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Managing Weeds in Organic Farming Systems: An Ecological Approach

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Weed management is an important challenge in all farming systems, but it is especially difficult in organic production without the use of chemical herbicides. Given favorable market opportunities for organic products, organic farmers would seem to have strong economic incentives to protect their crops from yield loss due to weeds and to increase the efficiency with which they suppress weed populations. Yet surveys of commercial farmers and assessments by researchers consistently find weeds to be one of the top constraints to organic production (Rasmussen and Ascard, 1995; Walz, 1999; Archer et al., 2007; Sooby et al., 2007; Cavigelli et al., 2008; Posner et al., 2008). This is perhaps not surprising, given the small amounts of money that have been invested in developing and implementing effective weed management strategies for organic farming relative to the billions of dollars invested in research and production to facilitate herbicide-based approaches. Moreover, herbicides generally have higher efficacy than cultivation, the most common direct form of weed control in organic farming (Buhler et al., 1992; Mulder and Doll, 1993).

Because organic farming systems lack the equivalent of inexpensive and nearly complete chemical weed control available for conventional systems, effective weed management for organic farming requires the concerted use of multiple physical, biological, and cultural tactics (Bàrberi, 2002; Bond and Grundy, 2001; Hatcher and Melander, 2003; Melander et al., 2005). Liebman and Gallandt (1997) characterized strategies composed of multiple weed suppression tactics that are individually weak but cumulatively strong, as the use of “many little hammers,” in contrast to the single large hammer that herbicides provide.

In this chapter, we describe major components of the weed management tool kit for organic farming, highlighting areas in which important advances have been made in the last decade. We then argue that instead of approaching the development of multitactic weed management strategies as a purely empirical, trial-and-error activity, the choice and deployment of weed management tactics

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should instead be informed by insights from ecological theory, following the process outlined in Chapter 2 (Drinkwater, 2009, this volume). Finally, we emphasize the need for ongoing dialog between empiricists and theoreticians and between scientists and farmers, so as to better direct scarce research resources and management time to where they are likely to be most beneficial. Multitactic weed management strategies informed by theory should be useful not just to organic farmers but also to conventional farmers who seek to reduce their reliance on herbicides due to concerns over herbicide resistance in weeds, rising production costs, and environmental and human health risks associated with herbicide exposure.

The Weed Management Tool Kit for Organic Farming

Weed management has three critical concerns. The first and most immediate concern is limiting the amount of damage weeds inflict on an associated crop through competition for resources, release of allelopathic chemicals, and physical interference with maintenance and harvest operations. This concern generally is addressed by killing or suppressing weeds emerging near the time a crop is planted and for a period of weeks thereafter. The second, longer-range concern is minimizing the size of future weed populations by reducing the production and survival of new weed seeds and vegetative propagules. The final concern is preventing the introduction of new, more problematic weed species into an existing weed flora through monitoring, sanitation, and targeted eradication efforts. Comprehensive approaches to addressing all three concerns comprise both therapeutic *control* and system-level design for *prevention* (Lewis et al., 1997; Anderson, 2007).

Conventional weed management focuses almost exclusively on using herbicides to kill weeds at the seedling stage. In contrast, weed management in organic farming includes direct control tactics, such as cultivation to limit seedling survival, but also more subtle tactics that affect weed germination, reproduction, and seed and vegetative propagule survival and dispersal. The physiological and ecological processes involved in the latter set of tactics are strongly linked to major components and interactions within organic farming systems, including diversified cropping systems, soil amendment and disturbance regimes, and feeding activities of pathogens and seed predators (Liebman and Davis, 2000).

The weed management tactics we review here are widely used in organic farming systems in temperate areas. Although many of the results we report were not obtained within organic systems, the tactics used are compatible with organic production practices and certification requirements.

Crop Rotation and Sequencing

Crop rotation plays a central role in organic farming due to contributions to soil fertility, soil conservation, and suppression of certain insect pests and pathogens. Crop rotation also has long been recognized as fundamental to weed management (Leighty, 1938). For many organic growers, weed management considerations play a central role in determining rotation length and crop sequence (Walz, 1999; Bond and Grundy, 2001). Diversification of crop characteristics within a rotation helps to disrupt weed life cycles and prevent any one species from becoming too “comfortable” within the cropping system (Liebman and Staver, 2001). Nonetheless, simple alternation of crops with contrasting characteristics may be insufficient to achieve weed control benefits.

An illustration of the latter point is shown in work reported by Anderson (2003), who found that weed density increased in rotations consisting of one cool-season crop followed by one warm-season crop (e.g., winter wheat [*Triticum aestivum* L.]–chick pea [*Cicer arietinum* L.]), whereas weed density decreased in rotations consisting of two different cool-season crops followed by two different warm season crops (e.g., pea [*Pisum arvense* L.]–winter wheat–maize [*Zea mays* L.]–soybean [*Glycine max* (L.) Merr.]). Diversifying crops by including species with different planting dates within warm-season and cool-season categories enhanced the ability to kill emerged weed seedlings, thus depleting the soil seed bank while limiting the production of new seeds. Weed seed densities in soil also declined due to natural decay processes. For the warm-season weed green foxtail [*Setaria viridis* (L.) Beauv.] and the cool-season weed downy brome (*Bromus tectorum* L.), only 20% of seeds remained viable in the soil seed bank one year after seed shed due to decay, and only 5% of seeds were alive after two years (Anderson, 2003). Within the two-year rotations, enough weeds survived to replenish the soil seed bank and allow weed populations to grow. In contrast, in the four-year rotations, weed seedling survival and reproduction were suppressed to the point that seed decay was greater than seed bank replenishment, and weed populations declined.

