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REVIEW

Weed management in conservation crop production systems

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Information on weed management in conservation crop production systems is needed as adoption of practices such as reduced tillage and cover crops becomes more widespread. This review summarizes recent research on weed management aspects in these systems. Changes in patterns of tillage, planting systems, and other management strategies can alter the soil environment and lead to shifts in weed populations. Weed patterns and populations are not always consistent and vary with locale, crop, and herbicide use. However, in many long-term conservation management studies, a general increase in perennial weeds and grass species has been observed. The development of low-dose herbicides, selective postemergence herbicides, and transgenic crops has greatly improved the flexibility of producers who use conservation systems where opportunities for tillage are limited. With a higher level of management inputs, producers can successfully implement conservation management practices.

Keywords: conservation tillage, cover crops, crop rotation, no-tillage, weed management.

INTRODUCTION

Use of conservation management production (e.g. reduced tillage, cover crops) systems has become more popular in recent years due to economics of crop production and regulatory mandates concerning environmental issues. Within conventional as well as conservation systems, herbicide application has been the basis for weed management during the last sixty years in many developed countries. Herbicides and improved mechanization enabled farmers to cultivate more land with less labor. Many of these technological advances were also adopted in less developed regions, greatly expanding their ability to produce food. Conservation practices often enhance and utilize soil and crop micro-environments to inhibit germination, growth, and spread of weeds while minimizing the use of synthetic herbicides. However, use of conservation practices as a weed management tool is often of secondary importance to herbicide application. In this review, we discuss aspects of weed management practices in the context of conservation crop production.

Conservation management systems, as defined here, integrate those practices that conserve or enhance inherent resources such as soil and water. For example, one goal of many conservation management systems is to increase accumulation of plant residue at the soil surface, i.e. a practice that leaves 30% or more of crop residues on the soil surface at planting (Schertz & Becherer 1995). Plant residue accumulation protects the soil from erosion, conserves soil moisture, and enhances soil tilth. Examples of conservation management practices that fit into a weed management program include reduced tillage, cover crops, crop rotation, variable row spacing, and timing of crop planting.

Reduced tillage

Reduced tillage encompasses management practices that exclude at least one major cultivation practice or minimize the intensity of tillage operations. Terms such

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as no-tillage, zero tillage, ridge tillage, or strip tillage describe types of reduced tillage practice. Before the advent of herbicides, hoeing and mechanical tillage (plowing, disking, or cultivation) were primary weed control methods. Herbicide use increased dramatically over the last fifty years, but there was no corresponding reduction in the use of mechanical tillage because it also was useful for preparing soil for planting, improving soil aeration, enhancing availability of soil nutrients, and post-planting weed control. Larger, specialized, and more efficient tillage implements were developed that may have actually contributed to a net increase in tillage intensity.

The less the soil is disturbed, the less it is vulnerable to erosion and evaporation processes, thereby conserving both soil and water resources. Tillage also aerates the soil and exposes weed seeds to light, thus promoting weed germination and rapid growth. Reducing tillage promotes the accumulation of plant residues at the soil surface, thereby potentially inhibiting weed seed germination because of shading or cooler temperatures.

Weed management is critical to obtaining profitable yields in reduced tillage systems, and achieving satisfactory weed control requires more intensive management from the farmer. When weeds are controlled, crop yield and net return in no-tillage systems are often equivalent or greater than corresponding conventional tillage systems (Heatherly *et al.* 1994; Kapusta & Krausz 1993; Mills *et al.* 1989; Buhler 1992). Inadequate weed management, however, can greatly reduce yields and net returns.

