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Chapter 13

Herbicide Fate Under Conservation Tillage, Cover Crop, and Edge-of-Field Management Practices

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INTRODUCTION OF DIFFERENT RESIDUE MANAGEMENT SYSTEMS

Conservation management systems are more widespread due to environmental regulatory pressure and a desire to reduce input costs. Conservation management systems are defined as those that integrate practices to preserve or enhance soil and water resources. Some examples of conservation management practices include reduced tillage, cover crops, crop rotation, variable row spacing, and timing of crop planting. One objective of conservation management systems is to increase coverage of the soil surface by plant residues to a level of 30 percent or more. Many benefits accrue from plant residue accumulation on the soil surface, such as protection from erosion, conservation of soil moisture, and enhancement of soil tilth. Soil and plant microenvironments are created within these systems and can be manipulated to achieve desired benefits. For example, coverage of soil by plant residues in cover crop systems or minimization of soil disturbance by cultivation may inhibit germination and growth of weeds, in turn reducing the need for herbicides. However, Teasdale (1998) observed that inhibition of weeds by cover crops early in the growing season did not provide adequate control later in the season; thus, herbicides were required. The use of conservation management practices also may alter herbicide dissipation in soil

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and plant residues, thereby influencing herbicide efficacy in controlling weeds. Sorption, degradation, movement in leachate or surface water, volatilization, and plant uptake are mechanisms of herbicide dissipation, and these mechanisms can be affected by management-influenced soil characteristics.

Although one goal of conservation management systems is to minimize input costs such as cultivation, we recognize that other inputs such as herbicides will likely remain as management tools within these systems. In this review, we will discuss herbicide dissipation in soil within the context of conservation management systems, evaluating how these practices modify herbicide fate. The discussion will focus on three areas of conservation management: reduced tillage, cover crops, and edge-of-field practices.

Tillage is considered to be reduced if at least one major cultivation practice is excluded or the intensity of the tillage operation is minimized. Other terms that describe forms of reduced tillage include no-tillage, zero tillage, ridge tillage, and strip tillage. Cover crops are used for a variety of purposes (e.g., weed inhibition, nutrient source, erosion control), and numerous species are utilized (Locke, Reddy, and Zablotowicz, 2002). Some of the more common cover crops include grass species such as rye, wheat, and ryegrass, and legumes such as clovers and vetches. Edge-of-field management practices are defined here as those practices at the perimeter of row crop fields that provide a buffer or barrier between the field and outlying areas. Some edge-of-field practices include vegetative buffer strips, vegetated furrows and ditches, and forested riparian areas.

EFFECTS OF CONSERVATION MANAGEMENT PRACTICES ON ORGANIC MATTER, MICROBIOLOGICAL CHARACTERISTICS, AND SOIL STRUCTURE

When left untilled, surface soil develops into a rich organic substrate to support microbial activity. Under a wide variety of cropping systems, total organic carbon in surface soils often increases as degree of tillage is reduced (Blevins et al., 1983; Doran, 1980; Franzluebbers, Hons, and Zuberer, 1994; Locke and Harper, 1991b; Locke, 1992; Locke, Gaston, and Zablotowicz, 1996), with only marginal changes in organic carbon at lower soil depths. The results of a study (Zablotowicz, Locke, et al., 2000) assessing the effects of long-term no-tillage on soil organic matter and microbial biomass in different soil depths are summarized in Table 13.1. After 11 years of continuous no-tillage practices, the organic carbon content of the surface 0 to 2 cm of no-tilled (NT) soil was 47 percent greater than that of the conven-

TABLE 13.1. Soil organic carbon, microbial biomass, fluorescein diacetate (FDA) hydrolysis, fluometuron sorption, and fluometuron degradation constants in long-term no-tillage and conventional tillage Dundee silt loam soil at four depths.

