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Source: Weed Technology, 27(1) : 218-230

Published By: Weed Science Society of America

URL: https://doi.org/10.1614/WT-D-12-00068.1

Weed Technology 2013 27:218–230

Weed Ecology and Nonchemical Management under Strip-Tillage: Implications for Northern U.S. Vegetable Cropping Systems

Daniel C. Brainard, R. Edward Peachey, Erin R. Haramoto, John M. Luna, and Anusuya Rangarajan*

In northern U.S. vegetable cropping systems, attempts at no-till (NT) production have generally failed because of poor crop establishment and delayed crop maturity. Strip tillage (ST) minimizes these problems by targeting tillage to the zone where crops are planted while maintaining untilled zones between crop rows, which foster improvements in soil quality. ST has been shown to maintain crop yields while reducing energy use and protecting soils in vegetable crops, including sweet corn, winter squash, snap bean, carrot, and cole crops. Despite potential benefits of ST, weed management remains an important obstacle to widespread adoption. Increased adoption of ST in cropping systems for which effective, low-cost herbicides are either limited (e.g., most vegetable crops) or prohibited (e.g., organic systems) will require integration of multiple cultural, biological, and mechanical approaches targeting weak points in weed life cycles. Weed population dynamics under ST are more complex than under either full-width, conventional tillage (CT) or NT because weed propagules—as well as factors influencing them—can move readily between zones. For example, the untilled zone in ST may provide a refuge for seed predators or a source of slowly mineralized nitrogen, which affects weed seed mortality and germination in the tilled zone. Greater understanding of such interzonal interactions may suggest manipulations to selectively suppress weeds while promoting crop growth in ST systems. Previous studies and recent experiences in ST vegetable cropping systems suggest a need to develop weed management strategies that target distinct zones while balancing crop and soil management tradeoffs. For example, in untilled zones, optimal management may consist of weed-suppressive cover crop mulching, combined with nitrogen exclusion and high-residue cultivation as needed. In contrast, weed management in the tilled zone may benefit from innovations in precision cultivation and flame-weeding technologies. These short-term strategies will benefit from longer-term approaches, including tillage-rotation, crop rotation, and cover cropping strategies, aimed at preventing seed production, promoting seed predation and decay, and preventing buildup of problematic perennial weeds. However, a concerted research effort focused on understanding weed populations as well as testing and refining integrated weed management strategies will be necessary before ST is likely to be widely adopted in vegetable cropping systems without increased reliance on herbicides.

Nomenclature: Carrot, *Daucus carota* L.; cole crops, *Brassica* spp.; snap bean, *Phaseolus vulgaris* L.; sweet corn, *Zea mays* L.; winter squash, *Cucurbita moschata* Duchesne ex Poir.
Key words: Tillage, vegetable crops, weed control.

En los sistemas de cultivos de vegetales del norte de Estados Unidos, los intentos de producción con cero labranza (NT) generalmente han fallado debido a un establecimiento pobre y madurez tardía del cultivo. El cultivo en bandas (ST) minimiza estos problemas al enfocar la labranza en la zona donde los cultivos son plantados mientras que mantiene zonas sin labrar entre las líneas del cultivo, lo cual mejora la calidad del suelo. ST ha mostrado la capacidad de mantener el rendimiento del cultivo al tiempo que reduce el uso de energía y protege el suelo en cultivos de vegetales, incluyendo maíz dulce, calabacín de invierno, frijol común, zanahoria y coles. A pesar de los beneficios potenciales de ST, el manejo de malezas continúa siendo un obstáculo importante para su mayor adopción. El incremento en la adopción de ST en sistemas de cultivos para los cuales herbicidas efectivos y de bajo costo son, ya sea, limitados (e.g., mayoría de cultivos de vegetales) o prohibidos (e.g., sistemas orgánicos), requerirá la integración de múltiples estrategias culturales, biológicas, y mecánicas dirigidas a los puntos débiles en los ciclos de vida de las malezas. Las dinámicas de poblaciones de las malezas en ST son más complejas que en labranza de cobertura total, labranza convencional (CT) o NT, porque los propágulos de las malezas, además de los factores que los influencian, pueden moverse ampliamente entre zonas. Por ejemplo, la zona no labrada en ST podría proveer refugio para depredadores de semillas o podría ser una fuente de nitrógeno de lenta mineralización, los cuales afectan la mortalidad y la germinación de las semillas de las malezas en la zona labrada. Un mayor entendimiento de tales interacciones entre zonas podría sugerir manipulaciones para suprimir las malezas selectivamente mientras se promueve el crecimiento del cultivo en sistemas ST. Estudios previos y experiencias recientes en sistemas de cultivos de vegetales en ST indican la necesidad de desarrollar estrategias de manejo de malezas que apuntan a zonas específicas mientras balancean los conflictos entre el manejo del cultivo y del suelo. Por ejemplo, en zonas sin labrar, el manejo óptimo podría consistir en usar cultivos de cobertura para la supresión de malezas, en combinación con la exclusión de nitrógeno y el uso del cultivo con altos residuos cuando sea necesario. En contraste, el manejo de malezas en la zona labrada podría beneficiarse de innovaciones en tecnología de cultivadores de precisión y de quemadores de llama. Estas estrategias de corto plazo se beneficiarán de estrategias de largo plazo orientadas a prevenir la producción de semillas, promover la depredación y degradación de semillas, y a prevenir el incremento de malezas perennes problemáticas. Sin embargo, un esfuerzo concertado de investigación enfocado no solo en entender las poblaciones de malezas, sino que en evaluar y refinar las estrategias integradas de malezas, será necesario antes de que ST sea ampliamente adoptada en sistemas de cultivos de vegetales sin una dependencia mayor en herbicidas.

DOI: 10.1614/WT-D-12-00068.1

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Minimum tillage (MT) systems, including no-tillage (NT) and strip-tillage (ST) have clear potential benefits for protecting and improving soils, reducing diesel fuel use, sequestering carbon, improving the resilience of cropping systems to extreme weather events, and reducing input costs (Blevins et al. 1983; Lal et al. 2004; Luna and Staben, 2002). In agronomic crops in the United States, the development of herbicide-resistant crops, coupled with low-cost herbicides has resulted in a large increase in acreage under NT.

For vegetable producers, NT is challenging because growers have traditionally relied on full-width, deep tillage or conventional tillage (CT) practices for incorporating crop residue and soil amendments, creating seedbeds, warming soils, releasing nutrients, breaking compaction layers, and killing weeds. In vegetable cropping systems, extensive research has been conducted evaluating the potential for NT, but adoption rates remain low, in part, because of the challenges associated with weed management (Hoyt et al. 1994; Luna et al. 2012; Mochizuki et al. 2007). When NT vegetable systems have been combined with cover crop residues to combat weeds, reduced yields or delayed harvest have been observed in crops including winter squash, zucchini (*Cucurbita pepo* L.) (Leavitt et al. 2011), garden tomato (*Solanum lycopersicum* L.), and pepper (*Capsicum annuum* L.) (Leavitt et al. 2011; Mochizuki et al. 2007). NT cover crop–intensive production systems are even more challenging in small-seeded crops like carrots, where a fine seed-bed is needed to successfully establish the crop (Brainard and Noyes 2012).

