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Integrated weed management for sustainable agriculture

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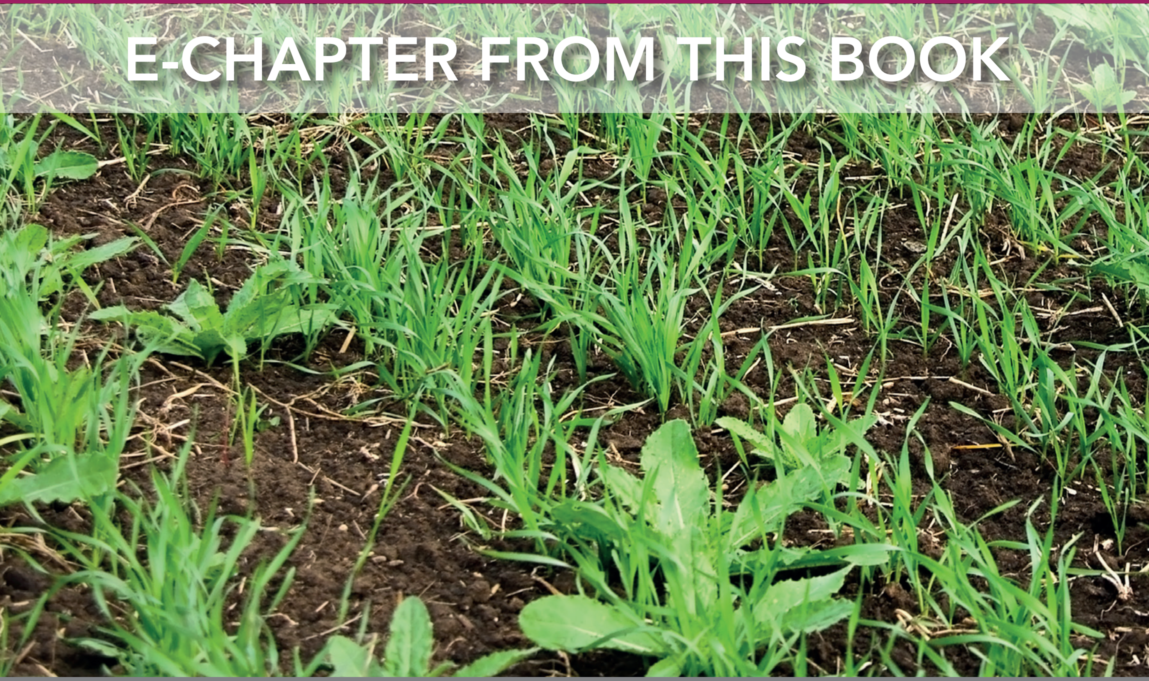

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Cultural techniques to manage weeds

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1 Introduction

Over the last half-century, herbicides have become the dominant tool for weed management in agricultural systems of industrialized nations (Gianessi 2013), as well as the focus of much of the research in weed science (Harker and O'Donovan 2013). Use of herbicides has, in many cases, increased farm profitability, facilitated the adoption of reduced tillage practices that contribute to soil and water conservation, increased farm labour efficiency, and improved farmers' quality of life (Gianessi and Reigner 2007; Gianessi 2013; Zimdahl 2013). Concomitantly, heavy reliance on herbicides has also resulted in cases of environmental contamination and widespread problems with herbicide resistance in weed populations (Liebman et al. 2016).

Integrated weed management (IWM) is seen by many analysts as a useful approach for improving the long-term effectiveness and reliability of weed suppression, while decreasing environmental contamination (Swanton and Wiese 1991; Harker et al. 2012; Shaner 2014; Liebman et al. 2016). Integrated weed management is characterized by the use of sets of farming practices that as a group suppress weed emergence, survival, growth, resource use, and competition against crops. Because IWM spreads the burden of weed suppression and crop protection across multiple tactics, risks of failure can be

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reduced relative to approaches that rely heavily on only one type of control tactic (Liebman and Gallandt 1997). Additionally, by minimizing the exposure of weed populations to any single control tactic, for example, particular groups of herbicides, rates of weed adaptation and resistance evolution are expected to be lower than for strategies that rely heavily on single tactics (Bottrell and Weil 1995; Owen 2016). While IWM does not exclude the use of herbicides, the development and implementation of IWM systems is contingent on a better understanding of the effects and coordinated use of non-chemical as well as chemical tactics (Harker et al. 2012; Harker and O'Donovan 2013).

Elsewhere in this volume, the authors examine a wide range of farming practices and weed control tactics that can be included in IWM strategies, including cover cropping, intercropping, rotation sequencing, release or conservation of biological control agents, cultivation with specialized machinery, and site-specific herbicide application. The focus of this chapter is on cultural techniques that can also contribute to effective weed management strategies, including choice of crop density, crop arrangement, and crop genotype, and manipulation of initial crop size, soil fertility, and soil moisture conditions. Weed management strategies that make use of cultural factors seek to reduce weed density, resource consumption, biomass production and competition with crops. They also seek to prevent colonization of fields by weed species not previously present. Additionally, by altering the availability of light, water and nutrients in space and time, and by challenging weeds with allelochemicals, cultural tactics are intended to improve crop performance (Liebman and Mohler 2001; Mohler 2001).

As noted earlier, a key feature of IWM strategies is that by combining complementary control tactics, practices that may be individually weak can collectively provide much greater levels of weed suppression (Anderson 2007, 2009; Liebman and Davis 2009). The effects of combinations of tactics may be additive or synergistic. Examples of the consequences of multi-tactic weed management strategies are examined at the end of this chapter.

2 Crop population density

Planting crops at higher densities can increase crop competitiveness against weeds, thereby reducing weed growth, lowering weed seed production and increasing crop yield under weed-infested conditions (Mohler 2001a; Lemerle et al. 2004). This approach is especially well suited to low-input and organic farming systems or conventional systems in which herbicide resistance in weeds is problematic. Ecological theory predicts that as the density of a crop population increases, the proportion of available light, water and nutrients captured by the crop and usurped from associated weeds should increase (Mohler 2001a; Lemerle et al. 2004). These shifts in interspecific competition for resources are also accompanied by shifts in intraspecific competition. To understand these relationships, it is important to distinguish between individual- and population-level responses.

Evaluated at the level of an individual plant, as crop density increases, intraspecific competition among crop plants increases, leading to reductions in individual plant size and reproductive output. However, evaluated at a population level, interspecific competition by the crop against associated weeds also increases with increased crop density, leading to reduced weed growth and, in many cases, higher crop yields per unit area under weedy conditions (Lemerle et al. 2004; Kristensen et al. 2008; Place et al. 2009; Olsen et al.