Cover crops

Typically, cover crops are planted in early fall to establish them before winter and produce sufficient biomass by early spring. The cover crop provides a layer of plant residue on the soil surface that can suppress weeds by exhibiting allelopathic effects, compete for soil nutrients and light, and/or enhance conditions unfavorable for weed germination and establishment (Teasdale *et al.* 1991; Teasdale 1998). Adversely, cover crops may also compete with the crop of interest. Cover crops during early spring sometimes deplete soil moisture reserves (Munawar *et al.* 1990). To avoid competition with a subsequent crop, cover crops are usually chemically desiccated prior to planting. Early desiccation of the cover crop in the spring may lengthen the duration of adequate soil moisture conditions during the growing season. Benefits in suppressing weeds, however, often are obtained if cover crop desiccation is delayed as long as possible (Teasdale & Shirley 1998). Teasdale and Daughtry (1993) observed that a live winter cover of hairy vetch (*Vicia villosa* Roth) reduced total weed density and biomass, but when the vetch was desiccated, weed suppression benefits were not as evident as weed emergence and establishment increased. Sometimes weed suppression benefit from cover crops occurs early in the season. In no-tillage corn (*Zea mays* L.), hairy vetch suppressed weeds early in the growing season without herbicides, but for season-long control and optimum yields it was necessary to use herbicide (Teasdale 1993). Elsewhere, Weston (1990) observed increasing crop biomass and growth over time following desiccation of grass cover crops under no-tillage management.

Inadequate kill of a cover crop can adversely affect the yield of the subsequent crop (White & Worsham 1990). Some cover crops are difficult to kill and may require more than one herbicide application (Griffin & Dabney 1990) or varying combinations of herbicides for sufficient desiccation (White & Worsham 1990).

Cover crop species vary in their suitability for certain cropping systems. Some cover crops cannot be used because of herbicide carryover from the summer crop. Certain legumes such as clover (*Trifolium* sp.) and vetch (*Vicia* sp.) species can provide overwintering habitats for plant pathogens and insects. For example, crimson clover (*Trifolium incarnatum* L.) is an alternate host for *Heliothis*, which presents a problem for cotton (*Gossypium hirsutum* L.). It may sometimes be necessary to kill a cover crop earlier than is optimum for weed control benefits in order to minimize potential damage to seedlings from diseases, insects, or nutrient/moisture competition from the cover crop.

From a farmer's perspective, use of cover crops must be justified economically by reduced herbicide input and/or increased yield. Although cover crops may suppress winter annual weed species during early spring and provide partial weed suppression during early-season crop growth, cover crop residues often do not remain long enough to provide total weed control in summer crops (Teasdale 1998). Therefore, eliminating herbicides in summer crops is not usually a viable option. In cover crop systems, there are added costs of seed, time and labor for planting and chemical desiccation. Recently, an economic analysis by Reddy (2001a) showed negative net returns in soybeans with seven cover crops compared to soybeans with no cover crop. This net loss primarily was due to lower soybean yield in the cover crop systems. In another study, using a rye cover crop in soybean was less profitable than a no-cover crop system, even though the soybean yields were similar with or without the rye cover crop (Reddy, unpublished data). Thus, from a weed control perspective, cover crops may not always be economically competitive with herbicides.

Crop rotation

Crop rotation involves alternating crops over a series of growing seasons. Rotating crops aids in conservation by breaking cycles that may be detrimental to long-term management of a particular field. One of these cycles may be where one weed species or weed population has an advantage under a monoculture system. Rotating to another crop may increase weed diversity and prevent one particular weed community from becoming unmanageable.

Regardless of tillage, crop rotation is an effective practice to use for weed control. Because of fewer selective herbicides available and the development of weed resistance to some herbicides, it may not be practical or economical to control certain weeds in a particular crop. When crops are rotated, new herbicides and practices may control problem weeds. In addition to weed control, crop rotation often results in improved crop yields and soil properties. Our own data indicate that cotton yield following rotation with corn increased by 10% in the conventional cultivar and by 19% in the glyphosate-resistant cultivar compared to continuous cotton (Reddy *et al.* 2002). Corn yield also increased by 12% in the conventional cultivar and by 5% in the glyphosate-resistant cultivar when rotated with cotton.

Row spacing

Traditionally, crops such as corn, cotton, and soybeans are grown in rows wider than 50 cm. Planting in narrow rows (19 to 25 cm) is an option for many crops and can be integrated into most conservation management programs. As a soil conservation measure, canopy closure in narrow rows can provide protection against soil erosion from raindrop impact. Faster canopy closure also may reduce weed germination, growth, and establishment by shading. Soybean planted in 19 cm rows reduced total weed biomass, increased soybean yield, and resulted in similar to higher net return compared to soybean planted in 57 cm and 95 cm rows (Reddy 2002). However, slow initial growth of the crop may allow weeds to establish before complete crop canopy closure. Late emerging weeds can be a problem since the narrow row spacing prohibits inter-row cultivations or post-directed herbicide applications. For example, in ultra narrow row (25 cm row spacing) bromoxynil-resistant cotton, late-season weed growth reduced yields where preemergence herbicides were not applied (Reddy 2001b).