To overcome some of the constraints associated with NT systems, ST systems have received increased attention in recent years (Luna et al. 2012; Mochizuki et al. 2007; Overstreet 2009). Under ST, primary tillage is limited to the intrarow (IR) zone where crops will be planted, whereas the between-row (BR) zone is left undisturbed or is mowed or cultivated later in the crop cycle. This system takes advantage of the benefits of tillage where it is needed most—in the crop row—while facilitating benefits of NT between crop rows (Figure 1). Strip tillage is sometimes referred to as either deep- or shallow-zone tillage, depending on the depth of soil disturbance. The continued development and commercialization of Global Position Systems (GPS) and Real-Time Kinetic (RTK) tractor steering systems makes ST more feasible for large-scale growers because it facilitates precise planting in the center of tilled zones.

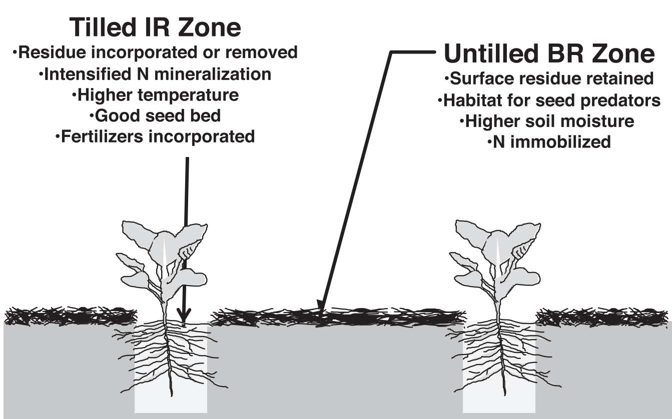

Figure 1. Characteristics of in-row (IR) and between-row (BR) zones of strip tillage systems that influence weed population dynamics.

ST has been shown to reduce fuel and labor costs, protect soils, and maintain crop yields in vegetable crops including sweet corn (Luna and Staben 2002; Luna et al. 2012; Brainard et al. 2012b), winter squash, snap beans (Bottenberg et al. 1999; Brainard et al. 2012a), carrots (Brainard and Noyes 2012), cabbage (*Brassica oleracea* var. *capitata* L.) (Haramoto and Brainard 2012; Hoyt et al. 1996; Mochizuki et al. 2007; Mochizuki et al. 2008), garden cucumber (*Cucumis sativus* L.) (Lonsbary et al. 2004; Wang and Ngouajio 2008), and broccoli (*Brassica oleracea* L. var. *botrytis* L.) (Luna et al. 2012). ST systems allow retention of cover crop or crop residues between crop rows, which can improve soil moisture retention (Haramoto and Brainard 2012; Hendrix et al. 2004), provide windbreaks for vulnerable crops like carrot (Brainard and Noyes 2012) and sugarbeet (*Beta vulgaris* L.) (Overstreet 2009; Tarkalson et al. 2012), reduce incidence of certain diseases (Wang and Ngouajio 2008), and in some cases, increase beneficial insects (Bryant et al. 2012) and earthworms (Luna and Staben 2002; Overstreet et al. 2010).

Although ST offers potential benefits for vegetable producers, weed management remains an important constraint to widespread adoption (Hoyt et al. 1994; Luna et al. 2012; NeSmith et al. 1994; Walters and Kindhart 2002). When primary tillage is not used to uproot, sever, or bury weeds, other weed management strategies are often used more intensely to compensate (Hoyt et al. 1994). For example, the adoption of MT practices in many crops has been tightly linked to the availability of new and inexpensive herbicides that effectively suppress weeds in the absence of tillage (Hoyt et al. 1994), as well as herbicide-resistant crops (Givens et al. 2009; Tarkalson et al. 2012).

Increased reliance on herbicides under ST systems is not always possible or desirable. Although herbicides have been an important tool for facilitating adoption of MT practices in many cropping systems, overreliance on herbicides has exacerbated problems of herbicide resistance and raised public concerns about potentially adverse environmental and human health consequences. Moreover, effective herbicide options are often either unavailable (especially in "minor crops" and in international settings) or prohibited (in organic production). Herbicides are also often less effective under MT systems because many rely on soil incorporation and because crop and cover crop residue present on the soil surface under MT systems can intercept herbicides or interfere with their activity (Hoyt et al. 1994; Locke and Bryson 1997). For example, the efficacy of *S*-metolachlor, a commonly used herbicide in many vegetable crops is reduced in MT systems in part because of interception by surface residues (Banks and Robinson 1986; Locke and Bryson 1997).

The goal of this review is to identify strategies that can reduce or eliminate the need for herbicides to manage weeds in ST vegetable cropping systems. Specific objectives are to (1) synthesize existing literature on the effect of ST on weed population dynamics to help identify strategies targeting weak points in weed life cycles, (2) summarize existing and new approaches and technologies that may enhance weed management under ST without greater reliance on herbicides, and (3) identify research needs to alleviate weed management constraints and improve the sustainability of ST systems for vegetable production in northern climates. This information will be useful for promotion of ST systems both for organic vegetable growers and for conventional growers hoping to lower weed management costs in ST systems.

Weed Population Dynamics in ST Systems

Predictions of shifts in weed communities under ST systems are challenging because of the complex interactions between tillage and other management practices and a lack of empirical estimates of parameters affecting weed population dynamics under ST systems. Few studies have examined the long-term effects of ST systems on weed populations. However, evidence from short-term studies in ST and long-term studies in other MT systems, primarily NT, give insight into the probable trajectory of weed community shifts.

Weed Population Dynamic Framework. Weed population dynamics under ST systems are more complicated than they are under either CT or NT systems because of the distinct characteristics of untilled BR zone and tilled IR zone, the potential for movement of propagules between these zones, and the potential edaphic and biotic interactions between zones (like movement of soil moisture) (Figure 2). Predictions of species shifts and identification of optimal management strategies under ST may be facilitated by an understanding of the underlying biological processes that affect weeds in these distinct zones. Weeds and their propagules are likely to experience different rates of germination, emergence, survival, fecundity, predation, and decay in BR (Figures 2A–D) compared with IR zones (Figures 2E–H).

To some degree, literature on weed population dynamics under NT and under CT can be applied to explain differences in weed population dynamics in untilled BR zone and the tilled IR zone, respectively. However, weed population dynamics under ST is more than just the sum of its CT and NT components for several important reasons. First, weed propagules under ST can move between adjacent zones, resulting in different propagule densities than would be expected under homogeneous tillage systems. Second, both biotic and abiotic factors influencing weed population dynamics may be strongly influenced by adjacent zones. For example, soil moisture retention in the BR zone is often higher in ST than it is in CT, in part, because of retention of surface mulches (Haramoto and Brainard 2011; Hendrix et al. 2004; Hoyt et al. 1994); because moisture can move freely from BR to IR zones, moisture availability in the IR zone of ST is also sometimes greater than it is under CT (Hendrix et al. 2004). Similarly, biotic factors, including predators of weed seeds, may move between adjacent zones, thereby contributing to greater rates of predation in the IR zone under ST than there are under CT.