Soil depth	Organic carbon ($g \cdot kg^{-1}$)		Microbial biomass ($mg\ N \cdot kg^{-1}$)		FDA activity ($nmol \cdot g^{-1} \cdot h^{-1}$)		Freundlich sorption ($K_f \cdot L \cdot kg^{-1}$)		Fluometuron half-life (days)	
(cm)	NT	CT	NT	CT	NT	CT	NT	CT	NT	CT
0-2	30.1 a	20.3 b	175 a	85 b	1753 a	772 b	7.19	1.89	29.0	13.3
2-5	11.8 a	11.2 a	84 b	117 a	561 b	750 a	1.96	2.18	27.2	14.7
5-10	5.9 a	6.9 a	21 b	35 a	249 b	496 a	1.41	1.04	69.0	36.6
10-25	3.3 a	4.4 a	<10	<10	91 a	83 a	1.46	1.16	72.5	135.1

Source: Adapted from Zablotowicz, Locke, et al., 2000.
Note: Means followed by the same letter are not significantly different ($p = 0.05$).

tionally tilled (CT) soil, while no significant differences were observed at lower soil depths.

Higher soil moisture below the surface crust and labile organic carbon substrate in the soil surface provide an ideal environment for microbial activity, influencing both the size and diversity of microbial populations under conservation management. Indicators of microbial activity, such as microbial biomass (Franzluebbers, Hons, and Zuberer, 1994; Zablotowicz, Locke, et al., 2000), aerobic microbes, facultative anaerobes, and denitrifiers (Doran, 1980; Linn and Doran, 1984), are often higher in reduced-tillage surface soils. Cover crop residues or organic amendments can also enhance soil microflora (Wagner et al., 1995; Zablotowicz, Locke, and Smeda, 1998). Increased bacterial populations, especially gram-negative bacteria such as *Pseudomonas* spp., have been associated with residue managed soils compared to CT soils (Reddy, Zablotowicz, and Locke, 1995; Wagner et al., 1995; Zablotowicz, Locke, and Smeda, 1998). As organic substrate declines with soil depth, differences in microbial activity attributed to conservation tillage also diminish. For example, in the upper 2 cm of soil, microbial biomass was 106 percent greater than that of conventionally tilled soil (Zablotowicz, Locke, and Smeda, 1998). In lower 2 to 10 cm depths, however, microbial biomass was greater in CT compared to NT soils.

Associated with enhanced microbial populations, soil enzymatic activities from reduced-tillage systems are often higher relative to tilled soils (Dick, 1984; Doran, 1980; Reddy, Zablotowicz, and Locke, 1995; Zablotowicz, Hoagland, and Wagner, 1998). Understanding soil enzyme activity in soil is important in ascribing soil quality indexes (Dick, 1997; Masciandro and Ceccanti, 1999) and in predicting herbicide metabolism (Zablotowicz, Hoagland, and Wagner, 1998; Zablotowicz, Hoagland, et al., 2000). Some hydrolytic enzymes of importance to herbicide metabolism in soil include amidases, chlorohydrolases, esterases, and nitrilases (Hoagland and Zablotowicz, 2000). For example, measuring hydrolysis of the traditional esterase/lipase substrate, fluorescein diacetate, correlated with deesterification of the herbicide fenoxaprop-ethyl in soil (Zablotowicz, Hoagland, et al., 2000). Fluorescein acetate hydrolysis activity (FDA) was 127 percent greater than that of conventional tilled soil (Zablotowicz, Locke, et al., 2000). However, in lower 2 to 10 cm depths FDA hydrolytic activity was greater than in CT compared to NT soils. The enzyme aryl acylamidase was responsible for cleavage of the amide bond in acylanilide herbicides, and the activity of this enzyme was severalfold higher in NT versus CT soils, as was sulfatase and phosphatase (Zablotowicz, Hoagland, and Wagner, 1998). Oxidative enzymes such as peroxidases, phenol oxidases, and tyrosinases also may be important in oxidative coupling of aromatic pesticides and their metabolites to soil humus (Bollag, Myers, and Minard, 1992). The role of these oxidative enzymes and herbicide dissipation needs to be further assessed in conservation residue managed soils.

Soil profiles that are left undisturbed often develop large pores and channels as a result of roots decomposing in situ, leaving voids, microfauna activity (e.g., earthworms, insects), or the formation of cracks 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, Hendrix, and Coleman, 1994).