INTEGRATING CONSERVATION PRACTICES WITH HERBICIDE USE

Public awareness of herbicide movement from farm land and its potential impact on the environment has increased in recent years. As a result, there is renewed interest in developing integrated weed management systems that reduce both mechanical tillage and herbicide inputs. These trends provide an interesting paradox due to the fact that weed management without herbicides necessitates more tillage. This may be true in many cases, but technological advances such as transgenic crops resistant to herbicides, provide weed management options that may result in a net reduction in both herbicide and tillage inputs.

Postemergence herbicide management

Reducing the number of tillage operations in a production system likely will require more careful weed management with postemergence herbicides, whether alone or in combination with preemergence herbicides. Without preplant tillage, nonselective postemergence herbicides are usually necessary to kill existing winter vegetation prior to planting. Depending on the density and type of vegetation present, a contact herbicide may not always be adequate. In a soybean–wheat double crop study, paraquat did not always completely kill existing vegetation, especially prickly sida (*Sida spinosa* L.), while glyphosate was more effective (Sims & Guethle 1992). A greater number of postemergence applications may be needed in reduced tillage systems during the growing season when shorter residual preemergence herbicides such as alachlor and metribuzin are used (Sims & Guethle 1992), or during the fallow season to minimize growth of troublesome winter weeds. For example, excluding fall applications of nonselective postemergence herbicides reduced both wheat yield and control of several annual grass species in a no-tillage system, while preemergence herbicide alone was sufficient for the conventional tillage (Wilson *et al.* 1986). If tillage is eliminated from a management program in a cereal or corn crop, control of grass weeds may be limited to direct applications of nonselective herbicides such as paraquat, MSMA, and glyphosate to weeds or adding a triazine as a preemergence herbicide if the crop can be safened. Selective postemergence herbicides such as nicosulfuron and primisulfuron for control of some grasses are another option for no-tillage production in a corn crop (Curran *et al.* 1994). Herbicide-resistant transgenic crops are another tool that can be used to improve weed control in reduced tillage systems. In a study with transgenic soybean, sufficient weed control and economic returns were obtained using only postemergence herbicides (Reddy 2001c).

Timing of herbicide applications

Timing of tillage and/or herbicide application is critical in any crop system in determining which weed species may predominate during the growing season. If weeds are allowed to establish between the time of planting and control input, additional cultivation or herbicide application may be required to achieve successful crop establishment. For grasses such as johnsongrass [*Sorghum halepense* (L.) Pers.] or quackgrass (*Elytrigia repens* L.) that propagate vegetatively with rhizomes, use of a postemergence herbicide such as glyphosate in the fall after harvest or just prior to planting a crop may reduce or eliminate the need for tillage to disrupt the rhizome development (DeFelice *et al.* 1987).

Carey and DeFelice (1991) found that it was crucial to desiccate existing weed cover with a nonselective herbicide (paraquat or glyphosate) at least 14 days prior to planting no-tillage soybean. Other researchers have found, however, that preplant herbicide applications may not be necessary any more than two weeks before soybean planting. For example, imazaquin plus non-selective postemergence herbicides applied two to five weeks prior to soybean planting provided sufficient weed control in stale seedbed management (Oliver *et al.* 1993). However, metribuzin plus chlorimuron was not suitable as a preplant treatment when applied more than two weeks before soybean planting. Werling and Buhler (1988) found that weed control in no-tillage soybean was superior in most cases with early preplant and split herbicide applications when compared to preemergence because the early preplant applications eliminated most existing vegetation and prevented weed establishment. Since existing vegetation was removed and early weed growth was inhibited, it was not necessary to use a nonselective herbicide at planting. However, control of high weed densities later in the season was reduced with the early application. Midseason postemergence applications may eliminate this deficiency.