Another unique feature of weed population dynamics under ST is the influence of the location of strips from year to year. In any given location in the field, tillage may occur every year, alternate years, every 3 or more years, or never, depending on the relative location and width of disturbance. Variation in the frequency of soil disturbance in a given location may influence weed population dynamics via changes in the vertical distribution of propagules, as well as tillage-mediated changes in soil characteristics that indirectly influence weeds at multiple stages in their life cycles.

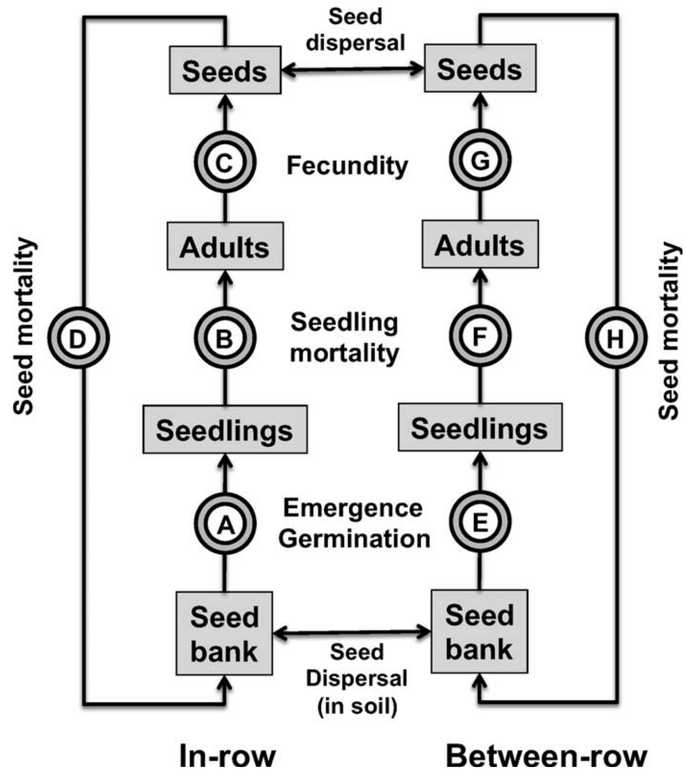

Figure 2. Flow chart describing the life histories of weeds in the in-row and between-row environments of strip tillage systems.

Effects of ST on Winter Annual, Biennial, and Perennial Weeds. Because tillage severs, uproots, and buries seedlings, survival and reproduction of weeds that have emerged before tillage will generally be higher in the BR zone of ST than they are in CT systems. Winter annual, biennial, and perennial weeds are often well established at the time of ST in the fall or spring, and in the absence of additional management practices (e.g., herbicides or winter cover cropping) to suppress these species, they can survive and reproduce in the undisturbed BR zone of an ST system. In Michigan, following a 3-yr sweet corn–snap bean–winter squash rotation, the seedbank density of winter annual weed seeds, including henbit (*Lamium amplexicaule* L.) and common chickweed [*Stellaria media* (L.) Vill.] was higher under ST than CT systems, presumably because of higher survival and reproduction in the untilled BR zone (Brainard et al. 2012a). Similarly, in a long-term study comparing seedbank densities in continuous corn, winter annuals, biennials, and simple perennials made up 53 to 62% of the seedbank following NT but were virtually absent under CT systems (Cardina et al. 1991).

The overall success of particular winter annual, biennial, and perennial weed species in ST may differ somewhat from that observed in long-term studies in NT depending on the species ability to recolonize tilled zones and the location of strips from 1 yr to the next. Wandering perennial weeds, such as horsenettle (*Solanum carolinense* L.), are likely to be more problematic in ST systems than are stationary perennials, such as dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), because of their ability to rapidly recolonize the disturbed IR zone following tillage via rhizomes. If the location of tilled zones varies systematically from 1 yr to the next, the entire field will receive tillage during the course of 1 to 3 yr, and the capacity of stationary perennials to establish will be more limited than they are in NT systems. After 4 yr in a vegetable cropping-system experiment, comparing CT to ST systems with alternate strip locations, the density of dandelion did not differ between tillage systems, but the ST system had a greater density of horsenettle (D. C. Brainard, unpublished data).

Short-Term Effects of ST on Summer Annuals. *Germination and Emergence.* The short-term population dynamics of summer annual weeds under ST, compared with CT, systems is strongly influenced by effects of tillage on seed germination and emergence. The germination of most summer-annual weeds is stimulated by tillage through a variety of mechanisms, including soil aeration, increased N mineralization, exposure of seeds to light, and increases in soil temperature (Mohler 2001). In untilled zones, soil temperatures are often lower (Hoyt 1999; Overstreet and Hoyt 2008) than they are in tilled zones, especially where cover crop or crop surface residues are present (Wagner-Riddle et al. 1997). Lower temperatures and lack of germination stimuli typically result in lower germination and emergence of most agricultural weeds in untilled areas relative to tilled areas. For example, Barralis and Chadoeuf (1980) observed 12% total emergence of germinable weed seeds following tillage compared with 8% from undisturbed soil. Likewise, reduced emergence of weeds under ST, compared with CT, systems has been observed in pickling cucumber (Wang and Ngouajio 2008), carrot (Brainard and Noyes 2012), corn (Hendrix et al. 2004), and cabbage (Haramoto and Brainard 2011).

Although weed emergence is often lower under ST systems, several studies suggest that, in dry years, ST systems may cause greater germination and emergence than do CT systems because of increased soil moisture retention. For example, in cabbage, under dry conditions, an ST system, in combination with an oat (*Avena sativa* L.) cover crop, resulted in greater emergence of Powell amaranth (*Amaranthus powellii* S. Wats.) compared to a CT system when seeds were sown 9 to 13 d after tillage; however, when supplemental irrigation was added to the microplots, those differences in emergence disappeared (Haramoto and Brainard 2011). Similarly, in a dry year, higher soil moisture and greater emergence of redroot pigweed (*Amaranthus retroflexus* L.) was observed under an MT system, compared with CT methods, in a potato (*Solanum tuberosum* L.) production system (Wallace and Bellinder 1989). On the other hand, Hendrix et al. (2004) observed higher soil moisture in a ST system, compared with a CT system, in both IR and BR zones, but lower total weed emergence.

Emergence of summer annuals under an ST technique is also indirectly influenced through interactions between tillage and other weed management practices, including herbicides and cover crops. For example, under ST management, surface residues present in the BR zone may reduce the efficacy of chloroacetamides, including *S*-metolachlor, because of interception by surface residues (Banks and Robinson 1986; Locke and Bryson 1997). In addition, herbicides requiring soil incorporation, including trifluralin, can be effectively used in banded IR applications under ST systems but are ineffective in the BR zone of an ST system because of the lack of soil incorporation (Hoyt et al. 1996). Likewise, the suppressive, allelopathic effects of certain cover crops (e.g., mustards [*Brassica* L. spp.]) on weed emergence are reduced when they are not macerated and incorporated into the soil, which prevents volatilization of isothiocyanates (Haramoto and Gallandt 2004; Norsworthy et al. 2011). On the other hand, weed emergence by many cover crops is enhanced under ST management because residues left on the soil surface reduce light penetration and provide a physical barrier that limits the capacity for small-seeded weeds to emerge (Teasdale and Mohler 2000). In fact, suppression of weed emergence through cover crop mulching is the foundation of most attempts to suppress weeds without herbicides in reduced-tillage systems (Teasdale 1998).