Rotation of perennial forage crops, such as alfalfa (*Medicago sativa* L.), with annual crops such as wheat and maize, also can contribute substantially to weed suppression. In a survey of farmers in Saskatchewan and Manitoba, Canada, 83% of respondents reported fewer weeds in grain crops after alfalfa and other forages than after grain crops (Entz et al., 1995). A subsequent survey of fields on commercial farms in Manitoba found that compared with cereal crops preceding cereals, alfalfa hay crops preceding cereals lowered densities of wild oat (*Avena fatua* L.), wild mustard [*Brassica kaber* (DC.) L.C. Wheeler], and Canada thistle [*Cirsium arvense* (L.) Scop.] but had no effect on population densities of redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), and wild buckwheat (*Polygonum convolvulus* L.) and led to increases in dandelion (*Taraxacum officinale* F.H. Wigg.) and field pennycress (*Thlaspi arvense* L.) (Ominski et al., 1999). Thus, particular crops select for and against particular weeds; a complex rotation is needed to select against a wide spectrum of weed species.

Cover Cropping

Cover cropping involves the use of actively growing nonharvested crops and their residues to increase soil productivity, suppress diseases and insect pests, and manage weeds (Clark, 1998). Depending on plant architecture, phenology, residue quality, and residue management, cover crops provide different weed management benefits (Teasdale, 1996; Gallandt et al., 1999).

Green manures, cover crops that are grown solely for incorporation into soil to improve soil quality (Pieters, 1927), can exert a strong influence on weeds through allelopathy, an effect of one plant on another mediated by chemicals emitted from living or dead plant tissue. Cereal and crucifer crops used as green manures are particularly well characterized with regard to their allelopathic effects on weeds (Gallandt and Haramoto, 2004; Boydston and Al-Khatib, 2006; Belz, 2007). Legume green manures may also have valuable allelopathic effects. In field experiments, crimson clover (*Trifolium incarnatum* L.) and red clover (*T. pratense* L.) green manures reduced common lambsquarters and wild mustard density, emergence rate, relative growth rate, biomass production, and competitive ability but enhanced sweet maize growth and yield (Dyck and Liebman, 1994; Dyck et al., 1995; Davis and Liebman, 2001). Aqueous extracts of crimson clover and red clover residues have been shown to be allelopathic under laboratory conditions (White et al., 1989; Liebman and Sundberg, 2006); for the latter species, phenolic compounds are believed to be responsible for allelopathic effects (Ohno et al., 2000).

Allelopathic responses can differ among target species, creating the possibility of selective control. Liebman and Sundberg (2006) found that red clover extracts had little or no effect on large-seeded crop species, such as maize, but strongly suppressed the germination and growth of small-seeded weeds, such as common lambsquarters and wild mustard. Phytotoxic effects of red clover green manure can result from by the combined action of phenolic acids and *Pythium* spp., which attack weeds, such as wild mustard, but not maize (Conklin et al., 2002). Advances in breeding methods that are compatible with organic production guidelines are supporting the development of cover crop cultivars with enhanced allelopathic properties (Belz, 2007).

When cover crop residues are killed and left on the soil surface as a mulch, they suppress weed germination and seedling establishment by blocking light transmittance to the soil surface and creating a physical impediment to seedling growth (Teasdale and Mohler, 2000). Thicker mulches are more suppressive of weed seedling emergence: velvetleaf (*Abutilon theophrasti* Medik.), redroot pigweed, common lambsquarters, witchgrass (*Panicum capillare* L.), curly dock (*Rumex crispus* L.), common chickweed [*Stellaria media* (L.) Vill.], and dandelion seedling emergence decreased in proportion to the amount of hairy vetch (*Vicia villosa* Roth) or cereal rye (*Secale cereale* L.) residues applied to the soil surface (Mohler and Teasdale, 1993). Chopped hairy vetch residues reduced common lambsquarters biomass within a no-till maize crop by 65%, but incomplete kill of the vetch cover crop resulted in maize yield loss (Hoffman et al., 1993). Advances in the design of tractor-pulled roller-crimpers intended to kill cover crops within no-till production systems (Kornecki et al., 2006) may offer practical options for managing weeds in organic production systems while avoiding crop yield losses to cover crop competition.

Intercropping

Intercropping combines two or more crops whose resource consumption patterns are physiologically, temporally, or morphologically complementary. Consequently, intercrops may use a greater share of available light, water, and nutrients and produce more yield per unit land area than at least one of the component crops in monoculture (Vandermeer, 1989; Willey, 1990). Greater resource use by intercrops than monocultures also can lead to improved opportunities for suppressing weeds through resource competition. For example, Baumann et al. (2000, 2001) found that shading reduced germination, growth, and seed production of common groundsel (*Senecio vulgaris* L.), an important weed that infests leek (*Allium porrum* L.) fields, and that leek–celery (*Apium graveolens* L.) intercrops intercepted more light earlier in the growing season and more effectively suppressed common groundsel than did leek monocultures. Similarly, Bulson et al. (1997) reported that when grown at the same relative density, an intercrop composed of wheat and field bean (*Vicia faba* L.) produced less weed biomass than field bean in monoculture but more weed biomass than wheat in monoculture. However, complementary patterns of resource use allowed wheat and field bean to be grown at higher densities than normal for monocultures, and when this was done, high-density mixtures contained substantially less weed biomass than normal-density monocultures of both crops.

Increasing Crop Competitive Ability

Crop cultivars vary in their ability to suppress weeds and to tolerate weed interference (Blackshaw, 1994; Lemerle et al., 1996; Mohler, 2001a). A host of crop characteristics, including leaf angle, leaf area index, crop stature, canopy duration, maximal relative growth rate, allelopathic potential, and many other attributes, contribute to cultivar effects on weeds (Callaway, 1992; Olofsdotter et al., 2002). The particular crop–weed combination may determine which attributes are most important. Jointed goatgrass (*Aegilops cylindrica* Host) seed production declined 33 and 46% in dry and wet years, respectively, within a highly competitive winter wheat cultivar compared to a less competitive cultivar (Ogg and Seefeldt, 1999). Reduced weed seed production was attributed to more rapid height growth in the competitive wheat cultivar compared with the less competitive cultivar. In dryland and irrigated sweet maize production, wild proso millet (*Panicum miliaceum* L.) fecundity was reduced by 33 and 60%, respectively, in a weed suppressive sweet maize cultivar compared to a nonsuppressive cultivar (Williams et al., 2007). Weed-suppressive ability was strongly associated with sweet maize canopy characteristics at time of anthesis, including leaf area index, interception of photosynthetically active radiation and allocation of leaf area to the top of the canopy. Variation in wild proso millet fecundity due to sweet maize cultivar characteristics propagated out beyond the first growing season, affecting wild proso millet population densities and yield of a snap bean (*Phaseolus vulgaris* L.) crop in the following year (Davis and Williams, 2007).

