True integrated weed management

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Introduction

Crop production is most often by the hectare, and in most cases, inputs are applied in kilograms and liters and averaged for an entire field using equipment that spans multiple crop rows (Tilman et al., 2002). While studies have shown within-field variability to be large at both macro- and micro-scales (Earl et al., 2003; Steiner et al., 2008; Verhulst et al., 2009), the overall adoption of technology for variable rate and site-specific management has lagged behind its development (Bullock & Lowenberg-DeBoer, 2007; HakJin et al., 2009).

In cropping systems, the needs of individual plants, including weeds, can change dramatically over very short distances. There are obvious requirements of plants, such as nutrients and water, and more subtle requirements, such as light, air and microbial interactions. In most conditions, plants must compete for resources, which end up diminishing their overall growth and development. Weeds in production systems often occur in patches of various sizes or as individuals growing among crop plants, yet they are managed in a way that is similar to the crop, large-scale and uniform. A combination of control methods, such as chemical, mechanical and cultural, are used at different times of the season or over several seasons, but rarely are single weed plants targeted. In many areas, farmers indicate that weeds are the number one problem (Gibson et al., 2005), yet weeds, like crop plants, are not managed at the individual plant scale, although this is becoming a focus of some research (van Evert et al., 2011; Zijlstra et al., 2011).
Current Integrated Weed Management (IWM)

Integrated weed management has been defined as an approach to managing weeds, which relies on multiple tactics to stress weed populations and increase the competitive ability of the crop (Smith et al., 2010). According to Swanton et al. (2008), integrated weed management is a cropping systems approach that relies on essential knowledge for its implementation and focuses on crop health. They view it as a series of interactions among several weed control components. Thomas et al. (2010) state that at the core of integrated weed management lies the principle of using knowledge of organisms and that of the agroecosystem and a variety of tools, to provide the needed selection pressure to keep the competitive balance in favor of the crop to the detriment of undesired species (e.g. weeds).

Much information exists on agronomic weeds, including their history, biology, ecology and methods for control. The integration of this information should result in knowledge-based evaluations and decisions that will guide their management (Swanton et al., 2008). In its present form, integrated weed management focuses on the reduction in weeds using individual techniques over a single season or multiple seasons and typically incorporates the use of broadcast-type equipment (e.g. cultivators, sprayers, mowers). As production costs have risen, weed control research has been conducted on ways to lower either inputs or the number of operations. In the case of herbicides, most studies have focused on reducing inputs through low-volume, over-the-row, or variable rate applications (Bohannan & Jordan, 1995; Riar et al., 2011). These techniques have resulted in fewer chemicals being released, but they have done little to improve application efficacy, where treatments are made directly to the target (but see van Evert et al., 2011; Nieuwenhuizen et al., 2010; Sogaard & Lund, 2007).

While integrated weed management has become commonplace in the weed science research community (Hamill et al., 2004), few studies are conducted in a broader context that incorporates site-specific treatments using real-time decision support systems across wide-ranging spatiotemporal conditions. Basic and applied weed science research has not often focused on the use of advanced technology, which may be due to the development of highly effective chemical controls (Gianessi & Reigner, 2007). As technology advances, so too should the traditional approaches related to weed management, especially for addressing field variability and the economics of crop production systems. As stated by Davis et al. (2009), ‘it is long past time for weed scientists to move beyond a dominating focus on herbicide efficacy testing and address the basic science underlying complex issues in vegetation management at many levels of biological organization currently being solved by others [biological systems engineers, computer scientists]’. Similar sentiments are echoed by EN-DURE (European Network for Durable Exploitation of Crop Protection Strategies), a European Network of Excellence (http://www.endure-network.eu), which sees integrated pest management as a continuously improving process with locally adapted solutions that contribute to diversifying agricultural systems.

The need for change

For agronomic weeds, herbicides, a heavily relied upon management tool, are receiving increased negative attention, because of the environmental issues of off-target movement and trace residues now found on fruits and vegetables (Tadeo et al., 2000; Barbash et al., 2001). Other disturbances, such as cultivation or plowing, can result in excessive soil loss that lowers productivity and contributes to undesirable environmental conditions, such as siltation of waterways, flash flooding and disruption of stream ecology (Pimentel et al., 1995). The environmental and economical impacts from the use of broadcast-type weed control tools are a major concern for producers, researchers and the public and should be enough incentive to focus more research on the use of advanced technology to develop truly integrated weed management programs.

Sensors and guidance technology are being developed for cropping systems that would allow for real-time recognition of target plants (e.g. weeds) and potential improvements in the discrete and targeted application of management tools at very fine spatiotemporal scales (Singh et al., 2011). By bringing a greater number of integrated weed management tools to the field for targeted and precise applications, the heterogeneous nature of agroecosystems, particularly weeds, can be managed in a safer and more sustainable way.

Because of rising public interest in sustainability and protection of natural resources and readily available research-grade technology, a greater number of studies are needed to identify approaches and develop systems that are truly integrated across spatiotemporal scales. By combining the knowledge-base on weeds (e.g. weed growth and development) with the developments in engineering and computer science, increases can be realized for environmental protection, public safety and grower profits.

New engineering developments

The development of machine-guided technologies for precision weed control has advanced rapidly in re-
cent decades (Slaughter et al., 2008; Singh et al., 2011). The robotics of weed management includes sensors for measuring biological and physical properties, decision-making capabilities to determine necessary agroecosystem manipulation(s) and actuators for making treatments (Harrell et al., 1988). Sensor-based equipment is being tested for accurate identification of pests (e.g. weeds) in the field at the individual organism scale in real-time (Tellaeche et al., 2008, 2011; Singh et al., 2011). Numerous research programs in the field of biological systems engineering in the US, Europe and around the world are making powerful discoveries in robotics and vision systems for use in agricultural production systems (Grift et al., 2008), including optically guided inter-row weed cultivators (Tillet and Hague Technology, Ltd., UK), autonomous tractors available in 2012 (Kinze Manufacturing, Inc., USA) and automated pruning and harvesting machine prototypes (Vision Robotics Corporation, USA).

