Weed Technology

cambridge.org/wet

Symposium

Cite this article: Young SL (2018) Beyond Precision Weed Control: A Model for True Integration. Weed Technol 32:7–10. doi: 10.1017/wet.2017.70

Received: 12 May 2017
Accepted: 3 August 2017

Associate Editor:
Krishna Reddy, United States Department of Agriculture

Key words:
Advanced technology; automation; decision support; true IWM; robotics; UAV

Author for correspondence:
S. L. Young, Adjunct Assistant Professor, Soil and Crop Science Section, and Director, Northeastern IPM Center, Cornell University, Ithaca, NY, 14853. (E-mail: sly27@cornell.edu)

© Weed Science Society of America, 2017.

Beyond Precision Weed Control: A Model for True Integration

Stephen L. Young[1]

[1]Adjunct Assistant Professor, Soil and Crop Science Section, and Director, Northeastern IPM Center, Cornell University, Ithaca, NY, USA

Abstract

Precision means being exact and accurate and is an important management component for cropping systems. However, precision does not mean integration, which encompasses spatial and temporal dimensions and is a necessary practice rivaling precision. True IWM merges precision and integration by incorporating advanced technology that allows for greater flexibility of inputs and enhanced responsiveness to field conditions. Examples of this approach are non-existent due to a lack of suitable technological tools and a need for a paradigm shift. Herein a potential model startup company is offered as a guide to advance beyond precision weed control to true integration. The critical components of such a company include grower connections, investor support, proven and reliable technology, and adaptability and innovation in the agricultural technology market. The company with the vision and incentive to make true IWM a reality will be the first to more fully integrate available tools using technology, thus helping many growers overcome ongoing challenges associated with resistance, soil erosion, drift, and weed seedbanks.

Weed Management: Past, Present, and Future

Growers use multiple tools (e.g., mechanical, chemical, cultural, biological) to control weeds in cropping systems. Herbicides and cultivation have proven to be very effective at controlling weeds, yet environmental and human health concerns have led farmers and regulators to search for ways to reduce their use (Slaughter et al. 2008). Most weed control applications are based on the assumption of uniform weed distribution. However, weeds exhibit patchy growth in crop fields, leading to unnecessary applications to bare soil, plant residue, or a crop (Nordmeyer 2006). Precision weed control reduces broadcast post-emergence applications and often involves the use of advanced technology to identify and then apply a tool (e.g., herbicide) directly onto an individual weed or small cluster for removal (Gerhards and Christensen 2003; Vrindts and Ramon 2002). Although precision weed control can significantly reduce herbicide inputs by placing more on the weed or patch and less on the surrounding area, this approach offers little advancement toward integrated weed management (IWM). True IWM incorporates multiple weed control tools along with decision support and high-speed, quickly actuating and articulating machinery capable of making micro-applications to individual weeds in a total systems approach (Young et al. 2017). Currently, no company sells equipment that can perform true IWM, although a few are making progress (e.g., Blue River Technology, Inc., Sunnyvale, CA).

Over the past several decades, research has proceeded rapidly in precision weed control that incorporates robotics, sensors, and advanced computer systems (Bogue 2016; Christensen et al. 2009). Worldwide, research on precision weed control has been conducted mainly on high-value crops, such as cotton (*Gossypium hirsutum* L.) (Lamm et al. 2002), broccoli (*Brassica oleracea* L.) and lettuce (*Lactuca sativa* L.) (Fennimore et al. 2010), carrots [*Daucus carota* subsp. *sativus* (Hoffm.) Arcang.] (Dammer 2016), sugar beet (*Beta vulgaris* subsp. *vulgaris*) (Nieuwenhuizen et al. 2007), and onions (*Allium cepa* L.) and cabbage (*Brassica oleracea* var. *capitata* L.) (Melander et al. 2015) as well as pastures (Van Evert et al. 2009). The basic approach has been to test a single tactic, either herbicide or cultivation, applied through a re-engineered implement or robotic platform equipped with vision sensors to locate the crop and fast-acting actuators to quickly spray or disturb the weed or weeds (Fennimore et al. 2010; Zhang et al. 2012). Slaughter et al. (2008), Fennimore et al. (2016), and others (e.g., Singh et al. 2011) provide extensive reviews that focus on many different aspects of precision weed control, such as weed and crop detection, weed control actuators, and cropping systems adaptation. Still, very little discussion focuses on IWM. In essence, precision weed control consists of scaling down what is practiced with large broadcast equipment into a smaller version. In this type of precision weed control, integration of tactics is still spatially and temporally discreet, similar to traditional IWM (Young et al. 2017) and dissimilar to true IWM (Young 2012).