Seedling Survival. In most CT vegetable crop systems, growers rely on a combination of herbicides and cultivation to kill emerged weeds. Under ST management, cultivation is either not used or is less effective than it is under a CT system because crop and cover crop surface residues can interfere with soil movement required to sever, bury, or uproot seedlings (Mohler 2001). Therefore, even though ST systems often result in reduced emergence of summer-annual weeds, compared with emergence in CT systems, the weeds that do emerge in the BR zone usually have higher survival rates under ST management than they do under CT systems. To compensate, nonorganic growers rely on more-extensive use of herbicides under ST systems (Hoyt et al. 1996; Luna and Staben 2002).

Growth and Reproduction. Under ST systems, the growth and fecundity of weeds that successfully establish and escape POST control is likely to be regulated by many of the same factors that are important in weed seed germination—soil moisture, nitrogen mineralization, and nutrient availability (Haramoto and Brainard 2012). For example, higher soil moisture in the untilled BR zone, particularly with surface cover crop residue, may promote growth and fecundity of weeds in those areas. On the other hand, lower rates of N mineralization in the BR zone under ST systems may put nitrophilic species, including common lambsquarters (*Chenopodium album* L.) and white mustard (*Sinapis alba* L.) (Blackshaw et al. 2003) at a competitive disadvantage relative to the same weed growing in the BR zone of a CT system.

Unfortunately, very few empirical studies have examined differences in growth and fecundity of individual weeds in the distinct BR and IR zones of ST systems, relative to that in CT or NT systems. Wang and Ngouajio (2008) reported that individual weed biomass in processing cucumber was twice as great under ST, compared with CT, management. This result may have been due, in part, to lower weed emergence under ST systems, resulting in less competition between weeds in

ST, compared with CT, systems, rather than because of improvements in edaphic conditions regulating weed growth under ST management. Direct effects of ST techniques on individual weed growth were examined by Haramoto and Brainard (2011), who sowed a fixed density of Powell amaranth seeds into the BR and IR zones of CT and ST treatments. In 1 out of 2 yr, 45-d-old Powell amaranth plants in ST plots were 50% smaller in the BR zone and 75% smaller in the IR zone than were their counterparts under CT management. However, these effects did not always persist to the end of the season, and differences in fecundity in the two systems were relatively small.

Effects of ST on Vertical Distribution of Weed Propagules. One of the most important factors determining the long-term effects of tillage on weed population dynamics is the vertical distribution of seeds in the soil profile. The depth of a seed in the soil has a major influence on its dormancy status, its susceptibility to predators and decay agents, and its capacity to reach the soil surface following germination (Cousens and Mortimer 1995; Teasdale and Mohler 2000).

Under ST treatment, the vertical distribution of propagules within the IR and BR zones is strongly influenced by both the vertical and horizontal movement of propagules (Figure 3). Studies examining the vertical movement of seeds resulting from different tillage implements (e.g., Mohler et al. 2006) suggest that seeds dispersed to untilled strips are more likely to remain on or near the soil surface, whereas those in tilled strips will be buried to greater depths because of vertical soil movement (Figures 3C and 3D). Therefore, growers transitioning from CT to ST systems are likely to observe a shift toward a seed distribution closer to that observed under NT, where a larger fraction of seeds tend to accumulate near the soil surface over time (Cardina et al. 1991; Roberts and Stokes 1965).

Vertical propagule distribution in ST systems varies by species, based in part, on (1) the zone (IR or BR) that favors their survival and reproduction, (2) the extent of dispersal of their propagules between zones (Figure 3A) before tillage, and (3) the location of future tillage events. For example, winter annuals in the BR zone may escape tillage in the spring and survive to shed seed on the soil surface. Based on the limited data available on seed dispersal distance, Cousins and Mortimer (1995) report that among weeds with "unaided" dispersal, most seeds are deposited within a distance approximately equivalent to the plant height. Many summer annuals that escape control measures may reach heights of 1 m or more; these plants are likely to disperse seeds into multiple zones. However, for smaller-statured weeds—including many winter annuals—dispersal of seeds is likely to cluster them in the zone where seed production occurred. Therefore, winter annuals producing seeds in the BR zone may disperse most of their seeds in the BR zone; when an ST treatment is targeted to the same zone every year, the seeds of those weed species are more likely to be concentrated near the soil surface then are those of tall summer annuals.

Effects on Weed Seed Predation. Tillage affects seed predation potential because (1) weed seeds may be buried beyond the reach of seed predators, (2) seed predators may be killed during tillage, or (3) critical habitat of seed predators may be destroyed (thus reducing survivorship).

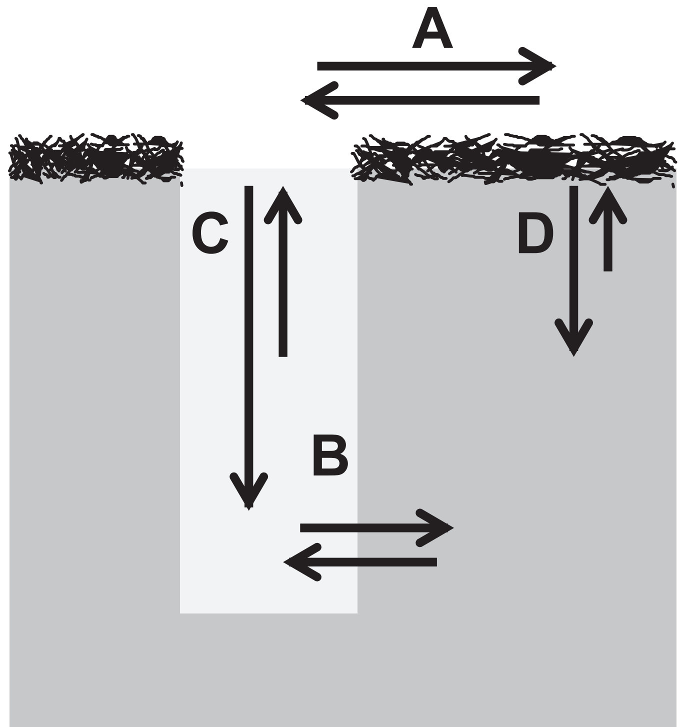

Figure 3. Diagrammatic representation of movement of weed propagules (e.g., seeds and rhizomes) as well as edaphic (e.g., nitrogen and water) and biological factors (e.g., seed predators) influencing weed populations under strip-tillage.