Organic producers often use row widths that accommodate cultivation equipment, but if row widths can be narrowed and crops sown in a more equidistant arrangement, weed suppression can be enhanced; this is especially true if crop densities can be increased concomitantly (Mohler, 2001a; Olsen et al., 2005). Crop species for which this approach may be successful include maize, pea, peanut (*Arachis hypogaea* L.), rapeseed (*Brassica napus* L. var. *napus*), safflower (*Carthamus tinctorius* L.), small grain cereals, and soybean. The use of increased crop density may be an inappropriate tactic for horticultural crops, since higher crop densities can translate into smaller size of individual harvestable units (e.g., cabbage [*Brassica oleracea* L.] heads), and crop value can be affected by unit size. The competitive ability of horticultural crops can be increased greatly, however, by transplanting rather than direct seeding (Weaver, 1984).

Soil Amendments

Managers of organic farming systems put considerable emphasis on long-term transformations of soil conditions through the accumulated impacts of organic matter amendments, such as animal manures and composts, as well as crop residues (Gallandt et al., 1999). These amendments and the manner in which they are used can affect weeds and their interactions with crops. Rasmussen (2002) found, for example, that band injection of liquid manure into soil, rather than broadcast surface application, increased barley (*Hordeum vulgare* L.) growth and competitive ability against weeds. In a study of weed and potato (*Solanum tuberosum* L.) performance in plots amended with green manure residues, cattle manure, and compost versus barley residues and high rates of synthetic fertilizers, Gallandt et al. (1998) found that after soil management treatments had been in place four years, weed biomass production was lower and potato yields were higher in plots receiving organic amendments. Ryan et al. (2006) measured the competitive effects of mixed-species stands of weeds on maize in two contrasting systems that had been in place for 26 years: a diversified organic rotation that contained legume green manures and that received manure versus a simpler, conventionally managed rotation without legume green manures and manure. The investigators found that a given density of weeds caused more yield loss for maize in the conventional than the organic system.

It should be recognized that organic matter amendments to soil do not always work to the benefit of weed management. In a field study of interactions between maize and three weed species, compost increased seed production by common waterhemp (*Amaranthus rudis* Sauer) and velvetleaf, although not by giant foxtail (Liebman et al., 2004). Compost also increased the competitive effect of common waterhemp on soybean (Menalled et al., 2004). Thus, while soil amendments can have beneficial effects on soil fertility and crop production, effective weed control practices are needed to limit the establishment, growth, and reproduction of species that are stimulated by amendments.

Conservation Biocontrol

Conservation biological control of weeds seeks to manipulate cropping system habitats with the immediate goal of fostering natural enemies of weeds and the long-term goal of reducing population densities of target weed species (Landis et al., 2000). One approach that holds particular promise focuses on habitat management to promote weed seed consumption by seed predators (Westerman et al., 2003; Menalled et al., 2006). Weed seed shed by summer annual weed species typically takes place in temperate agroecosystems during senescence and harvest of grain crops (Forcella et al., 1996). Short-term postdispersal predation of giant foxtail seeds in maize and soybean was substantially lower (18 and 5% of seeds consumed d^{-1}, respectively) during these fall months than in a red clover cover crop (up to 58% of seeds consumed d^{-1}) (Davis and Liebman, 2003). Greater weed seed predation in red clover was at least partially attributable to higher activity density of field crickets (*Gryllus pennsylvanicus* Burmeister), which are known seed predators (Carmona et al., 1999). Including small grains, red clover, and alfalfa within maize- and soybean-based crop rotations can increase season-long seed predation rates by creating canopy cover and thus suitable habitat for insect and rodent seed predators at times when canopy cover of maize and soybean is low (Heggenstaller et al., 2006; Westerman et al., 2006).

Delaying or eliminating primary tillage can also increase overall seed losses to postdispersal predation. Three months after seed dispersal at the time of maize harvest, 40% of giant ragweed (*Ambrosia trifida* L.) seeds resting on the soil surface in no-till maize plots in central Ohio were consumed by predators (primarily small vertebrates), whereas after 12 months, 90% of seeds were lost to postdispersal predation (Harrison et al., 2003). If primary tillage had taken place immediately after maize harvest, postdispersal seed losses would have been close to zero, as the seeds would have been protected within the soil profile.

Cultivation and Other Physical Control Tactics

Cultivation is the most important direct-control tactic available to organic growers. Nonetheless, reliance on this tactic should be tempered with the recognition that its overuse may cause reductions in soil quality indices, such as soil organic matter content and aggregate stability (Grandy and Robertson, 2006). On a shorter time-scale, heavy reliance on cultivation may introduce unwanted volatility and risk into weed management if extended periods of rainfall prevent timely field operations (Gunsolus and Buhler, 1999).

A wide variety of cultivation tools and improved guidance systems are now available to the organic grower (Bowman, 1997; Pullen and Cowell, 2000; Mohler, 2001b; van der Schans et al., 2006), each suited to a particular set of management objectives and crop and environmental conditions. Interrow tools, such as shovel cultivators, work between 50 and 70% of the soil surface between crop rows, whereas in-row and near-row tools, such as spyders, spinners, and full-field implements, such as spring tine weeders and rotary hoes, work the entire field but incur some crop loss (Mohler, 2001b). Weed seedling mortality rates in maize due to cultivation with rotary hoes or tine weeders followed by two interrow cultivations with a shovel cultivator varied between 43 and 74% over two field seasons (Mohler et al., 1997). Complementing a single pass of a rotary hoe with two passes of interrow shovels supplemented by a suite of intrarow and near-row tools (including spyders, torsion weeders, spinners, and spring hoes) increased the range of weed seedling mortality to between 72 and 90% over the study period.