HERBICIDE SORPTION AND MOVEMENT IN CONSERVATION-MANAGED SYSTEMS

When herbicide is applied directly to soil or is washed off foliage, affinity for sorption by soil greatly influences its dissipation. Herbicide sorption in soil is strongly influenced by the organic content and composition in soil. Sorption to humic and other organic substances involves several binding mechanisms including ion exchange, hydrogen bonding, covalent bonding, charge transfer, hydrophobic partitioning, Van der Waals attraction, and ligand exchange. Because sorption is often positively correlated with bulk, electronic, and hydrophobic properties of the herbicide molecules (Reddy and Locke, 1994), these relationships can be extrapolated to conservation residue managed soils with elevated organic carbon levels. Herbicide sorption was consistently greater in surface soil from reduced tillage than from tilled areas (Locke, 1992; Brown et al., 1994; Locke, Zablotowicz, and Gaston, 1995; Reddy et al., 1995), primarily attributed to greater quantities of organic carbon rather than to a stronger affinity or energy of sorption by organic components in the soils. For example, fluometuron sorption was greatest in the surface 0 to 2 cm of NT soil and about fourfold higher than that of the same depth of CT soil (see Table 13.1). Collaborative studies are assessing the use of NMR techniques for understanding herbicide sorption mechanisms (Kingery et al., 2000). They determined that a higher number of sorption sites (functional groups) in humic material from NT soil may account for greater herbicide sorption rather than differences in the composition and character of sorption sites.

Sorption characteristics of several other herbicides under varying tillage and residue management systems have also been evaluated, e.g., acifluorfen, alachlor, bentazon, chlorimuron, cyanazine, metolachlor, and sulfentrazone (e.g., Locke, 1992; Locke, Gaston, and Zablotowicz, 1997; Reddy, Locke, and Gaston, 1997; Reddy, Locke, and Zablotowicz, 1997; Reddy and Locke, 1998). Comparative sorption studies of metabolites versus the parent compound were conducted for acifluorfen (Locke, Gaston, and Zablotowicz, 1997), bentazon (Gaston, Locke, and Zablotowicz, 1996), cyanazine (Reddy, Locke, and Zabltowicz, 1997), and fluometuron (Locke and Zablotowicz, 2000). The formation of certain metabolites and their role in increased sorption has been demonstrated. For example, sorption of the derivative amino-acifluorfen was found to be significantly higher than the herbicide acifluorfen (Locke, Gaston, and Zablotowicz, 1997).

Some research has shown that characteristics of reduced-tillage soil profiles enhance herbicide leaching (Hall, Murray, and Hartwig, 1989; Hall and Mumma, 1994; Isensee and Sadeghi, 1994). As discussed earlier, reduced-tillage conditions promote the development of macropore channels through soil profiles. Preferential flow through macropore channels, particularly during saturated conditions, results in some solute (herbicide) bypassing the bulk soil matrix. As solute flows rapidly through macropores, very limited interaction and sorption occurs between solute and organic or mineral soil constituents, thus enhancing solute movement in leachate to lower soil depths. As macropore channels age, organic residues may deposit along the inner lining. The depositions of organic residues increase the potential for sorption of solute in the leachate (Shipitalo et al., 1990; Stehouwer, Dick, and Traina, 1994).

Soil forms a dry crust at the surface, and the accumulation of plant residues helps reduce moisture evaporation from soil. If the soil surface is very dry at the time of herbicide application, sorption may be enhanced because of differential effects on physical and chemical properties of mineral and organic colloids, such as increased organic matter solubility, increased acidity, and exposure of hydrophobic components (Chiou, 1989; Sparks, 1990). Higher soil moisture conditions or precipitation soon after herbicide application increase the likelihood of herbicide movement under reduced tillage (Shipitalo et al., 1990; Isensee and Sadeghi, 1995).