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2012; Lutman et al. 2013; Marín and Weiner 2014). Mohler (2001a) reviewed 91 cases in the literature and found only six failed to show decreasing weediness with increasing crop density; neutral or positive responses for crop yield under weedy conditions were noted for virtually all test cases. Crops for which increased density reduced weed biomass or weed density included barley, bean, cabbage, cotton, cowpea, flax, lentil, maize, oat, pea, peanut, perennial ryegrass, rapeseed, rice, safflower, soybean, sweet potato, timothy and wheat.

Several caveats for the high crop density approach for weed management should be noted. First, though it works well with cereals and pulse crops for which seed size is relatively constant despite variation in numbers of seeds per plant, the high-density approach is not appropriate for all crops, especially vegetables for which crowding-related decreases in size of harvestable units reduce market value (Mohler 2001a). Second, large increases in crop density are likely to result in lodging, disease, and other problems affecting crop yield and quality (Håkansson 2003). Third, the high crop density approach used alone can be insufficient for weed suppression under commercial production conditions. For example, Williams and Boydston (2013) reported that in experiment plots examining interactions between wild proso millet (*Panicum miliaceum*) and sweet corn grown across a wide range of densities, increased crop density led to a taller and thicker crop canopy, less weed biomass and lower weed seed production. However, in comparisons between a crop population currently used by commercial growers and a higher crop population known to optimize yield of certain sweet corn hybrids, there were only small reductions in growth and seed production by the weed. Thus, a combination of increased crop density with other weed suppression tactics is desirable (Lemerle 2004).

3 Crop spatial arrangement

Crop spatial arrangement has been shown to affect weed–crop interactions in some situations. For a given crop population density, narrowing the distance between crop rows increases a crop's uniformity in space. In many experimental studies, narrower row spacing is confounded with higher crop densities, but a considerable number of studies have been conducted in which crop arrangement and density are manipulated independently, allowing for examination of row spacing effects separately.

Mohler (2001a) assessed 48 studies testing the effects of narrower rows at constant crop population density (i.e., more equidistant crop spacing) on weed density or weed biomass production and found weed suppression in 48% of the cases, a neutral effect in 17% of the cases, a positive effect in 2% of the cases, and variable responses in 35% of the cases. Crops included in the review were barley, bean, cotton, flax, lupin, corn, oat, peanut, pearl millet, pigeonpea, rapeseed, safflower, sorghum, soybean, sunflower and wheat. In cases where narrower rows do result in fewer and smaller weeds, the effect is often coincident with increased crop ground cover, leaf area index, dry matter production, and light interception, especially early in the growing season (Mohler 2001a; Harder et al. 2007; Drews et al. 2009). In a study that investigated the effects of variable row spacing for wheat grown with and without nitrogen fertilizer, narrower rows increased weed suppression regardless of fertility level (Kristensen et al. 2008). In contrast, in another study with wheat, narrower rows led to weed suppression in one of three years when rainfall was adequate, but not in two years that were exceptionally dry (Olsen et al., 2012).

For both corn (Marín and Weiner 2014) and wheat (Kristensen et al. 2008; Weiner et al. 2010), increasing crop density while narrowing row spacing can have complementary

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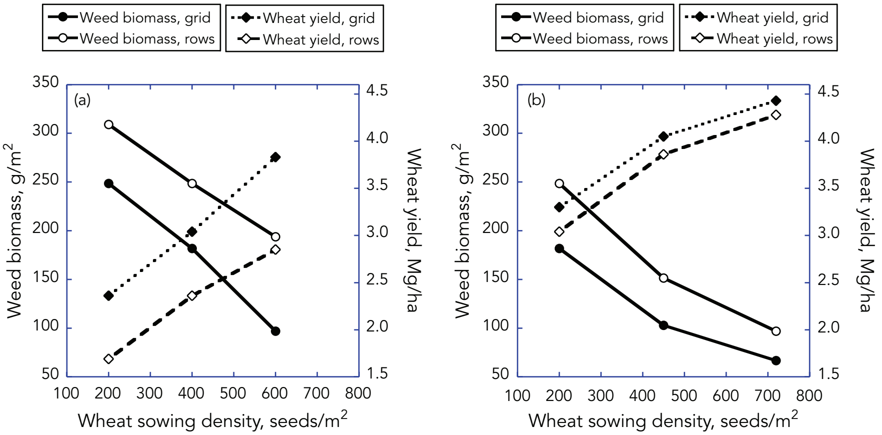

Figure 1 The effects of wheat sowing density and planting pattern on weed biomass production and wheat grain yield under weed-infested conditions in 1998 (a) and 1999 (b). Individual wheat seeds sown in the grid pattern were spaced nearly equidistantly, whereas wheat seeds in the row pattern were sown in rows spaced 12.8 cm apart. The experiment was conducted by Weiner et al. (2001).

effects, with the greatest weed suppression occurring with increased density and greater spatial uniformity. High-density, narrow row arrangements for corn resulted in an average of 65% less weed biomass and 46% greater yield relative to a standard lower-density, wider row arrangement (Marín and Weiner 2014). Sowing wheat at a high density in narrow rows rather than at lower density and in wider rows resulted in large reductions in weed biomass and substantial increases in wheat yield under weed-infested conditions relative to a standard lower-density, wider-row sowing pattern (Weiner et al. 2001, Fig. 1).

The utility of narrow row spacing may be limited for systems in which interrow cultivation is required and row distances interfere with the passage of cultivation equipment. Alternatively, in systems that use herbicides, computer-assisted guidance systems for precision cultivation, or full-width harrows that pass over a crop without damaging it significantly, narrow row spacing may be a useful addition to a grower's portfolio of weed management tactics.

4 Sowing time and transplanting

Weed species have distinctive patterns of release from dormancy, germination and seedling emergence that are driven by interactions between seed physiology and environmental conditions, especially soil temperature and moisture (Forcella et al. 1997; Hartzler et al. 1999; Myers et al. 2004; Werle et al. 2014). Through knowledge of the timing of species-specific pulses of weed emergence, and adjustments in crop planting date and preplanting weed control practices, weed emergence patterns can be exploited to reduce densities of weeds infesting crops.

For warm season crops such as corn and soybean, delaying planting for several weeks can allow large numbers of weed seedlings to emerge and be killed by tillage or herbicides before the crop is sown (Gunsolus 1990; Forcella et al. 1993). For example, in an experiment conducted over a three-year period in Minnesota, mean density of giant

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foxtail (*Setaria faberi*) in soybean grown with no supplementary weed control was 213 plants m^{-2} for an early-planted treatment, sown on 12–16 May, compared with 40 plants m^{-2} in a late-planted treatment, sown on 2–7 June (Buhler and Gunsolus 1996). It should be noted that while delayed planting may offer opportunities to reduce weed density, it can also lead to reductions in corn and soybean yield potential (Gunsolus 1990).