Preemergence herbicide efficacy and carryover

Conservation systems also present some challenges in the management of preemergence herbicides. Higher rates of preemergence herbicide are sometimes needed for adequate weed control in conservation tillage areas. In lieu of higher rates of preemergence herbicides, however, supplementing with postemergence herbicides such as glyphosate along with the preemergence herbicide may provide satisfactory control (Vanlieshout & Loux 2000).

Several factors can be attributed to the lower efficacy of preemergence herbicides in conservation systems. The higher organic matter levels in the soil surface may bind soil-applied herbicides, contribute to a lessened efficacy, and require a higher application rate. Herbicide efficacy in these systems is sometimes decreased by increasing levels of plant residue on the soil surface. For example, herbicide interception by wheat straw residues reduced the weed control potential for acetochlor, alachlor, and metolachlor (Banks & Robinson 1986). Herbicide sorption to the plant residues on the soil surface may result in less weed bioactivity or physically separate it from soil where it can be activated and inhibit emerging weeds. Increased microbial activities associated with plant residues also may enhance herbicide metabolism and subsequent detoxification.

Some herbicides are resistant to dissipation processes, and persistence in even extremely low doses can injure crops. Climatic variables such as temperature and precipitation interact with management variables to produce site- and herbicide-specific outcomes. Results are mixed as to whether a greater incidence of herbicide carryover is observed in reduced tillage systems (e.g. Walsh *et al.* 1993). Use of tillage to incorporate herbicides into soil in reduced tillage systems is a limited option. Incorporation in conventional systems can prolong the residence time for some herbicides by protecting them from volatilization or photodecomposition (Basham & Lavy 1987). Extending the residence time in the soil by incorporation may cause herbicide carryover problems in crop rotation systems (Curran *et al.* 1992; Ferris *et al.* 1989; Renner *et al.* 1988). However, phytotoxicity also may be reduced when a herbicide is incorporated because the herbicide is diluted by spreading it over a larger soil volume. Carryover injury to corn from trifluralin (Hartzler *et al.* 1989) and atrazine (Kells *et al.* 1990) increased in severity with reduction in tillage, suggesting that increasing tillage diluted the herbicide effect.

Low-dose and reduced rate of herbicide

A number of selective low-dose preemergence herbicides (e.g. sulfonylureas and imidazolinones) and postemergence herbicides (e.g. aryloxyphenoxy propionates and cyclohexanediones) are very compatible with residue management practices. Selective postemergence herbicides provide a means for controlling weeds effectively during the growing season without damaging the crop. Herbicides such as imazaquin or chlorimuron having both pre- and post-emergence activity can be used in reduced tillage to kill existing vegetation and provide residual weed control. One potential drawback of herbicides with selective mode of action is that their overuse, especially in monocrop systems, can lead to increased selection pressure for herbicide resistance in certain weeds (Powles & Holtum 1994). Integrating tillage with rotation of crops and herbicides with different modes of action is probably the best approach to delay or prevent weed resistance.

Utilizing mulch from a previous crop (in a double crop system) or cover crop may allow use of reduced herbicide rates. Moseley and Hagood (1991) observed that a preemergence application of chlorimuron and linuron to a wheat-soybean no-tillage double crop provided sufficient nonselective activity on winter vegetation so that it was unnecessary to use traditional nonselective herbicides. This was possible because the mulch residue from the wheat inhibited weed growth. In reduced tillage potatoes (*Solanum tuberosum* L.), the presence of a rye mulch suppressed weed growth and allowed the use of reduced rates of linuron, metribuzin, and oryzalin (Wallace & Bellinder 1990).

Several crops that possess genes rendering them resistant to herbicides have recently been commercialized. The impact of using glyphosate-resistant soybean in weed management was reviewed (Reddy 2001d). Use of herbicide-resistant crops greatly increases the flexibility of producers that are using conservation management practices. For example, weeds can be controlled successfully by using postemergence applications of glyphosate in glyphosate-resistant soybean (Reddy 2001d). Utilization of postemergence herbicide programs is a natural fit in conservation management systems where post-planting cultivation is minimized (Corrigan & Harvey 2000; Reddy 2001c).