Although larval stages of carabids (ground and tiger beetles; Coleoptera: Carabidae) have been shown to consume buried weed seeds (Hartke et al. 1998), most seed predation occurs at or near the soil surface (Saska 2004). When weed seeds remain near the soil surface, seed predation may be a key source of mortality in some cropping systems (Westerman et al. 2003). Therefore, the shallower distribution of seeds in ST, compared with CT, systems may favor greater rates of seed predation. However, even in the absence of tillage, vertical seed drift continues slowly as rainfall, earthworms (*Lumbricus terrestris*), ants (Hymenoptera: Formicidae), and carabid beetles collect and bury seeds or, sometimes, return buried seeds to the soil surface (Figure 3D) (Seguer and Westerman 2003; Smith et al. 2005).

ST may also affect rates of predation through direct effects on predators or indirect effects on their habitats. Key weed-seed predators in agricultural systems include invertebrates, birds (Tetrapod: Aves), and mammals (Tetrapod: Mammalia), although the significance of these organisms varies from system to system and site to site (Crawley 1992; Janzen 1971; Marino 1997, 2005). Modifications to the tillage system are more likely to affect weed seed predation by small mammals and invertebrates than by birds (Navntoft et al. 2009). CT is often cited as detrimental to seed predators and rates of predation (Brust and House 1988), but the results are far from consistent (Cardina et al. 1996). In some cases, the activity density of predatory carabid beetles has been shown to be greater in CT than in NT systems (Westerman 2003). Additionally, some studies have shown that generalist predators, such as the common black ground beetle (*Pterostichus melanarius*) are well adapted to disturbance, and there were no differences in activity–density when comparing NT and CT systems (Shearin et al. 2007). Tillage practices within a crop have also been shown to be less significant than is the crop itself in determining seed predator activity–density and seed loss (O'Rourke et al. 2006).

The negative effects of tillage on seed predator populations may be moderated by reducing or eliminating tillage (Brust and House 1988; Cardina et al. 1996; Stinner and House 1990) or by providing refuge habitat, such as herbaceous filter strips (Carmona and Landis 1999; Menalled et al. 2001), beetle banks, and hedgerows, where tillage is eliminated altogether (Collins et al. 2003; MacLeod et al. 2004). ST typically spares two-thirds or more of the field from disturbance, with the presumption that seed predation will be enhanced in these systems as well. These untilled BR zones emulate refuge strips on a smaller spatial and temporal scale and may provide essential habitat and refuge for carabid beetles during soil disturbance events.

To date, there is little data showing the effects of ST on seed predation potential. As with seedling emergence, attempts to predict outcomes are confounded by the interactions between the many system components, including surface residues, which are often inherent in ST systems. Cover crop residues may ameliorate mortality caused by tillage and cause higher-than-expected seed predation rates even under intensive tillage (Cromar et al. 1999). Trophic interactions, including those between significant seed predators, compound the difficulty of predicting outcomes. For instance, some rodents are known to be active predators of carabid beetles and other granivorous ground beetles, and any practice that reduces tillage is likely to cause an increase in rodent populations as well. One recent study contrasted seed predation potential of ST and CT plots at 2 sites for 4 yr. In contrast to expectations, carabid beetle activity density (primarily, *P. melanarius*) did not increase in ST plots compared with CT plots (Green 2010). Estimates of weed seed predation (using exclosures that allowed ground beetle access to weed seeds) were more than 50% greater in CT, compared with ST, systems, but only when broadcast insecticides were applied to these treatments.

Long-Term Effects on Weed Communities. Greater concentration of seeds at the soil surface under ST, compared with CT, treatments may result in weed community shifts away from species with seed characteristics that promote survival and emergence of buried seeds (e.g., dormancy, capacity to emerge from depth) and toward those that promote survival and emergence at the soil surface (e.g., tolerance to desiccation, resistance to predation). For example, greater concentration of seeds near the soil surface may favor weed species with (1) small seeds because they are often less susceptible to predation and more sensitive to burial depth for successful emergence, (2) less-dormant seeds (e.g., many grasses) because dormancy is less important for avoiding fatal germination when seeds are not buried (Cousens and Mortimer 1995), and (3) wind-dispersed seeds (R. E. Peachey, personal observation). Long-term tillage studies in agronomic cropping systems provide evidence for shifts toward small-seeded weeds (Buhler and Daniel 1988) and grass species (e.g., Buhler 1995; Cardina et al. 1991; Pollard and Cussans 1981) when tillage is reduced. After 3 yr of a sweet corn–snap bean–winter squash rotation, the ST system has resulted in a shift toward grass species, especially large crabgrass [*Digitaria sanguinalis* (L.) Scop.], when compared with a CT system (D. C. Brainard, unpublished data). However, interpretation of such studies is often complicated by potential interactions of tillage with other management practices, including herbicides (Cardina et al. 1991).

Evidence from various studies suggests that weed species diversity may increase under ST, compared with CT, treatments. For example, following 25 yr of continuous corn, Cardina et al. (1991) reported greater diversity in NT systems than found with CT systems, in part, because of the greater prevalence of winter annual, biennial, and stationary, perennial species. Although the long-term effects of ST management on species diversity have not been evaluated, an ST system may support a greater diversity of weed species then either a CT or NT system does because the two zones of ST treatments represent distinct niches, each supporting species best adapted to that zone. The capacity for movement between zones will be an important determinant of species' fitness under ST management. For example, annuals with limited seed-dispersal distances and perennials with non-creeping perennation are less likely to recolonize tilled zones following ST treatment. Conversely, species with wind-dispersed seeds or wandering perennials can rapidly recolonize. However, these long-term shifts in community diversity may not be realized or may take longer to develop if strip location varies from year to year because disturbance will still be a factor, albeit a less frequent one.

Ecological Weed Management under ST

When neither tillage nor herbicides are used, successful weed management will require identification and integration of numerous tactics that can be flexibly applied to meet a wide range of soil and environmental conditions (Kurstjens 2007). For northern vegetable growers adopting ST management, successful management will require an emphasis on prevention of propagule production, as well as an integration of promising tactics to suppress emergence, to promote predation and decay, and to increase seedling mortality, including integration of cover crop mulches and tillage rotation, manipulation of resource placement and timing, and targeted mechanical cultivation and flame weeding. Although these tools have been used widely for nonchemical weed management in vegetable cropping systems, important adaptations are required to optimize their use in ST systems.

Preventing Reproduction. Perhaps the most important element of successful, long-term weed management is prevention of weed propagule (seed and vegetative reproductive tissue) production. Because many weed propagules are highly persistent in soils, failure to prevent propagule production can greatly increase future weed populations and the long-term costs of weed management (Buhler et al. 1997). Prevention is often less expensive then treatment, thus "zero seed rain" strategies are sometimes advocated (e.g., Gallandt 2006). Although zero seed rain may not be a realistic or optimal approach in all situations, minimizing seed rain is an important goal, and the extra initial costs associated with reducing weed propagule production may often be justified by lower weed management costs in future years. In ST production systems, the importance of preventing weed reproduction is heightened because weed management is often more expensive when tillage is not an option. This has been observed in a northern organic vegetable ST system, which had to be plowed after 4 yr because of extensive weed pressure (A. Rangarajan, personal observation).