Delayed planting can also be used to reduce weed densities in cool season crops such as wheat. Lutman et al. (2013) conducted a meta-analysis of 19 studies investigating the effect of wheat planting date on densities of blackgrass (*Alopecurus myosuroides*) and found that delaying planting from September until late October reduced blackgrass densities about 50%. This effect was attributed to the destruction of a greater proportion of weed seedlings prior to sowing the crop, since the weed typically begins to emerge in late summer. In a subset of the studies that compared blackgrass densities in September-sown wheat (i.e. winter wheat) and wheat sown the following spring, densities of the weed were 88% lower for the spring-sown crop. Lutman et al. (2013) noted that while delayed seeding could offer weed management advantages, farmers in the United Kingdom might be reluctant to adopt the practice due to the risk of being prevented from sowing the crop at all due to progressively wetter conditions after September.

Weed emergence prior to planting a crop can be enhanced by using preplanting tillage to expose weed seeds to light and other environmental cues for germination. The false and stale seedbed approaches exploit this phenomenon and have been used in the production of sugar beet, carrot, onion, and other crops. Soil is disturbed by tillage several weeks ahead of crop sowing to promote weed emergence; weeds are then killed by flaming, shallow cultivation or herbicide application, and the crop is sown with minimal further soil disturbance (Mohler 2001b; Rasmussen 2003). Rasmussen et al. (2011) reported that planting 29 days after seedbed preparation and flaming eight days after the crop was sown reduced weed density in sugar beet 89% relative to a treatment that was sown one day after seedbed preparation and flamed 10 days later.

Transplanting crops allows crops to grow under relatively weed-free conditions in seedling beds or greenhouse trays during the early portion of the growing season before being placed in fields where weeds have been removed by tillage, flaming, flooding or herbicides. This 'head-start' in crop size relative to emerging weeds can convey large weed management benefits including reductions in the length of the critical period for weed control, weed biomass production and crop yield loss to weed competition (Weaver et al. 1992). In field experiments conducted in Ontario, Weaver (1984) noted that to prevent yield loss, the minimum weed-free period for transplanted tomato was five weeks as compared with nine weeks for direct-seeded tomato. While not suitable for all crops due to labour costs and other factors, transplanting is a valuable weed management technique for many horticultural crops and for rice in some regions.

5 Choice of crop genotype and breeding for competitive and allelopathic abilities

Within a given crop species, genotypes can differ substantially in their ability to suppress weed growth and sustain yield in the presence of weeds. Collectively, these two phenomena are often called 'crop competitive ability', though allelopathic interactions as well as resource competition can be involved (Bertholdsson 2011; Worthington and Reberg-Horton 2013). Mohler (2001a) noted that crop genotypes with superior weed-suppressive

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ability or weed tolerance have been reported for at least 25 crop species, including cereals, pulses, forages and vegetables.

As might be expected from studies of other ecological phenomena, a crop genotype's competitive ability can vary substantially among different environments and experiments (Lutman et al. 2013; Andrew et al. 2015; Jacob et al. 2016). An additional complicating factor is that while weed suppression and weed tolerance can be positively correlated, negative correlations or a lack of relation between the two phenomena can also exist (Lemerle et al. 2001; Watson et al. 2006; Colquhoun et al. 2009; Bertholdsson 2010). These complications notwithstanding, interest in developing crop genotypes with improved weed competitive ability is increasing in response to the evolution of herbicide resistance in weeds, environmental concerns associated with herbicide use, and the needs of organic producers and smallholder farmers who eschew or lack access to herbicides (Worthington and Reberg-Horton 2013; Andrew et al. 2015). Christensen et al. (1994), Williams et al. (2008a) and Gealy et al. (2014) have shown that competitive cultivars of wheat, barley, rye, sweet corn and rice can better reduce weed growth and maintain yield when treated with reduced rather than full doses of herbicides.

Crop competitive ability against weeds can be conferred by a number of heritable traits including rapid emergence, rapid early growth, greater numbers of tillers and branches, tall shoots, and greater canopy area and light interception, as well as differences in the size and depth of root systems that affect access to water and nutrients (Lemerle et al. 1996; Watson et al. 2006; Zhao et al. 2006; Williams et al. 2008b; Beckie et al. 2008; Colquhoun et al. 2009; Drews et al. 2009; Andrew et al. 2015). These traits might serve as selection targets in breeding programmes, rather than selecting for competitive ability directly. A complementary approach to breeding for increased resource capture involves breeding for increased allelopathic ability, that is, an enhanced capacity to interfere with weed germination, growth and development via chemicals exuded from crop roots or shoots. Genotypes of rice, wheat, barley, oat, rye and sorghum have been identified with high allelopathic activity against weeds (Olofsdotter et al. 2002; Belz 2007; Seal and Pratley 2010; Bertholdsson 2011; Gealy et al. 2014), and efforts have been initiated to breed high-yielding, weed-suppressive cultivars through traditional techniques, quantitative trait loci mapping and marker-assisted selection (Belz 2007).

Selection of crop genotypes for both enhanced ability to compete with weeds for light, water and nutrients, and increased allelopathic ability has been pursued in research programmes for a number of cereal crops. Weed-suppressive rice cultivars are now commercially available in the United States and China, and weed-suppressive wheat and barley cultivars are being bred for commercial release in Sweden (Worthington and Reberg-Horton 2013).

6 Mulching

Mulch materials applied to the soil surface can suppress the emergence of weed seedlings and consequently reduce weed plant densities, biomass production and competition with crops. Mulch materials can also promote retention of soil moisture and alter soil temperature regimes (Liebman and Mohler 2001). As noted by Grundy and Bond (2007), mulch materials can be sheeted or particulate in form. Examples of the former include black polyethylene; geotextiles; needle-punched fabrics made from natural fibres; various types of paper products; and carpeting. Examples of particulate mulches include shredded

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and chipped bark or wood; sawdust; crushed rock or gravel; hay, grass clippings, straw, and other crop residues; and various industrial waste materials, such as shredded tyres.

