generic model of an innovative crop protection system. The first monitoring step and the subsequent decision step are performed before the growing period; the other steps are performed during the growing period (Reprinted with permission from Zijlstra et al. 2011)

based on novel monitoring tools and precision application technologies (Figure 4). With a historical account of the field and following the planting of the crop, monitoring is conducted on macro- and microscales. At any point, certain locations or "hotspots" could be targeted in the field with the appropriate and precise action made at individual plant scales. According to Zijlstra et al. (2011), the two-step monitoring from macro- to microscale levels would enable earlier detection of pests (e.g., weeds) and thus require new action thresholds and dose-response relationships, which would require substantial research effort.

The ability to monitor an entire field at the individual plant scale will require the use of communications, mobile devices, and decision support software, which make up swarm technology. In the future, the use of robots working in a coordinated effort to manage individual crop plants or swarm through a field may become more important than genetically engineered seeds or new fertilizer formulations. Dorhout R&D LLC (http://dorhoutrd.com/home/prospero_robot_farmer) has developed a small six-legged robot ("Prospero") that has successfully planted an Iowa cornfield in a test run (Figure 5). Robots can make very precise decisions about where and when to plant seeds based on different kinds of soil type within the same field. Rather than using a GPS device to lay a precise line of seeds in a field, the Prospero robots talk to each other as they crawl, staying within about 2 meters of each other. Eliminating a GPS unit helps keep the robots "brains" simple as well as lowering the cost of each unit.

Figure 5. Prospero, the robot that plants and manages crops fields of the future. (Reprinted with permission from Dorhout R&D LLC (http://dorhoutrd.com)

The next step for the small company is scaling up the robots and, as with all autonomous devices, pushing battery power to extend their daily life span. Given the increasing demands on farms to produce more food, and the small margins on which farmers operate, Dorhout R&D LLC and others expect to see more automation in the fields in the near future.

It is safe to say that if we could manage weeds without inputting toxins, causing erosion, and changing genetics, we would. Unfortunately, the population of the world is increasing, yet the amount of arable land available for producing crops is not. Therefore, we need to get more precise in managing crop production and at the same time take steps to protect and limit damage to the ecosystems that ultimately support all life forms in all parts of the globe.

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