Cover Crops for Weed Suppression in ST. Under ST treatments, cover crops can be used to enhance weed suppression through effects on virtually all phases of weed life cycles, including germination, emergence, growth and fecundity, and seed predation and decay. Surface cover crop and crop residues present in the BR zone in an ST system can help reduce weed emergence either by reducing seed germination or by increasing postgermination seedling mortality below the residue surface. Several mechanisms may contribute to reduced emergence where surface cover crop residues are present, including reduction in light penetration to the soil (Teasdale and Mohler 1993), physical obstruction resulting in seed-reserve depletion before emergence (Teasdale and Mohler 2000), and increased seed predation or decay (Cromar et al. 1999).

Cover crops in MT systems may be helpful for suppressing weeds, but care must be taken to avoid crop interference (Teasdale 1998). Indeed, one of the primary rationales for ST systems is to avoid problems with stand establishment and growth, where heavy crop or cover crop residues are present (Luna et al. 2012). Even in ST systems in which cover crops are removed from the IR zone via row-cleaners, interference can occur through a variety of mechanisms, including reductions in soil temperatures, immobilization of soil N, or allelopathic effects (Hoyt et al. 1994). For example, in ST cabbage production, bare soil treatments out-yielded treatments with wheat (*Triticum aestivum* L.) or cereal rye (*Secale cereale* L.) cover crops (Hoyt 1999; Mochizuki et al. 2007; Rangarajan 2008). In snap beans, yields under NT were reduced by 63% compared with CT, and when rye was combined with ST management, yields improved relative to the NT system but were still reduced by 20% compared with CT treatment (Bottenberg et al. 1999).

Under ST management, cover crops offer unique challenges and opportunities that are distinct from those encountered in either CT or NT systems. In particular, the optimal choice of cover crop species and management is likely to vary between the two distinct zones under ST treatments. For example, to maximize weed suppression and moisture retention in the BR zone, a thick mulch from a high carbon cover crop, such as winter rye may be desirable. However, that same mulch may be detrimental to crop establishment and growth in the IR zone. Recent research in ST pepper production found that moving rye mulch residue from the BR zone into the IR zone after crop establishment reduced IR weeds and improved the effectiveness of BR weed management with a high-residue cultivator (Rostampour 2010). Such physical movement of crop residue after crop establishment is one promising approach to overcoming barriers to cover crop use in ST vegetable systems.

To tailor cover crop services to the unique requirements of BR and IR zones, different cover crop species can be planted in these zones. For example, winter rye can be planted in the BR zone to maximize the amount of weed-suppressive residue produced, whereas cover crops such as winter-killed oats and peas (*Pisum sativum* L.), or hairy vetch (*Vicia villosa* Roth) can be planted in the IR zone to improve soil tilth or provide N where the crop will be planted. Innovative growers have begun adopting segregated strips of cover crops in ST systems in parts of the Midwest (Gruver 2011); however, adoption in vegetable cropping systems has been limited. In a recent study, yield of ST broccoli grown with an oat–pea mixture planted IR and a rye–hairy vetch mixture planted BR had similar yields to bare-soil controls and higher yields than produced in a rye–hairy vetch mixture planted both IR and BR (A. Rangarajan, personal communication). Similarly, in ST sweet corn, targeted planting of hairy vetch IR and rye BR can provide N to crops while minimizing N availability to weeds in the BR zone; this approach may also help minimize the potential problem of hairy vetch regrowth often seen in MT systems in which herbicides are not used (C. J. Lowry and D. C. Brainard, unpublished data). Mustard species (e.g., radish, *Raphanus sativus* L.) planted in the IR zone can be incorporated with an ST implement to maximize the suppressive effect of their glucosinolate by-products (Gruver 2011). With the advent of GPS tractor-guidance systems, such targeted cover-crop placement is a more realistic approach now than it has been in the past.

In addition to dead cover-crop mulches, ST systems can accommodate preestablished living mulches that may provide multiple ecosystem services including weed suppression. For example, in ST carrot production, growers in western Michigan grow wheat or barley (*Hordeum vulgare* L.) cover crops before carrot planting and retain those covers between crop rows as a windbreak until carrots are well established (Brainard and Noyes 2012). This system has no adverse effect on crop yields, and in some cases, contributes to weed suppression relative to CT management. Living mulches have also been tested in production of cabbage and other vegetable crops in combination with MT or ST treatment, but these systems have not gained widespread acceptance by growers, in part, because they often compete too aggressively with the crop (Andow et al. 1986; Grubinger and Minotti 1990; Teasdale 1998).

Although an important tool for weed suppression, cover crops alone are unlikely to eliminate the need for other weed management approaches in northern vegetable cropping systems. In northern climates, the shorter growing season makes it more challenging to produce sufficient cover crop biomass ($> 8{,}000$ kg ha^{-1}) to achieve full-season weed suppression (Mohler and Teasdale 1993). Poorly managed cover crops can also interfere with crop establishment, promote insects and diseases, and entail costs for seeds, establishment, and maintenance—all factors that reduce their

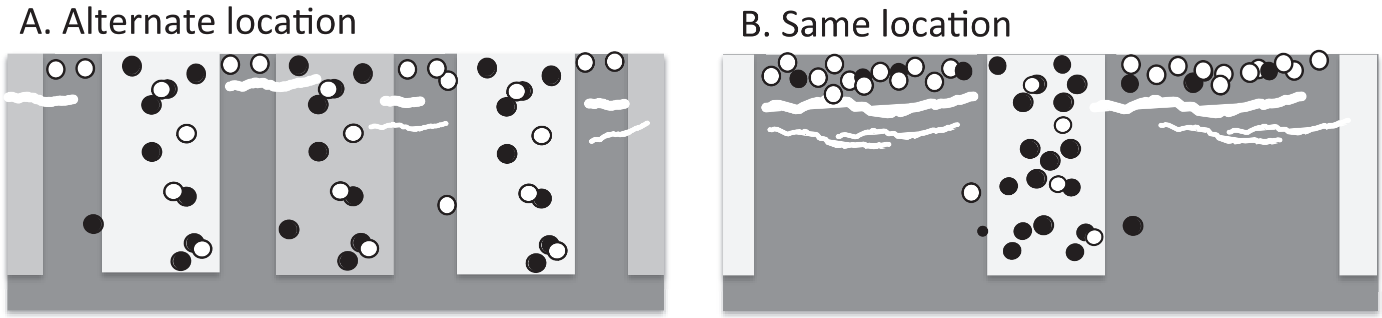

Figure 4. Diagrammatic representation of hypothetical weed propagule distribution and soil characteristics following continuous strip tillage in which the location of tilled strips is (A) alternated, or (B) placed in the same location each year. White circles represent seeds better adapted to conditions on the soil surface (e.g., those with tolerance to desiccation and predation); black circles represent seeds better adapted to burial (e.g., large or persistent seeds); white line segments represent rhizomes of creeping perennials; soil zones with darker shading have higher soil organic matter and improved physical and biological properties relative to lighter shaded zones.

practicality in some vegetable production systems (Luna et al. 2012).