Choice of mulch materials for weed suppression is determined by local availability, cost and management considerations. In general, mulching is used for weed suppression in high value crops, such as tomato (Anzalone et al. 2010), apple (Arentoft et al. 2013) and medicinal herbs (Duppong et al. 2004), for which the investment in materials and labour for application and removal is justified by the savings in total weed control costs and increases in crop quality or yield. Mulching can strongly suppress weed growth (Fig. 2). However, managing weeds that emerge at the edges of sheeted mulches can be problematic, while particulate mulches are generally ineffective against established perennial weeds (Grundy and Bond 2007).

Sheeted mulches can restrict access to light needed to cue weed seed germination, as well as physically obstruct the emergence of weed seedlings (Grundy and Bond 2007). Additionally, polyethylene sheet mulches can be used for soil 'solarization' whereby tarped soil is heated by sunlight well above ambient conditions, and weed seeds and newly germinated seedlings are killed thermally (Liebman and Mohler 2001). Weed seed death due to solarization is also related to changes in soil ethylene and carbon dioxide concentrations, and can be promoted by increasing soil moisture levels and incorporating phytotoxic crop residues prior to tarping (Liebman and Mohler 2001). Unlike other sheet mulching techniques used when crops are growing, solarization is used before or after crop production.

Weed suppression by particulate mulches increases as mulch depth increases (Ozores-Hampton et al. 2001a) and generally requires a mulch depth greater than 7 cm for satisfactory levels of control (Marble 2015). Teasdale and Mohler (2000) investigated seedling emergence of four weed species from beneath a variety of particulate mulch

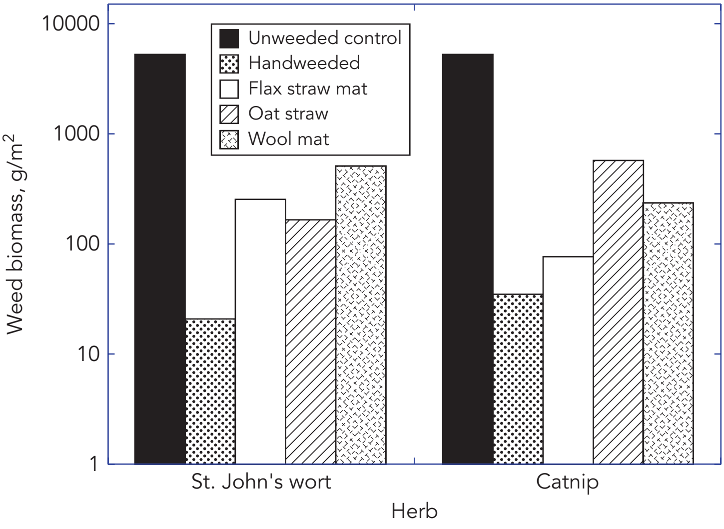

Figure 2 Weed growth in response to different weeding and mulching treatments used for St. John's wort and catnip production in an experiment conducted by Duppong et al. (2004). Means of two consecutive years of observations (2001–2002) on the same plots are shown.

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materials and attributed successful emergence to the capacity of seedlings to grow around obstructing mulch elements under limiting light conditions. Large-seeded species were more likely to be able to emerge through mulch layers than small-seeded species. Two-parameter models that included terms for mulch area index (mulch surface area per unit of ground area), and either light extinction by mulch or the fraction of mulch volume that was solid, explained 53–75% of the variation in suppression of seedling emergence, depending on weed species. Particulate mulches made from organic materials such as municipal solid waste, yard trimmings and livestock manure can also suppress weed emergence and growth chemically, through emissions of organic acids, phenolic compounds, ammonia and other materials (Ozores-Hampton et al. 2001b). Care must obviously be exercised to minimize threats to crop growth and development by such materials. Consequently, mulch materials with phytotoxic properties have been proposed for use between, rather than in, crop rows (Ozores-Hampton et al. 2001b).

7 Soil fertility management

The maintenance of soil fertility through the application of mineral fertilizers and/or organic materials, such as plant residues, manure and compost, is a critical component of sustainable cropping systems. Nitrogen, phosphorus and potassium are typically the nutrients that most limit crop productivity in the absence of fertilization. Weeds can also be highly responsive to fertilizer application, though differences exist among species in the degree of response (Blackshaw et al. 2003, 2004a; Blackshaw and Brandt 2008; Storkey et al. 2010; Moreau et al. 2014). When crop and associated weed species differ in their height growth and canopy production responses to soil fertility conditions, large shifts in competitive relations can occur (Liebman and Mohler 2001). Variations in the timing, placement and form of fertility amendments have been shown to be capable of affecting weed population dynamics and crop-weed competition, and thus might serve as components of IWM strategies (Liebman and Mohler 2001).

Blackshaw and colleagues investigated the effects of fall versus spring fertilizer application on crops and weeds in a series of experiments conducted in Alberta and Saskatchewan (Blackshaw et al. 2004b, 2005a, 2005b). Cropping systems included continuous spring wheat, a spring wheat-canola rotation and a barley-field pea rotation. Weed infestations were created intentionally by sowing weed seeds as single species or species mixtures at the inception of the experiments, each of which ran for four years. In general, application of fertilizers (N, P and/or S, depending on the experiment) when crops were sown in the spring (April or May) maintained or increased crop yields, and had a neutral or negative effect on weed biomass production, relative to treatments in which fertilizer was applied the previous fall. After four years, spring rather than fall fertilization lowered weed seed densities in the soil seed bank by 21–24% for the wheat-canola rotation (Blackshaw et al. 2005a), but had no effect on weed seed densities for the barley-field pea rotation (Blackshaw et al. 2005b). For the continuous wheat experiment, in which individual weed species were sown separately, spring fertilization reduced soil seed bank density of wild oat (*Avena fatua*) and common lambsquarters (*Chenopodium album*), but had no effect on seed density of green foxtail (*Setaria viridis*) and wild mustard (*Brassica kaber*) (Blackshaw et al. 2004b). With the observed desirable or neutral, but not negative, effects on crops and weeds, spring fertilization would appear to offer advantages over fall fertilization for spring-sown crops on the Canadian prairies.

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Johnson et al. (2007) investigated the effects of delayed fertilizer application on corn and giant ragweed (*Ambrosia trifida*) performance in Indiana, comparing a full dose of N fertilizer (200 kg N ha^{-1}) at planting with a late fertilizer treatment, in which all N was applied at the five- or eight-leaf stage of corn development, and a split fertilizer treatment, in which a half-dose of N was applied at corn planting and another half-dose was applied at the five- or eight-leaf stage. The latter two treatments were investigated as possible strategies to increase corn N use efficiency by better matching crop N demand with N supply. The crop and weed were grown in mixture at fixed densities, and a weed-free corn treatment was also included in the experiment. Compared with at-planting N application, the late and split fertilization treatments increased giant ragweed late season biomass 83% and 42%, respectively. In contrast, corn grain yield was unaffected by N fertilizer timing, and giant ragweed reduced corn yield 19% regardless of N fertilizer timing. Thus, from the perspective of crop yield protection and weed suppression, the at-planting N fertilization strategy was superior. These results and those of Blackshaw et al. (2004b, 2005a, 2005b) indicate that the impacts of fertilization practices may be site-, crop- and weed-specific.