Several factors contribute to reduced water and sediment runoff in conservation management systems. As plant residues on the soil surface slow water flow, the water has more time to infiltrate, especially through macropore channels if saturated conditions are present. In addition, the organic residues have a great capacity for absorbing and retaining water that would otherwise be lost in runoff. Sediments also have time to settle as water flow is reduced. Slowing water and sediment loss in conservation systems has an effect on herbicide loss. In some studies, total herbicide loss was reduced under conservation management (e.g., Hall and Mumma, 1994; Webster and Shaw, 1996). However, results have not always been consistent, resulting in mixed or lower herbicide losses occurring in conventional tillage (Gaynor, MacTavish, and Findlay, 1995; Myers, Wagger, and Leidy, 1995; Seta et al., 1993). These conflicting results in management impacts on herbicide runoff are attributed to variability associated with site-specific conditions, such as rainfall patterns, soil slope, or soil structural properties.

HERBICIDE DEGRADATION IN CONSERVATION-MANAGED SYSTEMS

Herbicide degradation in soil is controlled by the interaction of several factors, e.g., soil chemical and physical characteristics (texture, pH, moisture), climate (rainfall and temperature), the microbial community (magnitude of the population, presence of specific degraders, and their relative activity), and herbicide bioavailability. Thus, the effects of residue management practices on herbicide degradation depend upon these factors as well the chemical and physical characteristics of the particular herbicide, and the nature of the management practice. Three approaches are commonly used to assess management effects on herbicide degradation: (1) in vitro laboratory assays under controlled, usually static conditions; (2) laboratory column studies using intact soil cores; and (3) field dissipation studies. Understanding the fate of metabolites as well as the parent compound is very relevant in assessing environmental impacts of pesticides. Metabolite degradation is dependent on both the soil properties and chemical properties of the metabolite.

As reviewed elsewhere (Locke and Bryson, 1997), many well-designed laboratory studies have assessed comparative herbicide degradation in conventional and no-tillage soils. Overall, no clear conclusion on tillage effects and herbicide degradation can be generalized due to the wide range of herbicide chemistries and differences in cropping systems. Once initial degradation of herbicide occurs, however, differences have been observed in patterns of metabolite accumulation and degradation. Work with radiolabelled herbicide has determined that a large proportion of herbicide residues are not extractable from soil and that, in many cases, a greater proportion of applied herbicide or metabolites is trapped (nonextractable) in conservation tillage soils than conventional soils (Kells et al., 1980; Locke and Harper, 1991a,b; Reddy et al., 1995; Locke, Gaston, and Zablotowicz, 1996). Higher microbial activities and organic carbon levels found in conservation tillage soils may lead to greater polymerization and binding of herbicides or metabolites in humic material.

Initial studies by Kells and colleagues (1980) assessed the dissipation of ^{14}C-atrazine in CT and NT soils under field and laboratory conditions. These studies indicated that there was a more rapid incorporation of ^{14}C-atrazine into the nonextractable fraction of NT compared to CT soils. These effects were reversible by liming, and the authors concluded that chemical hydrolysis was responsible for enhanced degradation under NT conditions. Hydroxyatrazine, the product of chemical hydrolysis, is more prone to sorption by humic materials and not readily extracted by methanol (Lerch, Thurman, and Kruger, 1997). Levanon and colleagues (1994) observed delayed atrazine mineralization in CT compared to NT soil attributed to a lower initial population of atrazine-mineralizing microorganisms in the CT soil. However, a similar total mineralization was observed in both soils at the end of the incubation. Atrazine was more rapidly dissipated in the NT soil accompanied by a more rapid incorporation of ^{14}C into nonextractable residues in the NT soil compared to the CT soil.

The degradation of ^{14}C-ring labeled alachlor in surface soils of NT and CT Dundee silt loam was studied in a laboratory biometer flask study (Locke, Gaston, and Zablotowicz, 1996). Similar alachlor dissipation was observed in both soils. However, in the NT soil about 13 percent of the alachlor was mineralized during a 55-day incubation compared to 7 percent in the CT soils, with greater alachlor incorporated into nonextractable residues in the NT compared to CT the soil. In the CT soils, there was a greater accumulation of polar metabolites, e.g., the sulfonic acid derivative. Increased microbial activity in no-tillage soil was likely responsible for a shorter residence time for polar metabolites such as sulfonic acid found in NT soils.