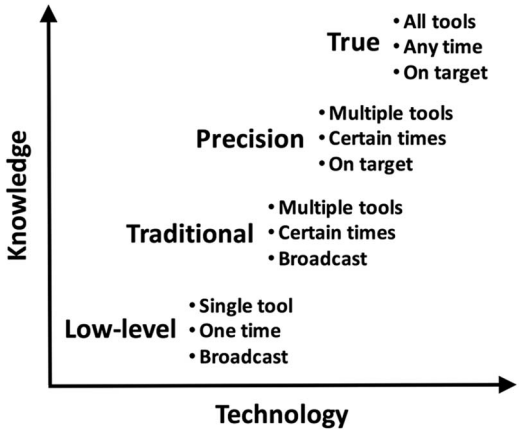


Figure 1. Integrated weed management (IWM) continuum from low, traditional, precision, to true IWM. The corresponding requirement for increasing the level of advanced technology (x-axis) and user knowledge (y-axis).

True IWM requires high levels of plant ecological and biological knowledge and the corresponding technological machinery and algorithm-based decision-making controls that can respond to changes in weeds and the environment (Figure 1). Young et al. (2017) categorized true IWM based on the degree of application specificity and level of integration of tactics or tools. From low-level IWM with low application specificity (e.g., broadcast) and integration (e.g., single tools) to traditional IWM (low application specificity, low integration) to precision IWM (high application specificity, low integration) to true IWM (high application specificity, high integration), the amount and depth of knowledge required increases with increasing specificity and integration. In addition, the incorporation of technology is largely scale dependent, as smaller farms can have high specificity and integration without the use of robotics and advanced technology (e.g., hand hoeing), whereas larger farms can maximize computerized technology.

Field-scale examples of true IWM are non-existent because the technology is not ready (Emmi et al. 2014), nor is it incorporated in most university or grower weed control programs (Owen et al. 2015). Optimal weed control occurs when a particular method or a set of methods is precisely matched with plant type and growth stage in a range of environmental conditions. Such ideal control can be difficult to achieve with automated systems, as the incorporation of many electronic components for performing various functions impairs reliability and increases the cost (Emmi et al. 2014). Research-grade robotic fleets that perform specialized tasks and operate together via either ground-based or aerial (e.g., unmanned aerial vehicles or UAVs) control systems can reduce the impediments associated with carrying excessive hardware and software on a single platform while maximizing ease of integration (Young et al. 2014). In addition to the need for readily available technology, research and extension weed science programs must undergo a paradigm shift that includes the concepts of true IWM. Beckie and Harker (2017) and Norsworthy et al. (2012) list their top choices or best management practices for controlling herbicide-resistant weeds; yet neither mentions computer-based sensors and automation technology as major advances to help in implementing the fundamental principles for sustainably managing weeds in cropping systems.

In the near future, the practice of true IWM will most likely come from a combination of university research and company investment where outside-the-box thinking is routine. In 2016, 128 robotics-related startups received funding from investment groups for a total of $1.95 billion (Tobe 2017). Increasingly, agriculture is a focus of these startups, which are gaining the interest and attention of large companies seeking innovative ideas. Monsanto, which reinvests $1.5 billion annually into research and development, reviewed over 300 venture capital opportunities and made investments in more than 20 startups, which included robotic technologies for weed control (Hamer 2016). Many universities now have centers for venture development leading to startup companies and incubators that bring together academic and company researchers to accelerate innovations for solving problems and creating new ideas (Etzkowitz et al. 2000).