Placement of fertilizer into the soil in bands near crop rows rather than broadcasting it on the soil surface can improve crop performance and constrain weed growth. This has been shown for crops that include bean, soybean, peanut, alfalfa and rice (DiTomaso 1995), and presumably reflects improved access to nutrients by crops and reduced access by weeds growing between crop rows. Rasmussen et al. (1996) compared the effects of fertilizer placement in three years of field trials in Denmark and reported that band application of N into soil 5 cm below rows of barley rather than surface broadcasting increased barley yield an average of 28% and decreased weed biomass an average of 55%. Similarly, in a four-year experiment conducted with spring wheat in Alberta, incorporating N fertilizer into the soil in bands and especially by point injection, rather than surface broadcasting, tended to reduce weed growth (Fig. 3) and weed seed density in soil and increase wheat yields (Blackshaw et al. 2004b).

Nutrients can be supplied to crops through manure applications, but manure may also contain weed seeds (Cudney et al. 1992), leading to concerns over infesting fields

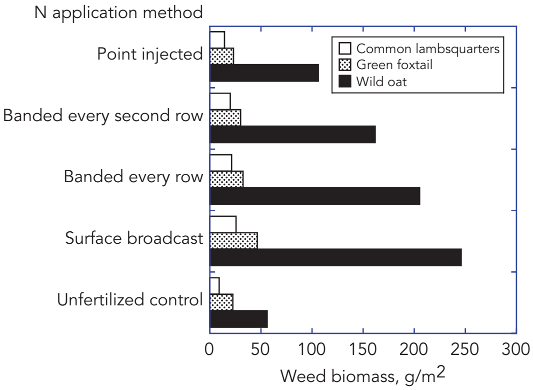

Figure 3 The effects of different methods for nitrogen fertilizer on biomass produced by common lambsquarters (*Chenopodium album*), green foxtail (*Setaria viridis*) and wild oat (*Avena fatua*) grown with spring wheat in an experiment conducted by Blackshaw et al. (2004b). Means of four consecutive years of observations (1998–2001) on the same plots are shown.

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with species not previously present, or increasing the densities of resident weed species. However, results of an on-farm study conducted in Wisconsin indicate such threats may be minimized where weed control practices are effective. Cook et al. (2007) measured weed densities on 11 cash grain farms that received manure from neighbouring dairy farms and found that manuring did not introduce new weed species, nor did it increase weed densities; these results were attributed to the high levels of weed control achieved with existing practices used by the farmers. Additionally, threats of introducing or augmenting weed populations through seeds applied in manure can be greatly reduced by composting the manure, which kills seeds thermally and perhaps through their exposure to phytotoxins such as organic acids that are generated during the composting process (Ozores-Hampton et al. 1999; Eghball and Lesoing 2000; Larney and Blackshaw 2003).

Much remains to be learned concerning the effects of composted manure on crop-weed interactions and weed dynamics. In an experiment investigating corn grown in mixture with each of three weed species, application of composted swine manure increased seed production by common waterhemp (*Amaranthus rudis*) and velvetleaf (*Abutilon theophrasti*), but had no effect on seed production by giant foxtail and little or no effect on corn grain yield (Liebman et al. 2004). Composted swine manure also increased the competitive effect of common waterhemp on soybean (Menalled et al. 2004). Blackshaw (2005) conducted a four-year fertility regime experiment with wheat and a mixed species weed community, and found that after fertility treatments had been in place for a year, weed N uptake and growth with fresh and composted cattle manure was similar to or greater than that with broadcast N fertilizer. Manure and compost tended to have a greater positive effect on weeds than spring wheat, and at the conclusion of the study, the ranking of weed seed densities in soil was composted manure = fresh manure ≥ broadcast N fertilizer > banded N fertilizer. In contrast, Lindsey et al. (2013) examined composted dairy manure effects on potato grown with three weed species (common lambsquarters, giant foxtail and hairy nightshade (*Solanum physalifolium*)), and reported that compost did not increase biomass or seed production of any of the weed species, while increasing potato yield 5–15%. In a study of the effects of different fertility amendments on weed seed banks in a fodder beet-winter wheat-cabbage-perennial ryegrass-silage corn rotation sequence, De Cauwer et al. (2011) found that total weed seed bank density was lowest in plots amended with compost and highest in plots amended with liquid cattle manure. Reductions in weed seed densities in soil, especially of hard-coated species such as *Chenopodium* spp., were correlated with increases in total microbial biomass and soil organic carbon content. Taken together, results of these studies indicate that while manure and compost 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. More needs to be understood about the effects of different organic amendments on weed seed decay and mortality.

After decomposition in and on the soil, residues of certain legume crops can be important sources of N for succeeding crops, while also influencing weed dynamics and crop-weed interactions (Liebman and Ohno 1998). In field experiments, residues of crimson clover and red clover reduced common lambsquarters and wild mustard density, emergence rate, relative growth rate, biomass production and competitive ability, while enhancing sweet corn growth and yield (Dyck and Liebman 1994; Dyck et al. 1995; Davis and Liebman 2001). Aqueous extracts of crimson clover, hairy vetch and red clover 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 (Ohno

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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 corn, but strongly suppressed the germination and growth of small-seeded weeds, such as common lambsquarters and wild mustard. Weed-suppressive effects of phenolic acids in red clover residues can be enhanced by soil-borne pathogens such as *Pythium* spp., which can attack small-seeded weeds, such as wild mustard, to a greater degree than corn (Conklin et al. 2002).

In low-external-input and organic farming systems, farmers often combine the use of manure, compost and crop residues for soil improvement and enhanced fertility over the long term (Liebman and Davis 2000). Consequently, effects on weed and crop performance in such systems may reflect accumulated changes in soil properties, such as temporal patterns of nutrient release, water-holding capacity, bulk density, and microbial community composition and activity (Gallandt et al. 1999). In a study of weed and potato performance in plots amended with soil-improving crop residues ('green manure'), cattle manure, and cull potato compost versus barley residues and high rates of synthetic fertilizers, Gallandt et al. (1998) found that after the treatments had been in place four years, organic matter amendments had enhanced soil physical properties and fertility, and increased potato canopy production and tuber yield. When herbicides were not applied and cultivation comprised the only direct form of weed control, weed growth in the treatment receiving organic amendments was 75% lower than in the treatment that relied heavily on fertilizers, despite similar weed densities. Gallandt et al. (1998) attributed the latter effect to improvements in soil quality that promoted a more vigorous potato crop that was better able to compete with weeds.