Degradation of ^{14}C-chlorimuron was assessed in laboratory studies using three CT and NT surface soils (Reddy, Zablotowicz, and Locke, 1995). In a Miami silt loam and a Drummer silty clay loam with 72 and 140 percent greater organic matter content compared to their respective CT soils, greater mineralization was observed in the CT soils and a higher proportion of the ^{14}C was nonextractable in the NT soils.

The effects of tillage on bentazon degradation were studied in five soils with the duration of NT practices ranging from 3 to 18 years (Wagner et al., 1996); however, a significant effect of tillage was observed in only two of the soils, both of which had a long history of bentazon application. In a Dundee silt loam from Mississippi, more rapid bentazon dissipation and mineralization was found under CT soil compared to NT soil, while the inverse was observed in a Miami silt loam soil from Illinois. Gaston, Locke, and Zablotowicz (1996) and Gaston and colleagues (1996) also found that bentazon degradation was more rapid in Dundee CT soil than in NT soil, consistent with Wagner and colleagues (1996), and was leached more rapidly in the NT soil. There was higher organic carbon in the Dundee NT soil; thus for the same moisture content, water was held at a greater tension (Gaston, Locke, and Zablotowicz, 1996; Gaston et al., 1996). In addition, the NT soil had higher bulk density and higher volumetric water content;

thus it was more moist and likely less aerated. Initial degradation of bentazon in soil has been attributed to the ring hydroxylation by fungi (Huber and Otto, 1994), with greater degradation occurring under well-aerated soil conditions. More rapid bentazon degradation in the Dundee CT would have occurred under the more aerated conditions with relatively low organic carbon. As bentazon degrades, metabolites are less mobile and may become nonextractable, resulting in less bentazon leached in the CT soil.

The effect of a winter cereal rye cover crop and time of soil sampling on the potential for 2,4-D degradation was assessed in surface and subsurface of a Willamette silt loam soil (Bottomley et al., 1999). Populations of 2,4-D mineralizing bacteria were higher in the surface (0 to 20 cm) soil under cereal rye compared to winter fallow soil.

The effects of tillage and cover crop management on fluometuron degradation has been evaluated in several studies. In laboratory studies by Brown and colleagues (1994), fluometuron was more persistent in surface (0 to 4 cm) CT and NT soils managed under hairy vetch (half-life 71 and 78 days, respectively) compared to CT and NT soils with no cover crop (half-life 57 and 49 days, respectively). Other laboratory studies (Locke, Zablotowicz, and Gaston, 1995; Zablotowicz, Locke, and Hoagland, 1997) indicated fluometuron degraded more rapidly in surface (0 to 2 cm) NT and CT soils under a ryegrass cover crop compared to soils with no cover crop. Studies by Zablotowicz, Locke, and colleagues (2000) compared the degradation of fluometuron in NT and CT at four depths. In the upper 10 cm soil depths, fluometuron degraded more rapidly in CT compared to NT soil (see Table 13.1). Despite higher microbial biomass and activity in NT 0 to 2 cm soil, the increased sorptive capacity of the soil minimized the amount of fluometuron that was bioavailble for microbial degradation. In the lower 2 to 5 and 5 to 10 cm depths greater microbial activity and more labile organic matter in CT soils was responsible for greater fluometuron degradation compared to NT soils. Understanding interactions regulating bioavailability (sorption) and microbial activity is key in understanding herbicide transformations under NT practices.

Kinetics of metribuzin degradation in NT and CT soils were similar, but dynamics of metabolite accumulation and degradation differed (Locke and Harper, 1991a,b). Accumulations of extractable polar metabolites of metribuzin were greater in residue-managed soils than in CT and nonamended soils. Nonextractable herbicide residues were also greater in the NT.