Tillage and Crop Rotations. Rotation of crops, herbicides, and tillage intensity is important for managing many pests. Purposefully rotating tillage intensity is perhaps not common practice, but tillage can be strategically positioned within a given crop sequence to restrain pest populations. Rotational tillage sequences (variation of primary tillage practices within a crop rotation) are often implicit in crop rotations, but typically, the emphasis is on nutrient release and alleviating compaction, although they can also be specifically designed to minimize weed fecundity or weed seed survival in the soil. Some have proposed the use of rotational tillage systems to improve short-term nitrogen use efficiency and crop growth in predominately NT systems (Doran 1987), although this may reverse gains in soil quality (Grandy and Robertson 2006).

The effect of alternating ST and CT treatments on weed management has not been determined. Differences in weed seed drift and vertical distribution of weed seeds within the soil of the ST environment (Figure 3) make it difficult to predict the outcome of any tillage rotation sequence. An experiment over 6 yr in a three-crop rotation indicated that summer-annual weed density is reduced when direct seeding (using a slot planter that causes very little in-row disturbance) is alternated with full-width tillage. However, the outcome was dependent on the crop that was paired with the specific tillage system used and the sequence of the tillage rotation (Peachey et al. 2006).

The relative location of strips from 1 yr to the next may have a major impact on weed communities by altering both vertical seed distribution and the mortality of perennial weeds (Fig. 4). The most common practice among growers in continuous ST systems is to offset the tillage strip by one-half row each year so that crops are grown between rows in alternating years. Assuming that seeds are shed and dispersed uniformly on the soil surface (see discussion above), this would result in greater burial of seeds than would occur if strips were in the same location (Figure 4A vs. Figure 4B). Conversely, when strips are targeted to the same location, a greater proportion of seeds remain on the soil surface, resulting in shifts in weed communities in the BR zone similar to those observed under NT management.

Locating strips in the same location from year to year would likely provide soil health benefits relative to alternating-zone systems by restricting tractor traffic to noncropped zones and by facilitating increases in soil organic matter (Figure 4). Grandy and Robertson (2006) demonstrated that a single tillage event following years of NT production can substantially and permanently reduce desirable soil characteristics and suggested that NT soils need to be continuously maintained to protect aggregation and physically stabilized C pools. Improvements in soil physical, biological, and chemical characteristics in the BR zone of systems where tillage is restricted to the same location may favor growth and development of weeds in those zones. The extent to which such changes will alter weed–crop competition is difficult to predict but may be expected to favor weeds because crops are restricted to the tilled IR zone where soil health improvements may be more limited. As previously noted, restriction of tillage to the same location is also likely to favor buildup of perennial species, particularly in the BR zone (Figure 4).

Another option within continuous ST systems is to shift the location of strips from year to year so that the entire field surface undergoes primary tillage over the course of 3 yr. The effect of this system on weed communities is difficult to predict and has not been studied, to our knowledge, but may suppress the expected buildup of noncreeping perennial weeds.

In the Pacific Northwest, crop rotation requirements have limited ST systems to annual tillage rotations in both vegetables (Luna et al. 2012) and sugarbeets (Strausbaugh and Eujayl 2012). Continuous ST is not possible in these systems because these crops are often rotated with cereal crops with narrow row spacings that cannot accommodate an ST treatment. After vegetable crop harvest following a single season of ST treatment, fields are commonly left fallow over the winter or tilled with MT practices and planted with cover crops or cereal crops such as wheat. Although a few growers have experimented with NT seeding of cover crops following vegetable crop harvest, success has been limited (J. M. Luna, personal communication).

Resource Placement and Timing. Concentration of fertilizers in the crop-rooting zone can significantly reduce weed competition while maintaining or enhancing crop yields. For example, in CT systems, banding fertilizers in the crop row has been shown to improve yields while reducing weed density and biomass relative to broadcast fertilization applications (DiTomaso 1995). Banding of fertilizer at depths of 5 cm or more may offer weed management benefits, especially for large-seeded crops or transplants that can more rapidly access deep placed fertilizer than many smaller-seeded weed competitors (Liebman and Davis 2000; Rasmusen and Peterson 1996). This approach is most successful where background surface fertility levels are low, so that weeds have insufficient initial fertility to rapidly compete with crops (Cochran et al. 1990; Liebman and Davis 2000).

Under ST management, fertilizers can be conveniently placed at desired depths directly below the crop row via adjustment of fertilizer applicator tubes installed behind the ST shank. This approach has been adopted by ST users in both field and sweet corn production (Rangarajan 2008) and holds promise for reducing weed interference. Maintenance of high-carbon crop residues on the soil surface under ST systems may enhance the benefits of deep-fertilizer placement by supporting microbial populations in the surface soils that serve to reduce soluble soil N and thereby fertility available to weeds.

In organic production systems, targeted placement of organic amendments, including cover crops, composts, or mulches, may also promote crop growth and suppress weeds. For example, because high rates of compost can suppress germination and emergence of some weeds without adversely affecting crops (Lowry and Brainard 2012; Menalled et al. 2005), surface placement of compost in the IR zone of ST treatments may suppress weed emergence while maintaining or improving crop yields (Lowry and Brainard 2012). However, weed response to compost is variable, and some combinations of weed species and compost rates may increase weed emergence. For example, Brainard and Noyes (2012) observed a threefold increase in Powell amaranth emergence where compost was used in ST carrot production. In such cases, incorporation of compost in the IR zone of ST would be preferable from a weed management perspective. Clearly, a better understanding of the mechanisms by which compost and other soil amendments influence emergence and growth of specific crops and weeds would be helpful for developing strategies for selectively suppressing weeds in ST systems.

Mechanical Cultivation. The rapid development and commercialization of GPS and RTK tractor-steering systems in the 1990s has greatly expanded the opportunities for precision weed-control technology, although adoption rates among vegetable growers are not known. These technologies make mechanical cultivation and other physical means of weed control easier and more effective through straighter crop rows. They are particularly well suited to ST systems where conditions in the BR zone and IR zone may require different tools for optimal management.

In traditional CT, the BR zone has been managed relatively easily using sweeps, rolling cultivators, or other equipment. Cultivator shields can be used to protect the crop row from moving soil, and the previously tilled soil easily accommodates the cultivation equipment. In ST systems, however, the BR zone frequently contains living cover crops, weeds, or residue from previous cropping and is often not cultivated until many weeks after the crop is planted, if at all. Cover crops residues that suppress or delay weed emergence allow cultivation to be delayed so that crops are less at risk and may reduce the number of cultivations needed to control weeds and cover crop regrowth. However, crop residues are often an impediment to near-row cultivation, particularly to stationary sweeps that collect and drag residue. The BR vegetation may be managed by mowing (sometimes several times) or by using an undercutter (Creamer and Dabney 2002) or a high-residue cultivator to kill the standing vegetation (Luna et al. 2012). The Buffalo Cultivator (Fleischer Manufacturing Inc., Columbus, NE) employs heavy-duty sweeps with hardened points for cultivation in untilled soil. These high-residue sweep cultivators can undercut cover crops and weeds growing in the BR zone; however, additional passes with power takeoff–driven rotovators or other cultivation equipment are sometimes needed for adequate weed control. This intensive cultivation may conflict with the goals of MT system if farmers adopt MT treatments to help maintain or improve BR soil quality.

