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Introduction [to *Automation: The Future of Weed Control in Cropping Systems*]: Scope of the Problem—Rising Costs and Demand for Environmental Safety for Weed Control

Stephen L. Young
University of Nebraska - Lincoln, syoung4@unl.edu

Francis J. Pierce
Washington State University, fran.pierce@gmail.com

Pete Nowak
University of Wisconsin, pnowak@wisc.edu

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CHAPTER 1

Introduction: Scope of the Problem – Rising Costs and Demand for Environmental Safety for Weed Control

Stephen L. Young,[1] Francis J. Pierce,[2] and Pete Nowak[3]

1. Department of Agronomy and Horticulture, West Central Research & Extension Center, University of Nebraska-Lincoln, 402 West State Farm Road, North Platte, NE 69101, USA e-mail: steve.young@unl.edu
2. Departments of Crop and Soil Sciences and Biological Systems Engineering, Washington State University, Irrigated Agriculture Research & Extension Center, 24106 North Bunn Road, Prosser, WA 99350, USA e-mail: fran.pierce@gmail.com
3. Nelson Institute for Environmental Studies, University of Wisconsin, 40 Science Hall, Madison, WI 53706, USA e-mail: pnowak@wisc.edu

Corresponding author – S. L. Young

Abstract
Many 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. This chapter addresses the problems of mechanized agricultural systems to set the stage for the introduction and adoption of more advanced technology to meet the needs of growers and satisfy the desires of consumers.

1. Timeless Weeds

Autonomous robotic weed control systems hold promise toward the automation of one of agriculture's few remaining unmechanized and drudging tasks, hand weed control. Robotic technology may also provide a means of reducing agriculture's current dependency on herbicides, improving its sustainability and reducing its environmental impact. Slaughter et al. (2008)

While biblical Adam was promised thorns and thistles as part of his punishment (Genesis 3:18), Timmons' (1970) review states that few agricultural leaders or farmers became interested in weeds as a problem until about 1200 A.D. One can correctly imagine, however, that from the development of primitive forms of agriculture, weeds have presented a formidable challenge for food, feed, and fiber production. Our ancestors recognized weeds as limiters of desirable plants, sources of health problems, and degraders of aesthetics over a broad range of environments. But what are weeds? Weeds are most simply defined as "plants out of place." A more poetic description was provided by Ralph Waldo Emerson who declared that "a weed is a plant whose virtues have not yet been discovered." Indeed, the ongoing search for genetic materials from plants that may prove to be beneficial confirms the need for a flexible perspective in managing those plants we call weeds.

2. The Number One Pest Problem

In both early and modern agriculture, weeds clearly rank as the primary pest problem. Today, weeds plague even the most advanced and progressive farming operations regardless of their management approach, whether organic, conventional, or sustainable. Holm and Johnson (2009) state that "throughout the history of agriculture, more time, energy and money have been devoted to weed control than to any other agricultural activity." In the USA, the vast majority of crop acres are treated with herbicides (Gianessi and Reigner 2007) accounting for about two-thirds of the pesticide expenditures for US farmers in the late 1990s (Donaldson et al. 2002). Today, the development of herbicide-resistant weeds is the major concern for farmers relying on chemical weed control, while in organic production systems, the cost and effectiveness of hand removal of weeds is a concern due to expenses, labor availability, and, in large-scale systems, the social acceptability of employing large numbers of migrant labor. Farmers are increasingly facing environment and economic consequences of emerging weed management challenges, restrictions on the availability and effectiveness of chemicals, changing government policies, and dynamic markets that can reward or punish depending on how weeds are managed.

There is no immunity to weeds and the problems they cause, whether for a large farmer or a typical home gardener. Without continued and focused management and control efforts, a low or an apparent nonexistent weed population can very quickly get out of hand with direct (e.g., lower yields) and lasting (e.g., soil weed seed bank) effects. Because weed impacts are significant and have been passed on through countless generations, there is a continually evolving array of the types and numbers of different approaches for controlling weeds. In commercial cropping systems these options are vast and include the categories of mechanical, chemical, biological, and cultural control.

3. Management: Then and Now

Prior to the development of herbicides, weeds were largely a management challenge that was addressed with planning and the use of high amounts of disturbance. Crop rotation was important, and whatever new ground was available was used once the "old" location had become too infested with weeds. The movement between and to new land parcels was, in itself, a type of rotation, although not what is typically practiced today.

Early day cropping systems relied on routine disturbances to reduce weed pressure. The use of cultivation was important for disrupting weed growth and could be applied in the simplest of forms. Unfortunately, early day cultivation could not be applied selectively, except in rows, and bare soil, which resulted in high amounts of erosion, was common in many fields. In the Midwest, the Dust Bowl of the early 1900s was caused by excessive tillage, as the prairie sod grasses were eliminated in favor of annual cropping systems. When Lowdermilk (1939) wrote his report on the demise of ancient civilizations due to excessive erosion, the cultivation of weeds in irrigated cropping systems was identified as a likely culprit. As noted earlier, weeds are timeless, and as we have to relearn again and again, the various forms of disturbance used to manage weeds may have significant consequences that ripple across both time and space.