WEED POPULATION SHIFTS

Shifts in weed populations and dynamics are a concern in conservation systems. The extent and direction of weed shifts due to conservation tillage practice are dependent upon a number of factors such as region, crop, and soil type, and extensive reviews are available that discuss the effects of agronomic management practices on the composition of weed flora (e.g. Haas & Streibig 1982; Froud-Williams 1988). Modifications of agronomic practices such as herbicide use and crop rotation, together with altered soil characteristics can result in shifts in the density and composition of weed flora. Increased soil moisture improves germination conditions for weed seeds. Weed species more tolerant to shade or that are vigorous under wet, cool conditions would have an advantage. Arrowleaf sida (*Sida rhombifolia* L.) germinates at lower temperatures and from shallower soil depths than other closely related species (e.g. prickly sida) and have the potential to be more troublesome in reduced tillage systems (Bryson 1993; Smith *et al.* 1991). Plant residues reduce herbicide efficacy in some cases, shifting the balance in favor of certain weed species.

As a result of long-term evaluations of effects of management factors on weed populations, some pictures are emerging. However, more studies need to be initiated to confirm these trends in other regions and with various management combinations. Buhler *et al.* (1994) monitored perennial weed populations after 14 years of varying tillage and crop rotation (continuous corn *vs* corn-soybean) in the midwestern United States. Populations of perennial weeds tended to be greater and more diverse in the reduced tillage systems (no-tillage, chisel plow, ridge-tillage *vs* moldboard plow). Grass weed species such as green foxtail [*Setaria viridis* (L.) Beauv.] and foxtail barley (*Hordeum jubatum* L.) were observed with more frequency in no-tillage than in conventional tillage after five years in a corn–soybean rotation system (Wrucke & Arnold 1985). However, they observed fewer consistent tillage differences in populations of broadleaf species. Effect of tillage and wheat in rotation with other crops (continuous wheat, fallow, spring canola, or lentil) resulted in greater weed populations in no-tillage regardless of the rotation (Blackshaw *et al.* 1994). No clear trend in a general population shift to predominantly annual or perennial species was observed, but rather the crop rotation sequences and particular herbicides used influenced the composition of weed populations. Trends associated with reduced tillage systems in corn, soybean and winter wheat were increased incidence of common lambsquarters (*Chenopodium album* L.) and green foxtail [*Setaria viridis* var. major (Gaudin) Pospichel] (Thomas and Frick 1993). No-tillage fields had more redroot pigweed (*Amaranthus retroflexus* L.), crabgrass (*Digitaria* spp.) species, yellow foxtail, yellow nutsedge (*Cyperus esculentus* L.), dandelion (*Taraxacum officinale* Weber in Wiggers), and velvetleaf (*Abutilon theophrasti* Medicus) than conventional tillage. Bryson and Hanks (2001) observed over a five-year period of reduced tillage cotton and soybean a general increase in perennial weeds, especially woody and viney species. There were more variable and higher weed populations in reduced tillage, but control was possible using postemergence herbicide applications. Swanton *et al.* (1999) did not observe consistent relationships between weed density and tillage system, but found differences in composition of weed populations between conventional and no-tillage systems. For example, common lambsquarters and redroot pigweed were associated with conventional tillage and large crabgrass with no-tillage.

WEED SEED BANK

Soil disturbance strongly influences the size, profile distribution, density and species diversity of weed seed banks. Tillage prevents the repopulation of the weed seed bank by interrupting weed growth prior to seed development. Tillage may stimulate seed germination but subsequent cultivations or herbicide applications also prevent the weed from maturing and having the opportunity to replenish seed banks. Some weed species, including many winter annuals, require an undisrupted cycle to complete the reproduction process. If the soil is disturbed by tillage, the reproduction cycle is therefore interrupted. Timing of tillage may also be an important factor depending on whether it coincides with a critical stage in the reproduction cycle. During tillage, seeds may be transported to positions in the soil profile more or less favorable for germination. Egley and Williams (1990) evaluated the effects of tillage on weed seedling emergence and observed that in the first year of tillage, a greater number of velvetleaf, spurred anoda [*Anoda cristata* (L.) Schlecht], morning glory (*Ipomoea* spp.), and pigweed (*Amaranthus* spp.) seedlings emerged in untilled plots compared to tilled plots. They concluded that tillage may have buried seeds in lower depths of soil where conditions were unfavorable for germination and emergence. An exponential decline in the weed seed bank was measured over a five-year period. The rate of reduction was greatest in the untilled area because a greater percentage of the seeds germinated the first year, and the seeds which were left undisturbed in the soil surface may have lost viability due to exposure to extreme environmental conditions (such as wet/dry or hot/cold cycles). Buhler and Mester (1991) noted increased weed seedling emergence from shallow soil depths in no-tillage. They concluded that the most important factor was that absence of tillage reduced seed movement to greater soil depth. Other factors included greater moisture near the soil surface and protective effects of plant residue which contributed to favorable germination conditions.