Managing weeds in the IR zone of ST systems involves many of the same strategies and tactics used in CT systems because the strip for the crop row is tilled before planting. These methods typically kill weeds by uprooting, severing, or burying (Kurstjens and Kropff 2001) and are usually focused on the weed seedling stage when they are susceptible to mechanical damage. Unlike full-width CT systems, however, ST systems require mechanical weed cultivation to be performed in narrow, tilled strips, frequently 25 to 30 cm wide. As in CT systems, IR cultivation methods in ST systems usually depend on a size differential between the crop and weeds that allows the weed seedlings to be removed selectively by the mechanical device. Transplanted vegetable crops clearly offer a large size differential between the crop and the newly emerged weeds, providing some options that are not available with direct-seeded crops (Ascard and Fogelberg 2008). Compared to direct seeded crops, transplants also have a competitive advantage over weeds that may have escaped control from cultivation (Melander et al. 2005).

An array of tools are used in IR weeding, alone or in combination with others, including the rotary hoe (Gunsolus, 1990; Leblanc et al. 2006; Mohler et al. 1997), spring tine harrow (Peruzzi at al 2007), torsion weeder (Duerinckx et al. 2005), finger weeder (Barberi et al. 2000; Bowman 1997), brush weeder (Melander, 1997), the spiked-disk weeder (Raffaeli et al. 2010), and the pneumatic weed blower (van der Weide et al. 2008) Each tool offers distinct advantages and disadvantages for varying soil conditions, crops and stages of growth of crops and weeds.

Flame Weeding, Steam Weeding, and Sand Blasting. Several alternatives to cultivation may be helpful for integrated weed management in ST systems. Flame weeding is an alternative to cultivation that has been widely adopted on organic farms. However, because of the large amount of residue often encountered in ST systems, few growers (if any) have attempted to use it. The prospect of igniting residues is a strong deterrent to use. Equipment innovators have designed a variety of shielded flamers that protect crops. The two-row flamer (Steam Weeding Ltd, Lakeside Rd 3, Leeston, Canterbury, New Zealand) (Figure 5) was specifically built for use in high-residue ST systems (C. Merfield, personal communication). Flame is confined to the crop row with row covers, and microjets deliver water/organic herbicide in a curtain in front of the flamer to minimize the potential of the residue to ignite (R. E. Peachey, unpublished data). The effect of the curtain of spray on weed control efficacy requires further testing.

Steam weeding is an alternative to flame weeding and eliminates the possibility of igniting residues. These systems are highly efficacious but require large amounts of water (up to 500 L h^{-1}). Steam can also be applied to pasteurize the soil and kill weeds seeds and disease propagules, which was done in high-value crops for more than a century. Recent innovations are being tested to determine whether steam can be applied in narrow bands, just wide enough for the seed row (Melander et al. 2002; Melander and Kristensen 2011). This alternative is well suited for ST systems. Again, a large amount of water is needed, and the process is slow, but water use is much less than if applied to the entire field, and the system minimizes the risk of residue ignition.

An alternative tactic that can potentially help manage weeds under high-residue conditions involves propelling abrasive particles through a sand blaster to shred and kill weed seedlings (Forcella 2009; Nrremark et al. 2006). Forcella (2009) found that abrasive grit made from corn cobs and expelled at 517 kPa pressure killed small seedlings of common lambsquarters without adversely affecting corn. These results suggest that air-propelled grit may be an effective POST weed-management tactic for targeted control of weeds at either IR or BR zones in ST systems.

Figure 5. Two-row flame weeder designed by C. Merfield. Flame is confined to the crop row with row covers, and micro jets deliver water/organic herbicide in a curtain in front of the flamer to minimize the potential of the residue to ignite.

Conclusions and Future Research Needs

Ultimately, optimization of weed management for ST systems will require integration of multiple tools (Kurstjens 2007; Peruzzi et al. 2007) specifically targeted to the unique characteristics of IR and BR zones. Cover crop residues can be important in suppressing emergence of BR weeds under ST systems while providing other important ecosystem services (Luna et al. 2012). However, cover crops alone seldom provide sufficient weed suppression to eliminate the need for other weed management approaches, especially in northern climates (Mohler and Teasdale 1993). Moreover, cover crop residues in the crop row can interfere with crop establishment and growth, particularly of small-seeded vegetable crops or those with time-sensitive markets. Therefore, successful, nonchemical management of weeds under ST systems will require continued development and integration of POST weed management tactics, such as high-residue cultivation, thermal weeding, or air-propelled abrasives. In contrast, successful IR weed management under ST systems will likely benefit from continued advances in precision weed-management tools, including IR cultivators or shielded-flame weeders. Targeted management of weeds in both zones would benefit from exploitation of technological advances in tractor-guidance systems and real-time weed recognition systems.

Because of the inherent difficulty of controlling weeds without tillage, identification of strategies to minimize reproduction and to promote predation and decay of weed propagules is more important in ST systems than it is in CT systems, especially when herbicides are not used. ST systems may offer greater opportunities to promote seed loss than either CT or NT systems because of the more-diverse habitats that can be supported in distinct IR and BR zones. Greater understanding of the interactive effects of tillage and other management practices (e.g., cover crops and compost) on seed predators and decay agents will be helpful in designing weed-suppressive ST systems.

Greater understanding of population dynamics of specific weed species known to be problematic in ST systems—including many annual grasses and wandering perennial species—will be invaluable for designing management practices that efficiently target weak points in weed life cycles to prevent their buildup. For example, greater understanding of the mechanisms responsible for selective stimulation or inhibition of germination of propagules for specific weeds and crops would be helpful for optimizing weed suppression under ST management through adjustments in the type, rate, and timing of soil amendments, including composts and cover crops. Studies evaluating the effect of tillage rotation strategies on problematic, perennial, and grass weed species are also likely to improve weed management in ST systems; successful approaches may include shifting the location of strips from 1 yr to the next or using periodic, full-width tillage to prevent buildup of problematic species.

Identification of economical and effective, short and long-term weed-management strategies for ST systems will ultimately facilitate their adoption and the realization of soil health benefits they bring. Development of optimal ST systems for vegetable production will involve on-going evaluation of trade-offs among soil, weed, and other management objectives. For example, targeting tillage to the same zone from 1 yr to the next may improve soil characteristics but may also lead to an unsustainable build-up of perennial weed species in vegetable cropping systems where herbicides use is limited or prohibited.

Nonchemical approaches to managing weeds in ST systems will be of greatest potential value to organic producers but will also promote reduced herbicide use and reduced risks of herbicide-resistance development for conventional growers. A concerted research effort focused on testing and refining integrated weed management strategies for ST systems and evaluating their biological and economic impact on production systems will be critical for increasing adoption of conservation tillage practices and improving sustainability of vegetable production.

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Received April 22, 2012, and approved November 4, 2012.