The Model Company

True integrated management of weeds requires improved application specificity and tactic integration that incorporates technology allowing for greater flexibility of inputs and enhanced responsiveness to field conditions. However, growers are not willing to invest in clever and expensive, unproven gadgetry that fails or falls apart soon after installation (Alsever 2016). What characteristics must a startup company have to be capable of providing a true IWM approach for growers? To be successful in this field, a company must prioritize connecting with growers and then selling the idea of the technology––not necessarily the technology itself. Chesbrough (2003) describes open innovation as a new era of abundant knowledge, in which companies no longer lock up their intellectual property but instead find ways to profit from others' use of their technology that ultimately leads to value for them. The merging of ideas associated with traditional and new approaches to IWM is the epitome of open innovation, which some in the private and public sectors are now beginning to discover.

In addition to connecting with growers, a startup company that manufactures units that perform true IWM must have investors who are diversified and strongly committed to the company's mission. The technology must perform reliably and accurately while displaying obvious advantages over existing equipment or approaches––speed and precision being the primary functions. Over the course of 1 to 5 years, several iterations of a weeding robot could be developed with the ultimate goal of identifying and precisely targeting a suite of control tactics to individual weeds in real time as the platform moves autonomously through the field. During that same period, the crop or crops would need to be grown often enough in both controlled and uncontrolled conditions for thorough testing.

The actual technology that could be patented would perform a "three-step automated weeding process" for (1) identifying individual weeds, (2) determining the most effective micro-based tactic, and (3) making the application with advanced robotics that specialize in actuating and articulating capabilities (Figure 2). Whether the units are sold directly or provided as a service, the company would fully support the grower to ensure through education that the technology is being used for maximum efficiency, thus increasing customer satisfaction. In addition, the patented technology could be developed by the same company or others for application to other pests or systems.

Weed-specific control and detection could be one of several products supplied by a company that develops platforms for autonomous integrated cropping system management (Figure 3). The basic platform design could have applications for small-scale use, such as laboratory, hand-held, or remote installations, or field

https://doi.org/10.1017/wet.2017.70 Published online by Cambridge University Press

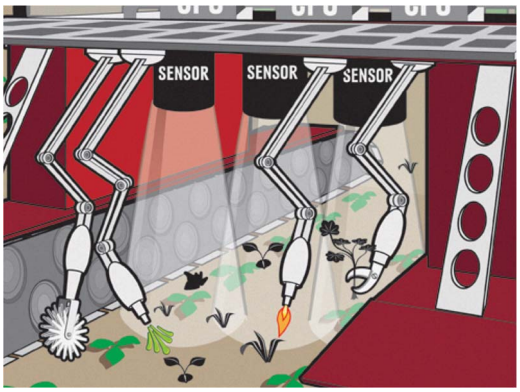


Figure 2. Diagram of articulating tools and sensor technologies on a field-based robotic platform for integrated weed control.

analyses, which in addition to weeds, could include other pests or parameters (e.g., nutrient) and whole cropping systems. Numerous markets exist for each design and may include individual growers, input suppliers, environmental businesses, and home gardeners. However, startup companies face significant challenges; 90% fail to advance a product to market, with the primary reason being a lack of perceived need (Patel 2015). The intent of this paper is not to cover every aspect of a startup company's evolution, but instead to provide an idea and general guidelines for what features a potential company might offer.

The value in the technology from a startup company developing true IWM approaches is being able to hit the target for sustainable crop production. Growers would value the precision that allows for greater flexibility of inputs and enhanced responsiveness to field conditions. A regulator would value the precision for the reduced environmental impacts from chemical inputs or soil disturbance. A consumer would value the precision for the absence of chemical residues on the produce they buy or the reduced threat of contaminated ground water. Broadcast applications of the same tactics repeatedly for controlling weeds is not sustainable and ignores advanced technology, an advantage that is replete in other areas, such as health care, medicine, and engineering.