With the invention of 2,4-D in the 1940s, weed control changed dramatically. The agricultural chemical revolution (i.e., the substitution of inorganic fertilizers and manufactured chemicals to replace manure, humus, and various forms of pest control) following WWII gave growers the ability to selectively manage weeds in cropping systems with chemicals designed to kill on contact or through movement within the plant. Later, new herbicides were developed that provided total, selective, or partial control of weeds, which gave growers great flexibility in managing weeds in their crops. These innovations also brought about an important change in the indigenous knowledge associated with weed management. Prior to the introduction of these chemicals, growers had to accrue a system of knowledge on multiple dimensions of weed control: what to do, when and how to do it, and what observations are needed to guide decisions. The increased ease associated with dependence on chemical control also meant less knowledge was required for managing cropping systems. Knowledge of weed ecology became less important, and a grower could focus on other important management aspects, including fertility, marketing, or crop selection.

Currently, the most relied upon techniques for controlling weeds in conventional cropping systems are the use of cultivation and herbicides. The invention of herbicide-resistant (HR) crops has allowed for a quick application of a single herbicide sprayed over the entire field to control weeds without harming the crop. The simplicity of this system has actually led to the emergence of HR weeds. The use of a single herbicide that is applied repeatedly in one season at high rates on mature weeds is a recipe for resistance, which occurs when an individual plant or population responds to intense selection pressure. In addition,

growing the same crop each year and using the same weed management program only exacerbates the problem. Add these "incorrect" management strategies together across large acreages and only time is needed for HR weeds to start appearing in grower fields, which they now have. Today HR weeds are a very significant problem, one that keeps increasing in size and scope, as we continue to fail in understanding that any new technology is a double-edged sword—there are many benefits, but mismanagement can lead to major problems.

In organic and some conventional cropping systems, the use of cultivation remains a heavily relied upon management tool for controlling weeds. The ability to systematically move through a field and physically disturb weeds has been one of the most relied upon control tools for centuries because there is no guess work and virtually all of the risk is eliminated. Large-scale operations use this tool because equipment manufacturers have created a wide range of implements appropriate for these operations. While the same range of equipment may not be available to small-scale growers, they have a greater capacity to respond to smaller or sudden changes than larger growers because they have an intimate relationship with their crops and fields. This type of knowledge or familiarity with the dynamics of weed ecology is extremely difficult at large scales, and since HR weeds are an increasing problem, scientists are looking to other forms of innovation to address this situation. One of the promising developments is automated and targeted weed control, a theme that is addressed in the remainder of this book.

4. Costs, Costs, Costs

All forms of modern-day weed control have costs associated with them. Some accrue to the grower, others to workers who may be exposed to chemicals, and still others to environment and society on the whole. Yet the lack of weed control diminishes yields and profits, thus resulting in an ongoing balance by growers to limit risk by falling somewhere between an "insurance level" and minimal level of control that will minimize the impact of weeds. In conventional systems, the exposure to chemicals by those who have to make the applications is a safety risk that is costly in terms of health and finances. Although some cases are suspect, there are links between health problems and the application of pesticides in crop production systems. In addition, the locations where chemicals are manufactured are "no shining stars" of environmental excellence either, but the same could be said for fertilizer manufacturers and their various distribution points.

Not only are applicators and manufacturers vulnerable to the ramifications of handling toxic chemicals, but the environment itself suffers from any level of chemical application. Weeds suffer, which is desirable from a production standpoint, but it is debatable, often on a site-specific basis, as to whether yield benefits justify potential harm to humans and surrounding ecosystems. Non-HR crops suffer from misapplications and even HR crops have been debated as to whether they are completely suitable for the environment. Off-target movement (e.g.,

Figure 1. Organic onion field in eastern Washington, USA, with a hand-weeding crew. Every other pair of onion rows has already been hand weeded and cultivated (Photos courtesy of Rick Boydston, USDA-ARS)

drift, runoff) of chemicals has numerous effects on animals, insects, birds, and fish, although all chemicals face rigorous testing mandated by EPA (in the USA) prior to commercial sales. Nevertheless, this testing does not prevent an off-label application made by mistake or in the wrong circumstance. The debate surrounding the accounting for benefits and costs is not new and has been with us with the emergence of each new form of weed management. While Rachel Carlson may have been a lone voice when she issued the warning associated with the use of chemicals in her book *Silent Spring,* today there are hundreds of books and reports on how we have allowed HR weeds to become a major agricultural issue (Beckie 2006; Beckie et al. 2006; Beckie and Tardif 2012; Bhowmik 2010).

