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Effect of Herbicides on Earthworms

Mohammad Javad Zarea* • Nasrin Karimi

Faculty of Agriculture, Ilam University, P.O. Box 69315516, Ilam, Iran

Corresponding author: * mj.zarea@ilam.ac.ir

ABSTRACT

Nature consistently integrates plants and animals into a diverse landscape as part of a major tenet of sustainable agriculture, which is to create and maintain diversity. Chemicals have become the weed control strategy employed most frequently, despite the fact that many important herbicides create water and environment pollution. Earthworms are an important component of the soil system. Earthworms are being increasingly threatened by the excessive application of herbicides to soils. Herbicides can influence earthworms' function, growth, reproduction and health. The mortality of earthworms in soils and excessive use of herbicides is still vague. The mortality of earthworms depends on the kind and concentration of herbicide and the duration to which earthworms are exposed to the herbicide. The adoption of conservation tillage has increased worldwide over the past decades. Weeds may become a problem, both in no-tillage systems and in reduced tillage systems. The use of effective herbicides into no-tillage planting systems may provide a feasible option for enhancing weed control, which can become a toxicological risk for invertebrates such as earthworms. This review treats the role of herbicide on the behavior of earthworms. This review will outline the current state of knowledge about fate of earthworm under conservation tillage.

Keywords: agroecosystem, conservation tillage, LC_{50}, toxicity

Abbreviations: CT, conservation tillage; **GST**, Glutathione-*S*-transferase; **N**, nitrogen; **NT**, no-tillage; **RT**, reduced tillage; **TT**, traditional tillage

CONTENTS

INTRODUCTION

In developed countries, herbicides account for more than 70% of the total pesticides available at the market (Muthukaruppan *et al.* 2005). During 1960-1985, herbicides saw an annual worldwide growth rate of 16.7%. Herbicides are most widely used in the United States. In the Asia-Pacific region, herbicide usage accounts for only 13.4% (Muthukaruppan *et al.* 2005). In the world market, the use of herbicides will continue to expand at 4.5% annually, which is the largest growth in the herbicide market so far (Adam 1976). In 2002, herbicides represented *ca.* 35% of the pesticides used in Europe (ECPA 2003). During 2009 Phillips McDougall undertook a survey of the leading global agrochemical companies designed to provide information on the comparative costs involved in the discovery, development and registration of a new conventional chemical crop protection product. The total cost of agrochemical R&D expenditure in 2007 for 14 of the leading crop protection companies was $2328 mil, a value equivalent to 6.7% of their agrochemical sales. These companies also provided expectations to discover, develop and register a new agrochemical expenditure in 2012; overall the expectation was for a 26.4% increase in expenditure over this five year timeframe, at an average rate of increase of 4.8% pa (McDougall 2010).

The adoption of conservation tillage (CT) has increased worldwide over the past few decades. Weeds may become a problem, both in no-tillage systems and in reduced tillage systems (Zarea 2010). The adoption of this tillage system changes the weed seed distribution in the surface soil layers and the date of weed emergence. Weeds, especially grasses and perennial weeds, may become a problem, both in no-tillage systems (Schwerdtle 1977) and in reduced tillage systems (Pleasant *et al.* 1990).

The role of earthworms in the soil ecosystem has become of great interest as farmers, researchers, and scientists promote management practices that encourage earthworms. Earthworms are an important component of the soil system, and can enhance plant growth by improving soil fertility and nutrient cycling (Lee 1985).

Herbicides in general show low toxicity toward worms, although there are some exceptions (Zarea 2010). The mortality of earthworms in soils and excessive use of herbicides is still vague. Brown (1978) reported that some herbicides are directly toxic to earthworms while others have virtually no effects. The purpose of this review is to outline the cur-

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Invited Review

rent state of knowledge about the effect of herbicides on earthworms. The paper outlines the effect of herbicide on behavior of earthworms. The practice of conservation tillage in crop production has been increasing worldwide in order to reduce production costs and to combat soil erosion. In such systems herbicide applications may reduce (Mahn 1984) or maintain (Derksen *et al.* 1995) weed diversity and increase the number of non-susceptible species (Fryer and Chancellor 1970). But they can become a toxicological risk for invertebrates such as earthworms. While the use of effective herbicides in combination with cover crops integrated into no-tillage planting systems may provide a feasible option for enhancing weed control, these compounds tend to accumulate in the soil and subsurface water (Jacobson *et al.* 2005) where they can become a toxicological risk for invertebrates such as earthworms that ingest large amounts of soil and play a key role in soil biology (Zarea 2010). This review will outline the current state of knowledge about fate of earthworm under conservation tillage.