A company focused on the true IWM approach could be well positioned in the marketplace, as in-field equipment is not part of most agricultural technology startups. The niche may have broad

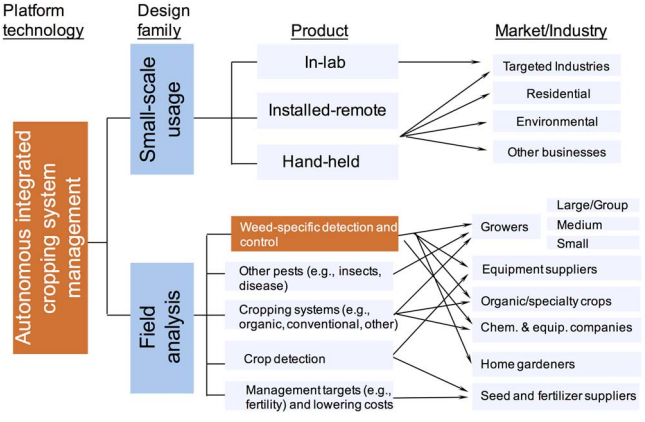


Figure 3. Map of potential applications and end points for a commercially available robotic integrated weeding unit.

appeal to investors, who are interested in seeing applications in the field for execution by growers for immediate results. As sustainability continues to be the focus of food suppliers and retailers, like Wal-Mart and Sysco, and other groups interested in the agricultural supply chain (e.g., Field to Market®), practices that match their guidelines will be required. True IWM fully supports such practices.

Conclusions

Many research engineers and a few companies are working on precision weed control with a focus primarily on single tactics, either herbicides or cultivation, applied to plants. The next step is true IWM. Weed scientists have strongly advocated for the "many little hammers" approach first described by Liebman and Gallandt (1997) that is common for traditional IWM. However, 20 years of technological advances have greatly expanded application specificity and tactic integration, such that the hammers are no longer blunt-force objects but instead smart and agile devices. The tactics of IWM applied together so as to be considered as truly integrated are still too few in most cases. Instead of reduced-scale versions of broadcast applications that are dependent on favorable field conditions, interested stakeholders should consider technology-enhanced, information-based, and decision-focused true IWM approaches as described by Young et al. (2017). The startup company that can (1) convince venture capital backers to engage in long-term support during the development phase of the technology, (2) consistently and economically deliver reliable weed control, and (3) convince growers to buy its integrated product will be able to capitalize on the concept of true IWM and help make it a market reality.

Acknowledgments. Funding for this work was provided by the National Institute of Food and Agriculture, United States Department of Agriculture under Agreement No. 2014-70006-22484 via the Northeastern IPM Center Advanced Production System Signature Program (Project No. 2014-07524).

References

Alsever J (2016) Is there an agtech bubble? *Fortune*, May 25. http://fortune.com/2016/07/25/agriculture-farming-tech-startup-bubble/. Accessed May 12, 2017.

Beckie HJ, Harker KN (2017) Our top 10 herbicide-resistant weed management practices. *Pest Manag Sci* 73:1045–1052.

Bogue R (2016) Robots poised to revolutionise agriculture. *Industrial Robot: An International Journal* 43:450–456, doi: 10.1108/IR-05-2016-0142 http://dx.doi.org/10.1108/IR-05-2016-0142. Accessed May 12, 2017.

Chesbrough H (2003) The era of open innovation. *MIT Sloan Management Review* 44:35–41.

Christensen S, Sogaard HT, Kudsk P, Norremark M, Lund I, Nadimi ES, Jorgensen R (2009) Site-specific weed control technologies. *Weed Res* 49:233–241.

Dammer KH (2016) Real-time variable-rate herbicide application for weed control in carrots. *Weed Res* 56:237–246.

Emmi L, Gonzalez-de-Soto M, Pajares G, Gonzalez-de-Santos P (2014) New trends in robotics for agriculture: integration and assessment of a real fleet of robots. *Sci World J* 2014:404059, doi: 10.1155/2014/404059

Etzkowitz H, Webster A, Gebhardt C, Terra BRC (2000) The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. *Research Policy* 29:313–330.