Various forms of tillage can be used to place weed seeds at particular locations in the soil profile, with resulting effects on seed survival and seedling emergence ability (Mohler, 2001b). In general, weed seed vulnerability to seed predators and other mortality factors is greatest on the soil surface, whereas seedling emergence ability tends to decrease with seed burial depth. In cases where production of new seeds can be prevented, zero tillage can lead to large and rapid losses of weed seeds (Anderson, 2007). Conversely, when production of new seeds does occur, deep tillage with an inversion plow can reduce weed densities due to inhibition of seedling emergence and ongoing seed decay (Mohler, 2001b). Zero-tillage systems involving direct seeding or transplanting into cover crop residues are being developed and tested for organic farming systems (Morse and Creamer, 2006).

Other physical control tactics suitable for organic production are in various stages of research, development, and implementation. These include mulches (Ozores-Hampton et al., 2001; Duppong et al., 2004), flame weeders (Ascard, 1994, 1995; van der Schans et al., 2006), in-row steam injectors (Melander and Jørgensen, 2005), and between-row mowers (Donald, 2006).

Models as Tools for Improving Weed Management

Given the growing number of tactics available for managing weeds in organic farming, and the possibility of using them in various combinations, how should researchers, farmers, and other agriculturalists proceed to develop the science and practice of weed management? One approach is to test and adapt methods empirically. Scientists taking this approach can construct ever-larger factorial experiments to examine huge numbers of individual tactics used alone and in combinations. Often, however, the experiments become unwieldy as the number of factors increases, and higher-order interactions become difficult or impossible to interpret. Alternatively, scientists and farmers can conduct "systems comparisons," in which the relative merits of suites of practices comprising different production systems are compared quantitatively. Such comparisons can approximate the reality of commercial farming but lack experimental controls that would allow mechanistic interpretations and identification of specific individual components that contribute directly to system differences. A final class of investigations involves field-scale studies in which spatially referenced information is related to overall system performance through geostatistical procedures. This approach allows for some mechanistic understanding of the impacts of biotic and abiotic factors but is very labor and information intensive and generally requires a very narrow focus within a given system (Dieleman et al., 2000).

An alternative approach to empirical experimentation that also allows for examination of whole-system properties is the construction and analysis of mathematical models (Holst et al., 2007). Models are simplified versions of reality that distill some aspect of our knowledge about a system into a formal structure that can be manipulated mathematically and tested against our observations of the world. Different models have varying degrees of realism, precision, and generality; no model has all of those attributes (Levins, 1966). Hence, multiple models of a system may be required to understand it from different perspectives. Models are more than intellectual exercises; they provide guidance for a thought-intensive, rather than a technology-intensive agriculture.

As the limits of experimental design for agroecological research are reached, models can help us to gain new insights in a variety of ways. First, they allow us to summarize a great deal of empirical data about the components of a dynamic system in an integrative manner that accounts for interactions between system components (Hanks and Ritchie, 1991). Incorporating what is known about an agricultural system into a model requires that assumptions about system organization be made explicit and therefore testable. Second, when a model adequately describes a system, it may then be used to perform thought experiments. Rather than conduct a series of experiments in which one factor after another is manipulated under a constantly changing environment, producing confounded results, one can use models to explore the consequences of environmental or management-related variation in system components. Finally, models may be used to identify gaps in our empirical knowledge of agricultural systems. Model results that are inconsistent with empirical observations, or that highlight the potential importance of a particular system component, can help focus limited funds and personnel on high-priority research areas.

Mathematical models of weed management systems generally fall into one of two groups: *demographic models*, which track changes over time in the number of individuals in a population of weeds (Cousens and Mortimer, 1995; Freckleton and Watkinson, 1998; Mertens et al., 2002), and *ecophysiological models*, which describe weed development, growth, and interference with crops (Kropff and van Laar, 1993; Grundy et al., 2000). Both types of models make use of species-level data on how dependent variables of interest respond to environmental conditions and management practices. Here, we use demographic models as a means of organizing our discussion of management effects on weed population dynamics and highlighting the importance of multi-tactic weed management in organic crop production systems.

Target Transitions: How Models Guide Weed Management

At its most basic level, demographic modeling is a form of ecological accounting: numbers of individuals in different life stages are recorded at an initial time point, and gains and losses to these groups, through reproduction, death, and dispersal, are followed over time. Because of the cyclic nature of farming system operations, with seasonal peaks and lulls in management activity and favorable growing conditions, recruitment of weed cohorts tends to be synchronized and nonoverlapping. Weed populations thus are often modeled as having discrete generations, represented with difference equations for unstructured populations and projection matrices for structured populations (Cousens and Mortimer, 1995; Caswell, 2001). In this section, we use difference equations in the MATLAB (MathWorks, Inc., Natick, MA) modeling environment to perform simulations of management effects on weed population dynamics. Numerous other excellent software packages are also available and could have been used for this purpose.

A population model's structure is dependent on the life history of the weed population to be studied. Weed species of arable systems fall into three broad life-history categories (Cousens and Mortimer, 1995): annuals, biennials, and perennials (represented by loop diagrams in Fig. 8–1). Annual weed species, such as velvetleaf or giant foxtail, complete their life cycle within a year, from seed to seed: some proportion of the seedlings that are recruited from seeds in the soil seed bank generally survive to reproductive maturity and produce new seeds to replenish the soil seed bank. Biennial weed species, such as wild carrot (*Daucus carota* L.) or common mullein (*Verbascum thapsus* L.) take two years to complete their life cycle: seedlings recruited from the soil seed bank grow to form compact rosettes (nonreproductive plants) by the end of the first year, and rosettes grow into mature plants that produce seeds and die by the end of the second growing season. Perennial weed species, such as Canada thistle and quackgrass [*Elytrigia repens* (L.) Gould], have seed banks and immature and mature plant stages like biennials, but their life cycles are not bound by strict temporal schedules and, depending on the species, they may reproduce either sexually (via seed production), vegetatively (via spread or fragmentation of perennating organs), or by both means.