Technological advancements specific to weed control have been made in many areas, including mechanical, chemical, thermal and electrical (Slaughter et al., 2008). For example, in the United Kingdom, a weeding robot and integrated band steaming were shown by Sørensen et al. (2005) to potentially reduce labor demand by up to 85% in sugar beet and 60% in carrots. In addition to sugar beet, mechanical weed removal using an actuator and hoe has been demonstrated for cotton, tomato, lettuce, broccoli and melon (Garrett, 1966; Astrand & Baerveldt, 2002).

The first published report of selective spot herbicide application technology was by Lee et al. (1999), who developed a prototype system with microcontroller actuated-specific solenoid valves, delivering liquid to the spray ports, based on the machine vision generated weed map and robot odometry. Improvements to this first prototype have been made by Lamm et al. (2002) and others. Published research has begun to increase on the assessment of micro-dose herbicide applications that target the weed in cropping systems (Giles et al., 2004; Sogaard & Lund, 2007; Nieuwenhuizen et al., 2010). In glasshouse studies, a typical rate of glyphosate (1.5 kg ha$^{-1}$) reduced by over 75% applied at 10 µL directly to the cotyledon leaves of Abutilon theophrasti Medic. (velvetleaf) killed 100% of the plants (Young, personal observations).

Several other weed control tools have been investigated for use in combination with robotic systems, including flame weeding, hot water, organic oils and high voltage electrical discharge (Slaughter et al., 2008). With advances in sensors and guidance technology, integrated weed management could change dramatically. By using technologically equipped machinery that can target individual weeds in real-time, there is no limit to the number of control tools for use in the field at any one time. The advances in the biological systems engineering field are evidence that ‘given enough time, an engineer can build anything.’ Biological research and the latest technological developments in weed control have the potential to radically change the current research approach to integrated weed management and help significantly reduce environmental impacts (e.g. drift, off-target movement) and the high cost of inputs and labor.

**True integrated weed management in the field**

Sensors and guidance systems are currently being developed for real-time identification of weedy plants, and research on targeted control systems is not far behind (Christensen et al., 2009; Kempenaar et al., 2011). Being able to combine recognition and application technology into a single platform is a critical area of research that requires biology, engineering and computer programming. There is a need for the development of a single platform with sensors and decision support software that has multiple application technologies for directed weed management. Ideally, a self-guided machine is needed that could comb the field in a systematic way to identify weeds and then apply the necessary control tool (e.g. spray, mow, cultivate) at the individual plant or patch scale (Figure 1).

From a biological approach, successfully integrating weed management requires an understanding of three key components: the effect of treatments on weed populations, weed growth and development stages and the critical period for applying control tools (Swanton et al., 2008). Control tools (e.g. mowing, spraying, cultivating) have differing effects on weeds, and without a complete understanding of the life history of the target weed(s) and crop, the development of effective and efficient robotic systems will be extremely challenging,
if not impossible. In all crops, there exists a period in which weed control is critical to avoid incurring yield loss (Knezovic et al., 2002). An autonomous robotic system that is designed without consideration for timing of weed removal will perform poorly in current cropping systems. Such a robotic system that can respond to critical periods of crop growth must be either manually sent into the field or programmed to perform weed control operations that are in synchrony with crop growth stage.

In integrated weed management, the identification of weeds and applications for their control could occur at various spatiotemporal scales using the latest machine-based guidance systems with sensors and decision support systems. A single-platform system with many different weed control tools will bring greater flexibility and responsiveness in managing current cropping systems (Figure 1). Individual weeds can be killed with a tool (e.g. spraying, cultivating, cutting) that is selected by an onboard computer with pre-programmed information on weed characteristics and images and tool efficacy. As the platform moves through a field, weeds are identified, categorized and killed without damaging the crop. For each field, a map is generated that has the location of the weed and the control tool used. The map is stored on the computer to prevent repeated use of the same tool for the next operation. The environmental conditions, such as soil moisture, wind speed, precipitation, temperature and relative humidity, are measured using instrumentation located onboard the single-platform system. Ultimately, this real-time integrated weed control system will reduce reliance on one tool (e.g. spraying, cultivating) and eliminate the current problems of herbicide resistant weeds, off-target movement and soil erosion, while lowering overall input costs. The primary constraint of this system would be that weed control will decline dramatically with weed maturation, a fact that has been known since the dawn of agriculture and is still being addressed today.

It is anticipated that with greater collaboration between the fields of weed science and biological and computer science, the following two goals can be achieved: (i) combination of weed management tools into one operation to allow for a truly integrated system and (ii) advance of sustainable integrated weed management programs through reductions in environmental contamination and human exposure to chemicals, with fewer inputs needed to economically control weeds.

**Final thoughts**

Combining recognition and application technology into a single platform for fast and efficient weed control across spatiotemporal scales will require precise information on weed biology and ecology and continued testing of technology for a wide range of field conditions (Slaugh ter et al., 2008; Singh et al., 2011). While a single platform for conducting real-time integrated weed management is futuristic, it is now possible to begin assembling the components and to think broadly while working across disciplines. One of the many common goals for biologists and engineers working in agriculture is the elimination of weeds while minimizing negative impacts to the environment and economics. It is apparent that technology can assist in addressing the current limitations of integrated weed management at micro-scales and at the same time help to meet the demand for food, feed and fiber in a sustainable way at macro-scales.

**References**