Fennimore SA, Slaughter DC, Siemens MC, Leon RG, Saber MN (2016) Technology for automation of weed control in specialty crops. *Weed Technol* 30:823–837.

Fennimore SA, Tourte LJ, Rachuy JS, George CA (2010) Evaluation and economics of a machine-vision guided cultivation program in broccoli and lettuce. *Weed Technol* 24:33–38.

Gerhards R, Christensen S (2003) Real-time weed detection, decision making and patch spraying in maize, sugarbeet, winter wheat and winter barley. *Weed Res* 43:385–392.

Hamer J (2016). A vision of new science and technology applications for agriculture: Monsanto growth ventures. *National Academy of Sciences Board on Agriculture and Natural Resources (BANR) Meeting on New Technologies for Agriculture Production and Research*. http://dels.nas.edu/Upcoming-Event/BANR-Meeting-Technologies/AUTO-5-91-79-R. Accessed May 11, 2017.

Lamm RD, Slaughter DC, Giles DK (2002) Precision weed control system for cotton. *Trans ASAE* 45:231–238.

Liebman M, Gallandt ER (1997) Many little hammers: ecological management of crop-weed interactions. In Jackson LE (ed.). *Ecology in Agriculture*. San Diego: Academic Press. Pp 291–343.

Melander B, Lattanzi B, Pannacci E (2015) Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. *Crop Prot* 71:1–8.

Nieuwenhuizen AT, Tang L, Hofstee JW, Müller J, van Henten EJ (2007) Colour based detection of volunteer potatoes as weeds in sugar beet fields using machine vision. *Precision Ag* 8:267–278.

Nordmeyer H (2006) Patchy weed distribution and site-specific weed control in winter cereals. *Precision Ag* 7:219–231.

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. *Weed Sci* 60:31–62.

Owen MK, Beckie HJ, Leeson JY, Norsworthy JK, Steckel LE (2015) Integrated pest management and weed management in the United States and Canada. *Pest Manag Sci* 71:357–376.

Patel N (2015). 90% of startups fail: here's what you need to know about the 10%. *Forbes*, January 16. https://www.forbes.com/sites/neilpatel/2015/01/16/90-of-startups-will-fail-heres-what-you-need-to-know-about-the-10/#3f6dc5cf6679. Accessed July 17, 2017.

Singh K, Agrawal KN, Bora GC (2011) Advanced techniques for weed and crop identification for site specific weed management. *Biosyst Eng* 109: 52–64.

Slaughter DC, Giles DK, Downey D (2008) Autonomous robotic weed control systems: a review. *Computers Elect Ag* 61:63–78.

Tobe F (2017). 2016 Best Year Ever for Funding Robotics Startup Companies. *The Robot Report*. https://www.therobotreport.com/news/2016-was-best-year-ever-for-funding-robotics-startup-companies. Accessed May 11, 2017.

Van Evert FK, Polder G, Van der Heijden GA, Kempenaar C, Lotz LA (2009) Real-time vision-based detection of *Rumex obtusifolius* in grassland. *Weed Res* 49:164–174.

Vrindts E, Ramon H (2002) Weed detection using canopy reflection. *Precision Ag* 3:63–80.

Young SL (2012) True integrated weed management. *Weed Res* 52: 107–111.

Young SL, Meyer GE, Woldt WE (2014) Future directions for automated weed management in precision agriculture. In Young SL and FJ Pierce (eds.). *Automation: The Future of Weed Control in Cropping Systems*. New York: Springer. Pp 249–259.

Young SL, Pitla SK, Van Evert FK, Schueller JK, Pierce FJ (2017) Moving integrated weed management from low level to a truly integrated and highly specific weed management system using advanced technologies. *Weed Res* 57:1–5.

Zhang Y, Staab ES, Slaughter DC, Giles DK, Downey D (2012) Automated weed control in organic row crops using hyperspectral species identification and thermal micro-dosing. *Crop Prot* 41:96–105.

https://doi.org/10.1017/wet.2017.70 Published online by Cambridge University Press