Life history and environmentally driven demographic differences between weed species, or among populations of a single weed species, contain valuable information about the type of weed management tactics that will be most successful at reducing weed population density and growth. Potential differences in management impact may be explored quantitatively through *perturbation analyses*, which offer a powerful means of asking "what-if" questions about demographic

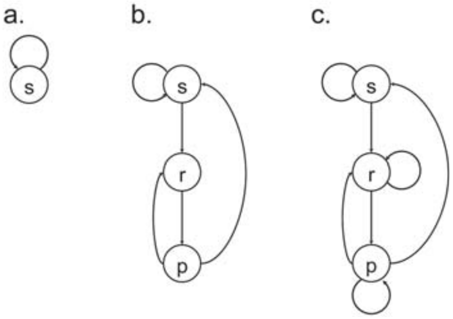

Fig. 8–1. Life history of arable weeds fall into three broad categories: (a) annuals, (b) biennials, and (c) perennials. Circles represent individuals at a given life stage; s = seed, r = rosette (immature plant), p = mature plant. Arrows represent transitions, following an annual time step, from stage to stage.

models. Sensitivity and elasticity analyses, the most commonly performed perturbations, quantify the partial effect on population growth rate when individual demographic transitions, such as seedling survival to reproductive maturity or seed survival in the soil seed bank, are subject to either additive or proportional changes in parameter values, respectively (Caswell, 2001).

Quantifying how changes in demographic parameters for a given species affect its population growth rate is the key to identifying *target transitions* (McEvoy and Coombs, 1999). Target transitions are those weed life stages that are most likely to produce a substantial reduction in population growth rate in response to a management intervention applied at that life stage. Target transitions can also be evaluated with regard to their relationships with various management metrics, such as production costs and crop losses to weed competition.

A broad comparison of target transitions associated with particular weed life histories highlights the importance of demographic information to guide management of a given species (Davis, 2006). For annual species, seed bank persistence is the main determinant of population growth rate, followed closely by seedling survival and fecundity. Survival of new seeds, seedlings, and rosettes is central to the demographic success of biennial species, whereas rosette survival is of prime importance to certain perennial species, with smaller contributions from survival of new seeds and seedlings.

Many Little Hammers: Theory and Application in the Management of Annual Weeds

Once target transitions are identified, weed managers must select tactics that apply pressure to these and other points of secondary importance in weed life cycles. Both empirical and theoretical evidence suggest that combining multiple tactics (“many little hammers”) that may be individually weak can result in synergistic gains for the weed management system as a whole (Liebman and Gallandt, 1997; Westerman et al., 2005). In this section, we introduce a demographic model, implemented in MATLAB, for the summer annual weed giant foxtail to explore the sensitivity of crop production costs to variation in control of weed target transitions, and to project the results of single- versus multi-tactic management approaches. The model does not include tillage effects and other factors that may be of interest, but it illustrates how empirical data and models can work together to identify where weed management efforts are best invested. The demographic model is available online at **[[ASA: insert URL here]]** so that readers can experiment with it.

Our model is composed of two submodels: a demographic model that keeps track of weed population density over time and an economic model that uses weed population density as an input to calculate weed management costs and crop revenue lost due to weed competition (Fig. 8–2). The demographic submodel follows individuals, at each annual time step, belonging to four life stages: dormant seeds in soil, small seedlings, large seedlings, and reproductively mature plants. Transitions between these life stages, represented by solid arrows, are governed by demographic rates shown in lowercase letters: s_s = seed survival in soil seed bank, g = germination, s_{cult} = seedling survival of cultivation, s_{hand} = seedling survival of hand-weeding, f = fecundity (seeds plant^{-1}), and s_{pred} = seeds surviving postdispersal predation. The curved dotted line between “mature plants” and the valve representing new inputs to the seed bank indicates that seed production is

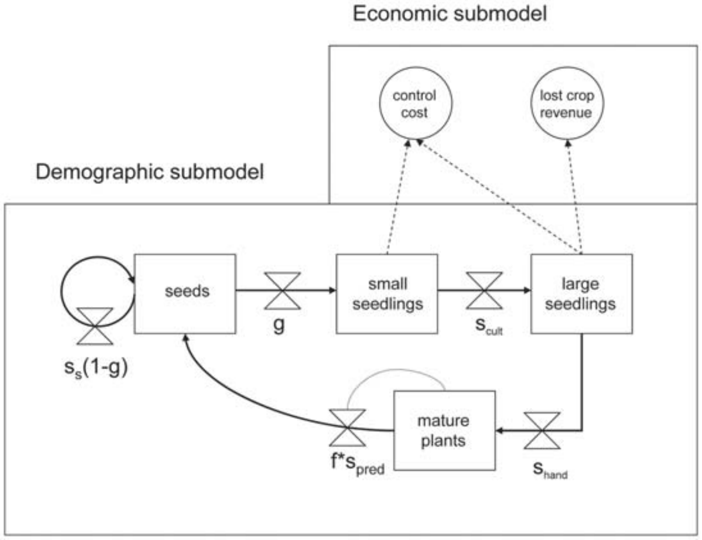

Fig. 8–2. Bioeconomic model of management effects on giant foxtail population dynamics and production costs. s_s = seed survival in soil seed bank, g = germination, s_{cult} = seedling survival of cultivation, s_{hand} = seedling survival of hand weeding, f = fecundity (seeds $plant^{-1}$), s_{pred} = seed survival of postdispersal seed predation.

density dependent, with fewer seeds produced by each individual as the population becomes crowded and more constrained by resource availability.

The demographic model intersects with the economic model through weed management costs and competitive effects of weeds on the crop (dashed arrows). Cultivation, the first weed management tactic applied to the population, is assumed to affect only the interrow area and is assumed to have constant efficacy, independent of seedling population density. A proportion of remaining weeds is then removed with hand labor. Guided by analyses conducted by Melander and Rasmussen (2001), we set time required for hand weeding as a linear function of weed population density

$$y = 4.00 + 1.022x \qquad [1]$$

where y = labor requirements in hour per hectare and x = seedlings per square meter. We calculated control costs using a fixed cost for cultivation (assumed to be \$50 ha^{-1}) and a variable cost for hand weeding, obtained by entering the population density of weed escapes into Eq. [1] and then multiplying the output by a labor cost of \$10 h^{-1}. Lost crop revenue was assumed to follow the rectangular hyperbolic model of density-dependent yield loss, with percentage yield loss increasing as a function of the population density of mature weed plants up to some maximum, after which yield loss reaches a plateau (Cousens, 1985). Fecundity was described using a piecewise regression to allow for density-dependent effects above a threshold of 1 plant m^{-2}.