Similar results were obtained by Ryan et al. (2009, 2010), who measured the competitive effects of mixed-species stands of weeds on corn in two contrasting systems that had been in place for 27 years: a diversified organic rotation that received residues of legume green manures and manure versus a simpler, conventionally managed rotation without legume green manures and manure. The investigators found that a given density of weeds and a given amount of weed biomass caused more yield loss for corn in the conventional than the organic system. Greater crop tolerance of weeds in the organic system was attributed to improved soil quality, diversification of nutrient sources, and niche differentiation and resource partitioning between crop and weed species (Ryan et al. 2009, 2010; Smith et al. 2010).

8 Irrigation and flooding: depth, timing and placement

Globally, soil moisture is the main factor limiting crop production in much of the world where rainfall is insufficient to meet crop demand (Steduto et al. 2012). Consequently, various forms of irrigation are widely used to enhance crop production. Water management can also be used to suppress weeds, though the responses of weed individuals and species are affected by the magnitude, timing and location of changes in soil moisture conditions.

Water management is especially important for rice production, the staple crop for about half the world's population and one of the few major crops that is adapted to flooded soil conditions (Rao et al. 2007). Rice can be grown under rain-fed conditions, but most rice production occurs with inundation for at least part of the crop cycle. Weed species in the Poaceae and Cyperaceae dominate the weed floras of rice crops, and many of the weed species present in rice fields are adapted to flooded conditions (Rao et al. 2007).

Due to rising costs of production, in many rice-producing regions there has been a shift in crop establishment practices from manual transplanting of seedlings to direct-seeding. Whereas transplanting creates a size differential between rice seedlings and newly emerging weeds that creates a competitive advantage for the crop, by removing this size difference, direct seeding increases the potential effects of weed competition on the crop. Water management, in concert with other weed management techniques, thus plays an important role in controlling weeds in direct-seeded rice (Rao et al. 2007; Chauhan and Johnson 2011).

Gealy et al. (2014) found that weed competition against rice was much greater with non-flooded furrow-irrigated conditions than with full-field flooding; rice yields were 76% lower in the former conditions than the latter. The investigators identified rice cultivars with high levels of competitive ability and allelopathic activity against weeds as desirable components of IWM strategies for rice. Chauhan and Johnson (2011) compared the effects of times of water application and flooding depth on *Echinochloa crus-galli* in direct-seeded rice and found that maximum reduction in the height and biomass of the weed was achieved when soil was flooded to a depth of 10 cm within two days of sowing the crop; decreasing water depth and delaying flooding increased the weed's growth. Similar results were reported by Williams et al. (1990). Other factors identified by Chauhan and Johnson (2011) as contributing to suppression of *E. crus-galli* included deep burial of seeds (>8 cm) by tillage prior to planting the crop, or alternatively, maintenance of a thick mulch of crop residues from the previous crop. Continual use of flooded conditions for rice production often creates shifts in weed floras towards water-tolerant species (Rao et al. 2007). Consequently, rotations of different crops with rice that create large differences in soil moisture regimes is likely necessary to disturb weed community dynamics and prevent increases in densities of adapted weed species (Williams et al. 1990).

The timing of irrigation water application can be used as a weed-suppression tactic not only in rice but also in non-flooded crops grown in arid conditions. In an experiment evaluating weed management strategies for lettuce production in California, Shem-Tov et al. (2006) compared the use of pre-plant irrigation of raised beds followed 7 or 14 days later by shallow tillage with a no pre-plant irrigation control treatment. Pre-irrigating and then cultivating resulted in the emergence and removal of up to 127 weeds m^{-2} before the crop was sown. The pre-irrigation and pre-plant cultivation treatments also reduced in-crop weed densities (Fig. 4a) and hand-weeding time up to 77% and 50%, respectively. The greatest gains in weed control were obtained by waiting 14 days between irrigation and cultivation (Fig. 4b); this treatment maximized the number of weed seedlings that emerged prior to their removal.

Discrete placement of irrigation water can strongly suppress weed growth while enhancing crop performance and resource use efficiency. Grattan et al. (1988) compared three water management systems for tomato production in California: sprinkler irrigation, which spread water uniformly over a plot; furrow irrigation, which concentrated water between crop rows; and buried drip irrigation, which concentrated water directly beneath crop rows. For each irrigation treatment, weed growth and crop yields were compared in plots not treated with herbicides and in those treated with napropamide and pebulate. All treatments were cultivated and hand weeded for seven weeks after planting the crop. In the absence of herbicides, weed biomass in the sprinkler and furrow irrigation treatments was >17-fold greater than in the buried drip irrigation treatment, with most of the weed growth occurring between crop rows. For the buried drip treatment, weed growth was similar with or without herbicide application and tomato fruit yield was higher than in the

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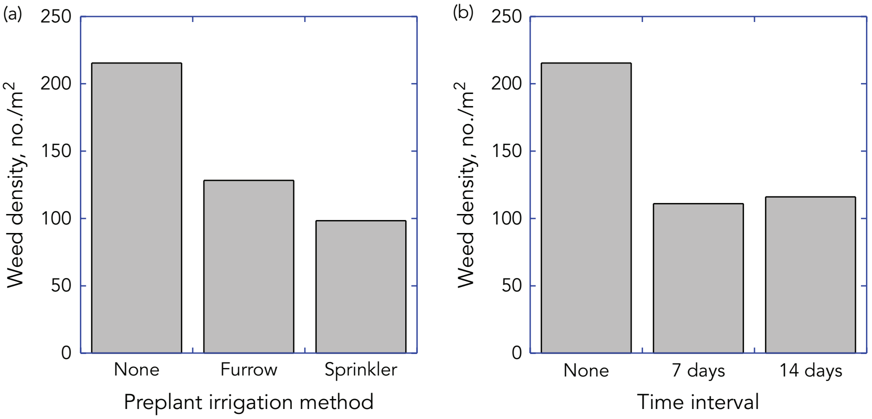

Figure 4 The effects on weed density of preplant irrigation methods (a) and time interval (b) between irrigation and tillage for seedbed preparation in a field experiment with lettuce conducted by Shem Tov et al. (2006). Means of four site-year combinations are shown.

other water management treatments, regardless of herbicide use, reflecting increased water use efficiency.