The effect of conservation management on dissipation of herbicides under field conditions is difficult to assess (e.g., Ghadiri et al., 1984; Gaynor, Stone, and Vyn, 1987; Curran, Liebl, and Simmons, 1992; Monks and Banks, 1993) because many factors may counter one another's effects. Retention at the soil surface may increase herbicide residence time, since sorption to organic residue impedes further movement. Likewise, photolabile compounds remaining on the soil surface may be subject to photodegradation. However, if the herbicide moves through the dry crust and encounters more moist conditions and active microbial populations, degradation may be enhanced. More developed macropores and better aggregation in the conservation soils also may provide channels for increased herbicide mobility.

HERBICIDE RETENTION AND DEGRADATION IN PLANT RESIDUES

Postemergence herbicides are an important part of reduced-tillage and cover crop systems. Live plants as well as plant residues intercept much of the herbicide. The intercepted herbicide may be taken up by the plant or sorb to plant tissue (Reddy, Locke, and Howard, 1995; Reddy and Locke, 1996). Some studies indicate that crop and weed residues can have a higher capacity for herbicide sorption than soil (Dao, 1991; Reddy et al., 1995; Reddy, Locke, and Gaston, 1997), and as these residues age, sorption capacity may increase even further (Dao, 1991). Plant residues also intercept and retain preemergence herbicides. Banks and Robinson (1986) found that the efficacy of several chloroacetamide herbicides was reduced because they were intercepted by wheat straw residue.

Decomposing residues harbor enhanced microbial populations, and these organisms may cometabolize intercepted herbicides. For example, laboratory studies demonstrated enhanced fluometuron metabolism in association with plant residues (Zablotowicz, Locke, and Smeda, 1998). The rate of fluometuron degradation was affected by increased moisture content. However, 2,4-D was poorly degraded under the same cover crop residues compared to soil.

CONSERVATION EDGE-OF-FIELD PRACTICES AND HERBICIDE DISSIPATION

Although numerous practices within the field can influence the rate of herbicide degradation and sorption, waterway management and edge-of-field practices present a final opportunity to prevent pollution of surface water bodies. Edge-of-field zones such as vegetated buffer strips (VBS), constructed wetlands, riparian zones, and grass waterways are inherently transitory zones between the agroecosytems and the aquatic systems receiving the runoff water. Proper management of these transitional zones may provide an effective and practical means of environmental protection.

Edge-of-field buffer zones can be effective in minimizing herbicide movement to surface aquatic systems through a variety of mechanisms. In the simplest case, the buffer zones provide a spatial barrier to off-target herbicide drift. Even with proper nozzle selection and timing of application with respect to meteorological conditions, some drift is likely to occur (reviewed in Akesson and Yates, 1988; Bode, 1987). A vegetated field buffer will intercept much of the drift and thus protect potentially sensitive adjacent areas. For example, Robinson and colleagues (2000) recommended a 30 m buffer zone for the helicopter application of asulam herbicide to avoid biologically active levels, although the herbicide was detectable up to 200 m downwind. A 3 m unsprayed buffer reduced drift to a ditch by 95 percent in another study (Geert, de Snoo, and de Wit, 1998).

Many of the same principles that relate to conservation tillage practices are applicable to field borders. Just as reduced tillage and cover crop establishment promote herbicide retention within the field through increased affinity for organic matter, increased microbial activity, and increased infiltration through improved soil tilth, a growing body of research supports the view that the same processes are occurring at the field margins. For example, in a comparison between a VBS and an adjacent cultivated field, Staddon, Locke, and Zablotowicz (2001) found more than twice as much organic matter in the VBS. Soil from the VBS also had higher metolachlor sorption and higher rates of metolachlor degradation in vitro.