We used the model to examine the sensitivity of production costs in the fifth year of a given management approach to changes in several mortality factors that producers can influence to some degree, including cultivation efficacy, hand weeding efficacy, seed bank decline, and seed predation (Fig. 8–3). Demographic

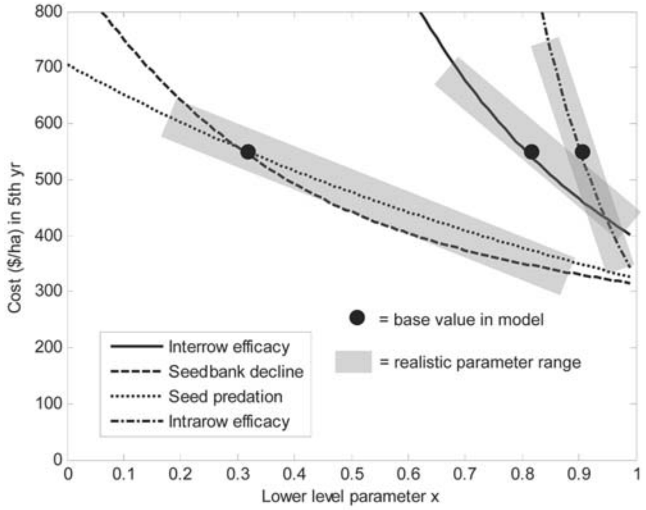

Fig. 8–3. Sensitivity analysis of the impact of variation in sources of weed mortality on total weed management costs after five years of production.

rates in the model took base values (represented by the black dot on each of the four sensitivity curves) at conservative levels, relative to published values (Davis and Liebman, 2003). The base value for cultivation efficacy of seedlings was set at 80%, near the lower end of the published range (Mohler et al., 1997), and hand weeding efficacy was assumed to be 90%. Under these assumptions, total production cost was approximately \$550 ha^{-1}. Varying model parameters within realistic ranges (represented by gray boxes covering each of the sensitivity curves) resulted in overall production costs that varied from \$300 ha^{-1} to \$700 ha^{-1}.

The degree of sensitivity of production cost to change in a particular parameter is represented by the slope of the curve relating production cost to parameter values. Clearly, production costs are most sensitive to changes in efficacy of seedling control, with greater sensitivity to intrarow control (hand weeding of escapes) than interrow control (initial cultivation). Intrarow control was of primary importance in determining production costs since the seedlings that escaped cultivation were assumed to have the greatest impact on crop yield loss due to their size, and the population density of these seedlings drove the labor requirements for hand weeding. Although increases in hand weeding efficacy above 90% would have a marked impact on weed population densities, there are only limited data on the incremental costs associated with increasing hand weeding efficacy (Riemens et al., 2007). This is a research question that merits further study.

The high sensitivity of production costs to cultivation efficacy indicates that it is critical to hone cultivation skills, cultivate in a timely manner, and create soil conditions that support optimal cultivation efficacy. However, even at the high end of the published range for cultivation efficacy, production costs still remain above \$400 ha^{-1}. To bring production costs down further, the key target transitions in this simulation are actually seed predation and seed bank decline. A conservation biocontrol approach to increasing seed mortality in this population has the potential to bring production costs as low as \$325 ha^{-1}.

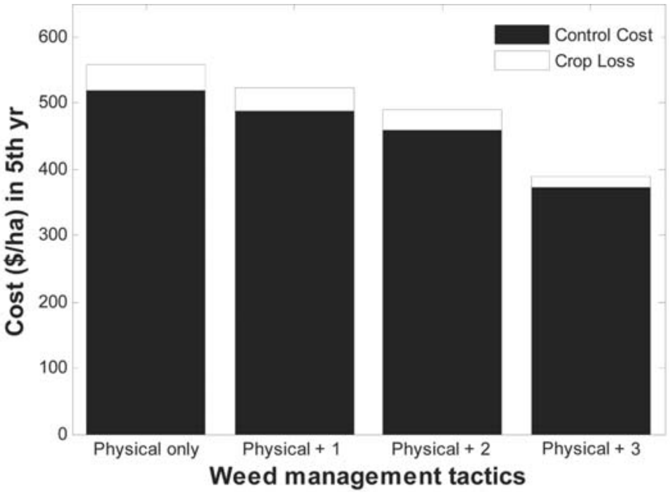

Fig. 8–4. Synergism between physical weed control and one, two, or three additional cultural control methods (Anderson 2005) reduced weed management–related production costs after five years.

Combining multiple management tactics can improve overall weed control and reduce production costs. In a study of various cultural weed management tactics, including narrower row spacing, higher crop population density, fertilizer banding, and delayed planting, Anderson (2005) found synergism between cultural tactics. A single cultural tactic reduced weed biomass in maize by 10%, two tactics combined reduced weed biomass by 25%, and three tactics reduced weed biomass by 60%. We revised our basic model to simulate moderately effective weed control (80% cultivation efficacy, 90% hand control) supplemented by one, two, or three cultural tactics. Under these assumptions, relying on cultivation and hand weeding alone resulted in production costs of approximately $550 ha^{-1}, whereas supplementing physical control with one, two, or three complementary cultural tactics resulted in declining production costs of $510 ha^{-1}, $480 ha^{-1} and $390 ha^{-1}, respectively (Fig. 8–4). A many-little-hammers approach to weed management in organic production systems that incorporates cultural control methods offers a clear path toward reducing dependence on physical weed control, improving overall weed management, and reducing production costs in organic production systems.

Ecological Management of Perennial Weeds

Perennial weeds, particularly those that spread by rhizomes, or "creeping" perennials, can present a considerable challenge to organic producers (Bond and Turner, 2006a,b). Canada thistle is a creeping perennial that spreads locally by rhizomes but also produces viable, wind-dispersed seeds that may travel long distances to colonize new fields (Donald, 1994). In this section, we discuss empirical studies of Canada thistle management and incorporate these results into a demographic model to explore the potential for a many-little-hammers approach to improve suppression of this species.