9 Effects of combining multiple practices: examples of 'many little hammers' at work

Liebman and Gallandt (1997) used the term 'many little hammers' (MLH) to characterize multi-tactic weed management strategies in which individual tactics may be insufficient to provide effective weed suppression, but whose cumulative effects prevent weed population growth and competition against crops. An MLH approach may also be expected to spread the burden of crop protection across a diverse range of stress and mortality factors acting on weeds, thereby reducing selection of weed populations for resistance, limiting shifts in weed community composition towards especially problematic species, and minimizing the risks of weed control failures due to mitigating factors such as weather conditions. Indirectly, by removing some of the burden of crop protection from 'large hammers,' that is, herbicides and soil disturbance through cultivation, MLH approaches may contribute to reductions in herbicide emissions to the environment and to better protection of soil quality. Other analysts of weed management strategies have expressed similar opinions (Anderson 2003; Blackshaw et al. 2008; Chauhan 2012; Mortensen et al. 2012; Norsworthy et al. 2012).

Over the past two decades, a considerable amount of empirical evidence has accumulated to support the MLH hypothesis with regard to the effects of combining cultural tactics for weed suppression. For example, Malik et al. (1993) evaluated the use of different bean cultivars, seeding rates and row spacings, and noted significant effects of all factors on weed biomass production. Two indeterminate, semi-vining bean cultivars suppressed weed biomass production 17–28% relative to a determinate, bush cultivar and use of a narrow-row, high-density planting pattern rather than a traditional wider-row,

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lower-density pattern reduced weed biomass 19–22%. Under weed-infested conditions, bean seed yields were higher for the two more competitive cultivars grown at higher-than-normal density in narrower rows than for the determinate bush cultivar grown with normal row spacing and density. In an experiment examining the effects of crop row spacing, population density, and herbicide rates, Teasdale (1995) found that when corn was grown with narrow row spacing at a twice-normal population density, reduced herbicide rates (¼ X) provided weed control and corn yield equivalent to what was obtained for corn grown at full herbicide rates with normal row spacing and density (Fig. 5). This effect was attributed to more rapid closure and greater early season light interception by the corn canopy in the narrow-row/high-density treatment. Kristensen et al. (2008) reported that when full rates of herbicides were used, no differences in weed competitiveness and wheat yield were detected among row spacing and crop density treatments, whereas when herbicides were not applied, increasing crop density consistently reduced weed biomass and increased crop yield; the effects of narrowing rows were less consistent, but generally reduced weed biomass and increased wheat yield.

Interactions between cultural practices, cropping system diversity and herbicide use can have important effects on weed dynamics and crop performance. O'Donovan et al. (2013) compared combinations of seeding rates (conventional versus twice-normal) and rotation sequence (barley–canola–barley–field pea–barley vs. continuous barley) grown with three herbicide rates at two sites in Alberta. The diverse rotation combined with the higher barley seeding rate resulted in higher barley yields and reduced wild oat biomass compared to continuous barley grown at a lower seeding rate. Wild oat (*Avena fatua*) seed population density in the soil tended to decline in a manner that paralleled aboveground biomass production of the weed, with up to 40-fold reductions in weed seed numbers observed for barley grown at high density in the diverse rotation with full herbicide rates relative to continuous culture of barley at normal density with ¼ X herbicide rate. At one site, the ¼ X herbicide rate in combination with the diverse rotation and the higher barley seeding rate resulted in less wild oat seed in the soil than the ½ X rate used with

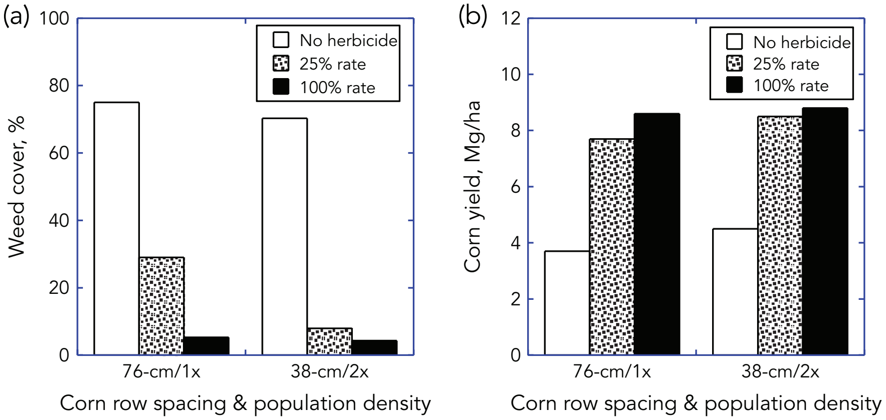

Figure 5 The effects of contrasting corn row spacing and population density combinations and different herbicide rates on weed cover (a) and corn grain yield (b) in a field experiment conducted by Teasdale (1995). The 25% and 100% herbicide rate treatments received a mixture of atrazine, metolachlor and paraquat. Means of four years of observations (1989–1992) are shown.

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continuous normal-density barley, suggesting that cultural practices may compensate for suboptimal herbicidal effects with regard to reducing wild oat in the soil seed bank. Similar results were reported from studies of barley-field pea and wheat-canola rotations grown with sets of cultural weed suppression tactics: higher crop density and spring rather than fall fertilizer application tended to reduce weed biomass, increase crop yields and permit reductions in herbicide application while maintaining effective weed control (Blackshaw et al. 2005a, 2005b).

Synergistic effects of combinations of multiple cultural tactics for weed suppression were reported by Anderson (2005), who examined the use of increased crop population density, narrower row spacing and delayed planting for sunflower production, and the use of increased crop density, narrower rows and banded rather than broadcast fertilizer placement for corn production. Relative to conventional crop production practices, the use of any one tactic reduced weed biomass 5–10%, combinations of two tactics reduced weed biomass 20–25%, but the use of three practices reduced weed biomass 60–85%. Synergistic effects of cultural practices were also noted by Ryan et al. (2011), who investigated the effects of combining mulching with higher than normal seeding rates for soybean production. Weed biomass decreased with increasing amounts of mulch composed of rye residue, and also decreased with increasing soybean density in two of four site-years. Also in two of the four site-years, combining rye mulch with higher soybean seeding rates resulted in greater weed suppression than would be predicted by the efficacy of each tactic alone. In practical terms, increasing soybean planting rate was able to compensate for lower rye mulch levels when the tactics were combined.