Forcella and Lindstrom (1988) studied weed seed movement and germination in ridge-tillage corn and soybean systems. Weed seed density in soils under continuous corn production was double the density in soils under a corn and soybean rotation. Truncation of ridges at planting displaced 31 to 37% of weed seeds from the ridge in ridge tillage corn, while 80 to 100% of the weed seeds were displaced in corn–soybean rotations. Removal of seeds from the ridge at planting reduced weed competition within the crop row until the seedbed ridges were reformed during the growing season. After ridges were reformed, control of the mid-season weed reinfestation required better residual herbicide activity or a postemergence herbicide application. Shallow ridging was suggested for minimizing weed reinfestation caused by ridging activities.

Reducing tillage limits redistribution of weed seeds and tends to concentrate weed seed accumulation at the soil surface. Schreiber (1992) reported that most seed of giant foxtail (*Setaria faberi* Herm.) was measured in the surface 2.5 cm of soil regardless of tillage or crop rotation. Tillage differences were observed only in the 0–2.5 cm depth, and no-tillage soils contained greater numbers of weed seed than conventional. Similarly, Yenish *et al.* (1992) found over 60% of all weed seed in the surface 1 cm of soil in no-tillage corn plots and 30% in chisel plowed plots. Moldboard plowed areas had uniform seed distribution in the surface 19 cm. In comparisons between moldboard and chisel plowing in a cropping sequence study, Ball and Miller (1990) found that reducing tillage led to a more rapid shift in species composition of the weed seed bank. Soil samples from three 25-year continuous corn tillage studies in Ohio were evaluated to determine the composition of weed seed banks (Cardina *et al.* 1991). Seed densities in the surface 15 cm were highest in no-tillage soils. Greater species diversity was also observed for no-tillage at two of the locations.

A higher level of weed management may diminish the differences observed in weed seed densities due to tillage. Vencill and Banks (1994) measured effects of tillage and weed management input on weed seed populations in grain sorghum production. They observed that the weed seedbank increased faster in zero and low input systems, primarily because of differences in weed control. Common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters, horseweed [*Conyza canadensis* (L.) Cronq.], and sicklepod [*Senna obtusifolia* (L.) Irwin and Barneby] seed densities tended to be higher in reduced tillage, while common cocklebur and large crabgrass seed densities were higher in conventional tillage.

ENVIRONMENTAL ISSUES

Herbicide dissipation in soil and plant residues occurs via sorption, degradation, movement in leachate or surface water, volatilization and plant uptake, and depends on several soil characteristics. The soil environment (e.g. moisture, carbon quantity and composition, microbial activity) is strongly influenced by the management system imposed on a particular site (Locke & Bryson 1997). Since the soil is a dynamic ecosystem, duration of a single management system is important in determining the extent to which management influences soil characteristics.

Residues of plant material decay in soil form stable humic components. Tillage aerates the soil and mixes plant residues in soil, thereby hastening residue decomposition. Organic carbon and microbial activity generally are higher in surface soil under reduced tillage management (e.g. Blevins *et al.* 1983; Doran 1980; Locke *et al.* 1996). Under long-term no-tillage in southern USA, little effect on organic carbon was observed below the surface 2 cm (Zablotowicz *et al.* 2000).

Soils that are not tilled often have large pores and channels through the soil profile caused by roots that decompose *in situ*, leaving voids or cracks formed during drying in high shrink-swell soils. Large (>0.25 mm) and more stable soil aggregates result from decomposing plant material, increasing porosity and potential for water infiltration (Beare *et al.* 1994).