Management Tactics

Soil disturbance through tillage and cultivation, often the primary tools in an organic farmer's weed management tool kit (Walz, 1999), must be used judiciously or these measures can exacerbate a Canada thistle infestation by severing rhizomes and dispersing fragments into uninvaded areas of the field (Edwards et al., 2000). As rhizome fragment size decreases, successful establishment of new shoots from deep within the soil profile also decreases (Håkansson, 1982). One strategy based on these ecological relationships is to follow rotary tillage with full-inversion plowing, thus sending small rhizome fragments to a soil depth from which they cannot regenerate (Mohler, 2001b). To minimize shoot regeneration, such an operation should be timed to correspond with seasonal lows in root carbohydrate reserves, in mid-spring before bud formation (Gustavsson, 1997; Wilson et al., 2006). Optimizing tillage timing and depth, as described above, has the potential to reduce Canada thistle shoot regeneration within the same growing season by 70 to 85% (timing) and 70 to 95% (depth), in comparison to poorly timed and shallow tillage (Gustavsson, 1997).

A contrasting approach to managing Canada thistle is to use competition from a weed-suppressive cover crop in combination with mowing to reduce thistle growth, replenishment of root reserves, and seed production (Donald, 1990; Bond and Turner, 2006b). Several years in a perennial cover crop, such as the forage legume alfalfa, are required for eradication of Canada thistle (Patriquin et al., 1986; Donald, 1990); however the weed management benefits of long-term cover cropping may not be economically justifiable if the farming operation does not include livestock or if the primary crop is of very high value. A short-term cover crop program may also substantially reduce Canada thistle population densities in the following crop, especially when combined with a second tactic such as mowing. Compared with unsown stubble of a spring barley crop, a grass–white clover (*T. repens* L.) mixture reduced Canada thistle shoot biomass regrowth in the following year by 38% (Graglia et al., 2006). Mowing reduced Canada thistle biomass in the following crop in direct proportion to mowing frequency, with a 23 and 84% reduction in biomass with two or six mowings, respectively. The grass–white clover cover crop plus six mowings reduced Canada thistle biomass in the following crop by 91%, compared with bare stubble with no mowing.

Biological control has also been investigated as an option for Canada thistle. Inundative biological control methods, such as the use of mycoherbicides, have shown promise in field trials (Guske et al., 2004) but have not been adopted, possibly due to the high cost of the agents or lack of commercial products, or both (Hallett, 2005). Moreover, inundative biocontrol at the seed stage using exotic control agents may be ill advised due to the potential for nontarget impacts on rare thistle species (Louda et al., 1997). Conservation biocontrol may hold more promise for this species. In field studies, pre- and postdispersal seed predators reduced fecundity of Canada thistle by 10 to 30% and 55 to 88%, respectively (Heimann and Cussans, 1996). Empirical data on habitat management for increasing seed predation levels for this species are presently not available and are needed to help guide conservation biocontrol efforts.

Insights from Ecological Theory for Canada Thistle Management

A demographic model of Canada thistle (Davis, 2006) was developed based on the perennial life cycle represented in Fig. 8–1c and parameterized with demographic

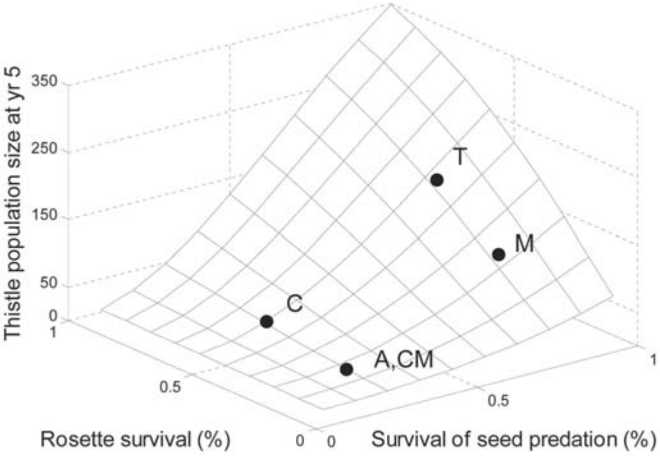

Fig. 8–5. Response surface representing the interdependence between rosette survival, seed survival of postdispersal predation, and Canada thistle population density after five years of organic production. A = continuous alfalfa for five years, C = cover crop alternating with row crop, CM = cover crop + mowing alternating with row crop, T = moldboard tillage in row crop.

rates calculated from Donald (1994). Elasticity analysis of this model indicated that management practices focusing on reducing rosette recruitment and survival, seed survival of predation, and seedling survival to the rosette stage should make the greatest contributions to reducing population growth rate of Canada thistle. For the present analysis, too few empirical data on economics and demographic impacts of management were available to run simulations of production cost per unit land area. Instead, we developed a response surface (Fig. 8–5) from the basic model for two target transitions, rosette survival to reproductive maturity and seed survival of predation, that were also likely to be affected by the aforementioned management systems. Each point on this response surface represents a projection of Canada thistle population size after five years of management (starting population density = 50 plants m^{-2}) in relation to a given combination of rosette and seed predation survival probabilities.

We placed five management systems described in the previous section, including (i) alfalfa for several years (A), (ii) a short-term legume cover crop plus mowing (CM), (iii) a short-term legume cover alone (C), (iv) mowing alone in small grain stubble (M), and (v) rotary tillage followed by moldboard plowing within a row crop sequence (T), on the response surface according to empirical results and qualitative predictions about their potential effect on rosette survival and seed predation. Both the A and CM systems were predicted to have low rosette survival and low seed survival of predation. Crop competition in both systems contributed to low rosette survival, with additional pressure from mowing in the CM system. The thick canopy offered by both systems was predicted to provide good habitat for seed predators; therefore, survival rates were reduced to the low end of the published range. The C system was predicted to have greater rosette survival than the CM system since rosettes were not mowed. Seed survival of predation in the M system was set at the upper end of the published range as bare stubble would provide little shelter for seed predators, and rosette survival was also increased due to the lack of competition from an actively growing cover crop. Both rosette and seed survival were placed at the upper end of the published range for the T system since primary tillage is reported to reduce rosette biomass within the same growing season, but there is no evidence that a single primary tillage event during a cropping cycle also reduces long-term rosette survival. Repeated tillage during a bare-fallow cycle, in contrast, can eradicate Canada thistle if continued for three years (Donald, 1990).