10 Future trends in research

Evaluating the combined effects of multiple weed suppression tactics in field experiments can be expensive, large in spatial extent, and challenging to manage if each individual tactic and each combination of tactics are included in a factorial design with multiple replications of each treatment. While the empirical data so gained are valuable, models of weed population dynamics in response to various farming practices can be complementary tools with which to design weed management strategies (Holst et al. 2007; Colbach and Mézière 2013). Such models can be especially useful for identifying key points in weed life cycles for interventions (Davis 2006). As computing speeds and power increase, it is likely that future research concerning cultural techniques for weed management will link empirical field studies (‘*in vivo*’) with modelling analyses (‘*in silico*’[1]) to examine the main and interactive effects of multiple factors driving weed dynamics (Colbach and Mézière 2013).

Colbach and Mézière (2013) and Colbach et al. (2013) constructed a simulation model to examine the effects of various farming practices and soil and climate conditions on the winter annual weed blackgrass (*Alopecurus myosuroides*), one of the most challenging species to manage in autumn-sown crops of Atlantic European countries. In addition to assessing the effects of tillage practices, herbicides, mechanical weeding operations and crop rotation systems, the investigators evaluated the effects of cultural practices such as crop sowing date, crop density, nitrogen fertilization, manure application, and straw

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[1] An expression used to mean performed on computer or via computer simulation.

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burial or removal. In general, soil and weather conditions, initial weed seedbank density, and direct weed control tactics (i.e. herbicides and mechanical weeding) had much larger effects on the number of *A. myosuroides* plants present at crop maturity than did cultural techniques for weed suppression. Nonetheless, delayed planting, increased crop density, straw removal and reduction of viable weed seeds in manure through composting were found to have beneficial effects on weed suppression. Colbach and Mézière (2013) concluded that the major advantage of the modelling approach they used was its ability to reveal the effects of different farming practices across a wide range of weather, soil and weed seedbank conditions. For example, according to the model, the first tillage operations for preparing a seedbed for winter wheat should be delayed until at least 50 mm of rain has fallen since harvest of the preceding crop; this would insure that a high proportion of potential weed recruits germinates and is killed before a winter wheat crop is sown. Colbach et al. (2013) noted that their modelling results highlighted the types of information that should be collected in farmer surveys and field monitoring activities. However, they also noted the need to develop population dynamics models for other weed species with dissimilar life histories.

Liebman and Davis (2009) used a population dynamics model to evaluate multi-tactic strategies for managing the creeping broadleaf perennial weed Canada thistle (*Cirsium arvense*). The model was parameterized with empirical data concerning the weed's life cycle and then used to examine the individual and interactive effects of tillage, mowing, competition from a short-duration cover crop, competition from a multiyear stand of alfalfa and seed predation. Model results indicated that a combination of competition from a cover crop and alfalfa, mowing, and high rates of seed predation resulting from improved seed predator habitat most effectively reduced the weed's rosette survival, seed survival and plant population density. Moreover, model results indicated that when multiple tactics were applied, the need for a high rate of efficacy of any individual tactic to suppress the weed was reduced, supporting the MLH concept. Though this example does not focus exclusively on the use of cultural techniques for weed suppression, it illustrates that modelling may be a fruitful approach for identifying non-chemical management tactics for perennial weeds.

11 Summary

Producing enough food and farm income while protecting environmental quality is one of the critical challenges facing humanity in the twenty-first century. Weeds constitute ubiquitous and recurrent threats in virtually all cropping systems and require careful treatment if farm productivity and profitability are to be sustained.

This chapter has described a diverse set of cultural techniques that can reduce weed population density, biomass production and competition against crops. Compared with the 'large hammers' that modern cropping systems rely upon for weed suppression–herbicides and mechanical cultivation–cultural techniques are 'little hammers' with generally weaker effects on weeds. Nonetheless, when used in particular combinations, the cumulative effects of cultural tactics may be substantial and can lessen the burden of crop protection placed on chemical and mechanical controls. When this occurs, selection pressure for herbicide resistance may be decreased, chemical pollution of air and water by herbicides may be minimized, and soil degradation due to cultivation may

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be ameliorated. Cultural techniques for weed management are not panaceas for the shortcomings of current strategies, but they could play an increasingly important role in future approaches.

Like many other approaches for improving agricultural sustainability, the use of cultural techniques for weed suppression is based on improved knowledge and decision-making rather than commercial products. Consequently, much of the innovation and refinement for the use of cultural practices is likely to come from public sector researchers and farmers, rather than from industry. It is worth considering that public sector funding for agricultural research in the U.S. has declined over the past quarter century (Wang et al. 2013). If this pattern continues and is representative of the situation globally, further development and provision of information about cultural techniques for weed management could become considerably more difficult in the future.

12 Where to look for further information

The subject of cultural techniques for weed management is not one for which abundant amounts of information are available. Insight into cultural techniques for weed management requires a reasonably well-developed appreciation of weed ecology, including the processes of germination, seedling establishment, resource use, interspecific competition, seed production, vegetative propagation and seed mortality. The more prominent role of weed ecology in informing weed management practices distinguishes cultural techniques from chemical and physical practices. The following list of information sources is by no means exhaustive, but is offered with the intention of pointing the reader in useful directions.

Foundational ecological literature for developing and implementing cultural weed management strategies includes Harper's (2010) *Population Biology of Plants*, first published in 1977; Grime's (2006) *Plant Strategies, Vegetation Processes, and Ecosystem Properties*, first published in 1981; and Grubb's (1977) review of the concept of the 'regeneration niche' in maintaining species richness in plant communities.

Cousens and Mortimer's (1995) *Dynamics of Weed Populations* provides a highly lucid analysis of the intersection between plant ecology, population genetics, agricultural practices and weed management. Håkansson's (2003) *Weeds and Weed Management on Arable Land: An Ecological Approach* offers a large amount of information on weed ecology in the context of agroecosystem management. Radosevich et al.'s (2007) text, *Ecology of Weeds and Invasive Plants: Relationship to Agriculture and Natural Resource Management*, covers similar topics, but includes consideration of weed management from social perspectives. Zimdahl's (2004) book *Weed-Crop Competition: A Review*, originally published in 1980, constitutes a thorough review of competitive interactions in agroecosystems and the different factors mitigating them. Texts with a particular emphasis on cultural weed management practices include Liebman et al.'s (2001) *Ecological Management of Agricultural Weeds*, and Upadhyaya and Blackshaw's (2007) *Non-Chemical Weed Management: Principles, Concepts and Technology*.

Over the past decade, an increasing number of articles concerning cultural weed management has appeared in the journals *Weed Research*, *Weed Science*, *Weed Technology*. The European Weed Research Society maintains a working group focused on physical and cultural methods for weed control.

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