Herbicide transformation

Increased microbial and enzyme activity in conservation managed soils can potentially facilitate herbicide degradation and transformation (Locke *et al.* 1995). Previous herbicide history can enhance microbial populations with accelerated degradation potential, and reduced tillage conditions may help sustain these populations (Wagner *et al.* 1996). Initial herbicide degradation may not always be influenced by conservation management but sometimes distinct differences in metabolite dynamics occur (Locke *et al.* 1996). Extractable polar metabolites of metribuzin were greater in residue-managed soils than in conventional tillage (Locke & Harper 1991), apparently because higher plant residues inhibited complete breakdown of the polar material to $^{14}CO_2$. Degradation of herbicides to soluble polar metabolites and subsequent accumulation may result in increased mobility in leachate or in surface runoff (e.g. Jayachandran *et al.* 1994).

Herbicide interception and sorption in soil and plant residues

Conservation tillage and cover crop systems often rely on postemergence herbicides as a major component of the weed control program. A large proportion of postemergence herbicide is intercepted by the weed or cover crop residues, and the extent of herbicide washed from residues into soil by precipitation depends on many factors, e.g. formulation, plant species, plant uptake, and retention to plant foliage (Reddy *et al.* 1995a; Reddy & Locke 1996). Plant residues often form dense mats covering a large proportion of the soil surface area and intercept herbicide (Banks & Robinson 1986). Crop residues have a strong affinity for retaining herbicides (Reddy *et al.* 1995b; Reddy & Locke 1996). However, herbicides may be prone to enhanced degradation in crop residues (Zablotowicz *et al.* 1998).

When herbicide is applied directly to soil or is washed from foliage, affinity for sorption by soil greatly influences its dissipation. Herbicide sorption in soil is strongly influenced by the organic carbon content and composition in soil. Herbicide sorption was consistently greater in surface soil from reduced tillage than from tilled areas (Locke 1992; Locke *et al.* 1995). A greater proportion of nonextractable herbicide or herbicide metabolites is often observed in reduced tillage (Kells *et al.* 1980; Locke *et al.* 1996; Locke & Harper 1991; Reddy *et al.* 1995b) than in conventional tillage soils. Increased sorption capacity and measured nonextractability of reduced tillage soils were primarily attributed to greater quantities of organic carbon rather than to a stronger affinity or energy of sorption by organic components in the soils. Strong sorption of herbicide to humic materials in the surface of residue managed soils may restrict their bioavailability for degradation, despite higher microbial activity and biomass (Zablotowicz *et al.* 2000).

Several studies showed that more herbicide leaching occurred in reduced tillage soils (Hall & Mumma 1994; Hall *et al.* 1989; Isensee & Sadeghi 1994). Factors contributing to differences in herbicide leaching under conservation management include precipitation and flow patterns, preferential flow path characteristics, and interception and retention by plant residues. Macropore flow involves solute movement via large channels bypassing the soil matrix, with preferential flow occurring primarily during saturated conditions. Characteristics such as initial moisture conditions and deposition of organic residues in the lining of macropores may influence herbicide susceptibility to movement through the pathway (Shipitalo *et al.* 1990; Stehouwer *et al.* 1994). Proximity of a rainfall event to the time of herbicide application is an important factor determining tillage differences in leaching, and the highest likelihood for preferential movement of herbicide is when there is intense rainfall soon after herbicide application (Isensee & Sadeghi 1995; Shipitalo *et al.* 1990).

Water and sediment runoff in conservation management systems is reduced because: (i) surface plant residues physically block flow; (ii) organic residues have a great capacity for absorbing and retaining water otherwise lost in runoff; and (iii) increased water infiltration via preferential flow. Conservation management practices reduced total herbicide runoff loss in some studies (e.g. Hall & Mumma 1994; Webster & Shaw 1996), but in other studies, tillage effects were mixed or lower losses occurred in conventional tillage (Gaynor *et al.* 1995; Myers *et al.* 1995; Seta *et al.* 1993). Difficulty in discerning management impacts on herbicide runoff is attributed to variability associated with site-specific conditions such as rainfall patterns, soil slope, or soil structural properties.

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