As the predictions of this model were based partially on speculation, this analysis is most useful for hypothesis generation. Nonetheless, we can learn several useful things about Canada thistle management from the exercise. First, quantifying the demographic context for a given cropping system can help prioritize management tactics (Shea et al., 2005). For rosette survival and seed survival of predation, the relative impact of changes to each parameter on population size depends on the value of the other parameter. If few seeds survive seed predation, as in the A, CM, and C strategies, the sensitivity of population size to changes in rosette survival is fairly low (i.e., the slope of the plot of population size against rosette survival is low). However, if many seeds survive predation, as in the M and T systems, the sensitivity of population size to rosette survival is much greater.

This leads to a second lesson learned: Management systems that target multiple life stages have a degree of buffering that single-stage tactics do not have. It can be seen in Fig. 8–5 that the slope of the response surface increases toward the top of the graph, where both survival rates are increasing toward 1. The steep slope in this region means that errors in weed management have greater negative consequences than in the lower region of the surface, where it flattens out. In the A and CM systems, even a 20% variation in either parameter will result in little change to overall thistle population size. This is an illustration of many little hammers in action. When multiple tactics are applied, it reduces requirements for any one management tactic to produce successful weed management outcomes. Suppressing Canada thistle with alfalfa is an interesting case, as it could be considered a single tactic, but it influences multiple life stages, beyond those described here (including reduced fecundity, seedling recruitment, and rosette recruitment from rhizome fragments). Finally, it appears that a thick vegetative cover included at some point in a crop sequence is critically important for reducing Canada thistle populations, both for its competitive effect and for the habitat it provides to seed predators.

Future Directions: Conversations, Experiments, Models, and Management

The management insights and hypotheses gained from the models presented in this chapter are a small part of a larger conversation that needs to take place between empiricists, theoreticians, farmers, and outreach specialists. Each of the parties in this conversation has something to gain through participation. By placing empirical results into a theoretical framework and putting forth testable hypotheses, we hope we have demonstrated how models can focus research efforts, saving empiricists time and money and increasing the potential impact of their work. At the same time, models are only as good as the data used to parameterize them, and it is difficult, if not impossible, to adapt data from many agronomic experiments for modeling purposes because they have not been collected with portability in mind. Expressing outcomes of management studies in terms of survival rates or fecundity, rather than biomass alone, or providing population densities along with biomass, would allow these data to be used again and again.

Farmers contribute to this conversation as innovators, observers, hypothesis generators, fact checkers, information gatherers, and early adopters. Although the traditional model for scientific outreach placed the research scientist at the top of a hierarchy, with extension agents in the middle, and farmers at the bottom, flatter models are beginning to prevail that emphasize multidirectional information flow (Staver, 2001). Because of their immense practical experience, and their site-specific knowledge as members of a group that is dispersed across the agricultural landscape, farmers possess a wealth of information that researchers cannot afford to ignore. Extensionists can play an important role in bringing researchers and farmers together, by identifying complementary interests and personalities and by facilitating interactions.

One way in which farmers, extensionists, and research scientists can come together is through learning communities (Jordan et al., 2002, 2006), which meet on an ongoing basis to develop understanding of sophisticated topics beyond the scope of any one individual's training or experience. Some of these groups work to improve their ability to apply the many-little-hammers concept. Others identify pressing management areas with need for further scientific support. One such learning community in Michigan worked together over the course of a winter to summarize what they knew about ecological weed management, to identify gaps in scientific knowledge, and to write a guide to ecological weed management in Michigan field crops (Davis et al., 2005). The group obtained funding for a series of on-farm experiments to address the knowledge gaps, with plans to reconvene, evaluate the research findings, and update the management guide.

Information exchange between farmers, researchers, and other members of the agricultural community could lead to potentially surprising practical outcomes. Consider, for example, a survey of 10 organic farms that found the most successful farm, from the standpoint of having the lowest labor requirement for weeding, was the one on which weed seed banks had been depleted by killing and removing weeds surviving other controls, before they produced and dispersed seeds (Vereijken, 1999). At first consideration, this result would seem to lead to the conclusion that farmers should seek to completely eliminate weed reproduction, following Norris's (1999) *zero seed threshold*. Modeling analyses of weed population dynamics conducted by Westerman et al. (2005) indicated, however, that because of weed seed consumption by indigenous insects and rodents, low levels of weed survival and reproduction could be tolerated without long-term growth of weed populations. Thus, as a complement to developing better weed control machinery, emphasis could be placed on developing strategies for habitat management to increase densities and impacts of weed seed predators. By maintaining weed populations at an acceptably low level, such a strategy has the added benefit of supporting biological diversity within a field (Marshall et al., 2003).

Continued growth in the organic farming sector in the coming decades will provide new opportunities for weed scientists to serve and engage with the agricultural community. New resources will be needed to test hypotheses concerning weed population dynamics on a broad scale and over the long term, on both commercial farms and research station plots. We believe the discipline of ecology offers the most appropriate overarching framework for conducting this work and for investing time and resources most effectively. When empiricists, modelers, and farmers engage in an ongoing conversation, sharing information freely and learning from one another, each iteration of this process will make considerable progress toward economically and environmentally sustainable weed management systems.

Discussion Questions

1. A weed can only be killed once. Why bother using multiple tactics for weed management in organic production systems?
2. In what specific ways can mathematical models be used to guide weed management? Argue the pros and cons of a quantitative approach to ecological weed management, and discuss how this strategy can be used to help set research priorities.
3. What are the reasons for farmers to develop distinct management practices for weeds with different life histories? Explain why and how those strategies should differ and under what circumstances, and also the conditions under which the strategies should be the same.
4. What are three critical concerns for weed managers, and how do they relate to the development and implementation of weed management strategies?
5. What are “target transitions” in weed life histories? How are they identified, and what is their importance for weed management?
6. Describe how farmers, extension personnel, and research scientists might jointly develop better weed management strategies.

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