A primary means of herbicide movement out of fields is through movement of suspended soil with bound herbicide. Clearly, any edge-of-field practice that slowed the velocity of runoff water and trapped suspended sediment would likely reduce the loss of herbicide from the field (Dillaha et al., 1989; Deletic, 2001; Ghadiri, Rose, and Hogarth, 2001; Jin and Römkens, 2001; Smolikowski, Puig, and Roose, 2001). The same practices, such as grassed waterways and filter strips, that have long been employed to reduce soil erosion have been shown to effectively reduce runoff of herbicides. Even in the case of metolachlor and metribuzin, two fairly soluble herbicides, a 2 m fescue filter strip consistently reduced losses in all three years of study and three different tillage regimes (Webster and Shaw, 1996). Similarly, the effectiveness of switchgrass as a filter strip was demonstrated for metolachlor and atrazine (Mersie et al., 1999). Rankins, Shaw, and Boyette (2001) evaluated four grass species in a 30 cm filter strip, all of which reduced fluometuron and norflurazon concentrations in runoff water by at least 53 percent and 46 percent, respectively, relative to unfiltered controls. The effectiveness of filter strips is clearly related to their ability to remove sediment by filtration, reduce runoff velocity and increase infiltration rate, and, in one example with switchgrass, even create backwater (Dabney et al., 1993).

In addition to removal of herbicides sorbed on suspended soil, VBS influence herbicide fate through other mechanisms. The plants themselves will intercept herbicides by uptake of the compound or binding to the phyloplane and rhizosphere. Plants may enhance herbicide degradation by direct uptake and metabolism or indirectly via accelerated metabolism within the rhizosphere (Zablotowicz, Locke, and Hoagland, 1997; Zablotowicz and Hoagland, 1999). The rhizosphere effect may be due to the niche it provides for microflora. In rhizospheres, herbicides are subject to transformation by metabolic and cometabolic proccesses. Rhizosphere bacteria cometabolize herbicides by activity of enzymes such as aryl acylamidase (Hoagland, Zablotowicz, and Locke, 1994), glutathione *S*-transferase (Zablotowicz, Hoagland, and Locke, 1994; Zablotowicz et al., 1995), and aromatic nitroreductase (Zablotowicz, Locke, and Hoagland, 1997) among others. Through root death and decay, plants also provide aeration and channelization that may lead to improved infiltration of herbicides (Muñoz-Carpena, Parsons, and Gilliam, 1999). Others have suggested volatilization as a means of herbicide dissipation within VBS (Dillaha et al., 1989). Understanding the contribution of plants to enhanced herbicide degradation may aid in developing better management recommendations for edge-of-field practices.

Before runoff water and associated sediments, nutrients, and pesticides leave the agroecosystem, they often must travel though a network of ditches. These often-overlooked conduits provide a final opportunity to prevent the pollution of valued water bodies. "Ditch" is an imprecise term that encompasses a range of topographic, hydrologic, and vegetative features that may affect the fate of herbicides. Consequently, the utility of ditches is not easily generalized. One study demonstrated very rapid and thorough removal of atrazine from water in a Mississippi Delta agricultural drainage ditch (Moore et al., 2001). Just one hour after exposure, 61 percent of the atrazine was found in association with the vegetation, and the authors concluded that for their experimental conditions atrazine could be completely removed within 50 m of ditch length. Although their study is encouraging, it is noteworthy that the atrazine removal was largely plant mediated and their study was conducted in July in Mississippi. A cooler climate or a ditch that is not as heavily vegetated, as may be typical when atrazine is typically applied, may produce very different results. Another study with linuron in the Netherlands noted only 1 percent of the herbicide associating with the vegetation and 6 percent in the ditch sediment, with the remainder associated with the aqueous phase of the ditch (Crum, Aaldernik, and Brock, 1998).

Edge-of-field practices can provide numerous other benefits in addition to herbicide containment and dissipation. These uncropped, and often largely unmanaged, areas serve as remnant "natural" patches in the landscape with disproportionately high biodiversity (Moonen and Marshall, 2001; Marshall, 2002). These refugia are important in the ecology of small mammals (Chapman and Ribic, 2002), birds, including species with potential utility in biocontrol (Jobin, Choinière, and Bélanger, 2001), and bumblebees (Bäckman and Tiainen, 2002). The soils in the field margins are often enriched in organic matter and, in the cases of ditches, riparian zones, and grassed waterways, the saturated conditions can lead to anaerobic conditions which facilitate denitrification (Ettema, Lowrance, and Coleman, 1999; Watts and Seitzinger, 2000).

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