In organic systems, similar costs to the environment can occur if an over-reliance on cultivation is used. The continued disturbance of the soil leads to excessive erosion by means of both wind and water. Since weed control can be more difficult in these systems, it could be argued that excessive weeds that are left uncontrolled are also polluting the environment. Probably, this is one of the main reasons why there are so few large-scale commercial organic farm operations. For those companies that are successfully producing organic crops, one of their biggest inputs is manual labor, a significant economic cost to the grower, and one that challenges the notion of a sustainable system due to these social dynamics (Figure 1).

The costs for weed control, other than to the environment and applicator, can range from minimal to financially devastating. In many countries, manual labor is used to control weeds because it is cheap and plentiful. Most often, in these situations, other challenges exist that relate to growing, processing, or delivery of crops to market. In locations where labor is not widely available, costs are reduced by using chemical weed control because it is relatively cheap and easy to use.

Increasingly, the environmental costs of weed control are being evaluated, not just by scientists but by the public, along with the financial costs that can escalate for companies and growers trying to expand their market in the organic area.

Whether mechanical, chemical, cultural, or biological, the goal of weed management should be to reduce or eliminate weeds and limit disturbance as much as possible because weeds most often thrive in disturbed systems.

5. The Need for Change

Crop production is most often conducted on a field scale, and in most cases, inputs are applied at rates averaged for an entire field using equipment that spans multiple crop rows. 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.

We also know that the strategies that growers use to manage weeds vary between growers, and between and within fields (Riemens et al. 2010). This means standardized or uniform approaches to weed management using emerging technologies are likely to fail in the same way that indiscriminate use of innovative HR products has led to HR weeds. Managing variation in biological systems has to be balanced with managing variation in the social systems or the differences between growers. This may mean targeted communication efforts that address key misperceptions while highlighting the benefits of weed management strategies based on an understanding of the grower situation (Wilson et al. 2009). Increasing the adoption of a dynamic and appropriate management strategy has to be the objective associated with the emergence of new technologies (Hammond et al. 2006).

The potential for new management strategies, a theme of this book, can be found by beginning with an understanding of a commonality of all current weed management strategies. 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, is used at different times of the season or over several seasons in most cropping systems, but rarely are single weed plants targeted. Weeds, like crop plants, are not managed at the individual plant scale.

The development of machine-guided technologies for precision weed control has advanced rapidly in recent decades. Technological advancements specific to weed control have been made in many areas, including mechanical, chemical, thermal, and electrical. 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. 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.

With rapid advances in sensors and guidance technology, potentials for weed control are changing 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 [really] can build anything." Biological research and the latest technological developments in weed control have the potential to radically change the current research approach to weed control and help significantly reduce environmental impacts (e.g., drift, off-target movement) and the high cost of inputs and labor. The potential for developing these precision weed management techniques is real, but challenges remain to do so in a cost-effective manner. Other questions related to scale neutrality or making these innovations available for both small and large operations remain to be addressed.

If it were possible to control weeds without disturbance, the environment would be better off, and growers would have more time to focus on the things that the invention of herbicides allowed for over 50 years ago. 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 continues to increase, yet the amount of arable land available for producing crops will 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 every single livelihood in every single culture that occupies every single part of the globe.

6. A New Resource

The remainder of this book has been written for the biologist and engineer; the expertise of both is needed to address the current challenges of protecting ecosystems and producing more food for future generations. The discrete and targeted control of weeds in cropping systems using advanced technology is a first step in addressing these challenges.

The six sections of the book include an introduction to the scope of the problem (this chapter) and organic and conventional cropping systems (Chapter 2) (first section). In the second section, a report on the latest advancements in the field of engineering (Chapter 3), a detailed description of weeds and their biology in cropping systems (Chapter 4), and a description of how engineering and weed biology have been combined and the field of biological engineering has advanced (Chapter 5) make up one of the most important sections of the book. In section three, three areas of automated weed control are the focus, including precision planting (Chapter 6), mechanical removal (Chapter 7), and chemical applications (Chapter 8). The fourth section expands the reader's view with examples from the Western Hemisphere (Chapter 9), Western Europe (Chapter 10), and Asia (Chapter 11), of the latest technology that is being used or under development. In the

fifth section, the economics of automated weed control (Chapter 12), an industry perspective (Chapter 13), and the potential for automated weed control in underdeveloped countries (Chapter 14) are discussed at length. Finally, the last section (Chapter 15) provides prospects for the future of automation and weed control in precision agriculture.

No other book cuts across two different disciplines with detail and thoroughness to inform readers on the current and provide insight into the future state of weed control. In addition, this book helps to inspire and bring together the next generation of biologists and engineers who are working in the areas of weeds and crop production systems.

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