BENEFICIAL OF EARTHWORMS IN AGROECOSYSTEMS

Earthworms are an important component of the soil system, and can enhance plant growth by improving soil fertility and nutrient cycling (Lee 1985). Earthworms can improve plant growth, enhance soil infiltration and decrease runoff which, in turn, are affected by the soil tillage practices adopted. The impact of earthworms on physical, chemical, and biological properties of soil is well established (Lee 1985; Edwards and Bohlen 1996). Scheu (2003) has provided an extensive review on the effects of earthworms in ecosystems. Earthworms may be an essential part of many agroecosystems and may be useful indicators for sustainability (Lee 1995; Buckerfield *et al.* 1997). The role of earthworms in the soil ecosystem has become of great interest as farmers, researchers, and scientists promote management practices that encourage earthworms. When present, earthworms can play a major role in soil fertility and productivity (; Lee 1985; Edwards and Shipitalo 1998). They are an important component of the soil system, and can enhance plant growth by improving soil fertility and nutrient cycling (Lee 1985). Earthworm can stimulate microbial activity in the soil during its passage through their gut (Binet *et al.* 1998). Enhanced N mineralization is the best documented mechanism of earthworms and is generally thought to be the most important (Curry and Byrne 1992; Lavelle *et al.* 1992; Subler *et al.* 1997; Scheu 2003; Brown *et al.* 2004; Zarea *et al.* 2009). Earthworms increase mineralization of the soil organic matter, which increases nutrient availability (Curry and Byrne 1992; Lavelle *et al.* 1992; Subler *et al.* 1997). They are beneficial in terms of plant growth, mycorrhizal colonization rate, and nitrogenase activity of free-living N-fixing microorganisms, and soil microbial biomass (Zarea *et al.* 2009, 2010; Zarea 2010).

Among the mechanisms by which earthworms modify plant growth at the individual or community levels (Scheu 2003; Brown *et al.* 2004), five have been suggested as responsible for the positive effects noted on plant production: (i) increased mineralization of soil organic matter, which increases nutrient availability (Curry and Byrne 1992; Lavelle *et al.* 1992; Subler *et al.* 1997), especially nitrogen, the major limiting nutrient in terrestrial ecosystems; (ii) the modification of soil porosity and aggregation (Blanchart *et al.* 1999; Shipitalo and Le Bayon 2004), which improves water and oxygen availability to plants (Doube *et al.* 1997; Allaire-Leung *et al.* 2000); (iii) the production of plant growth regulators via the stimulation of microbial activity (Nardi *et al*. 2002; Quaggiotti *et al*. 2004); (iv) the biocontrol of pests and parasites (Clapperton *et al.* 2001; Blouin *et al.* 2005); and (v) the stimulation of symbionts (Gange 1993; Furlong *et al.* 2002). Herbicides in general show low toxicity towards worms.

BENEFICIAL OR HAZARDS HERBICIDES IN AGROECOSYSTEMS

Weed interference against crop and vegetable crops is one of the main components of yield reductions in agricultural settings, increasing production costs and reducing quality.

By means of herbicide use in conventional farming it is possible to grow cereals year after year. For example, In Iran, chemicals have become the weed control strategy employed most frequently, despite the fact that many weeds are becoming resistant to many important herbicides and creating water and environment pollution. The low cost of herbicides compared to other strategies encourage farmers to use the chemical method to control weeds (Zarea *et al.* 2010).

Weed competition occurs for nutrients, water, light, and space. Among these essential factors, nutrients have been recognized as an important source for weed–crop interactions (Alkamper 1976; Moody 1981; Liebman 1989; Di Tomaso 1995). Farmers generally prefer simplified herbicide-based cropping systems and insufficiently anticipate resistance (Lemerle and Sutherland 2000; Hartzler and Owen 2003). The available wide range of effective herbicides has been a key to the successful development and wide adoption of simplified, cost-saving and soil-conserving tillage systems (Lyon *et al.* 1996; Denton and Tyler 2002). Herbicide reliance and non-chemical weed management have remained inferior issues in tillage research, as new herbicide development, improved application technology and herbicide-tolerant crops have strengthened the belief that new technologies will solve future weed problems (Bradley 2002; Llewellyn *et al.* 2002; Tranel and Wright 2002). In several countries, consumer aversion towards pesticides and their negative environmental impacts have resulted in serious governmental restrictions on herbicide availability and use in the European Union (EU) (e.g., EU Agricultural Pesticides Directive 91/414/EEC; Watts and Macfarlane 1997). In the EU, the reduced number of registered formulations is already problematic in several minor crops (Gillott 2001). The costs to discover, develop and register a new agrochemical have increased dramatically, from 25 Ms in 1975–1980 to 200 Ms in 2000 (McDougall 2010). Saturated, shrinking herbicide market will probably sustain the declined herbicide innovation rate observed over the past decade (Kalaitzandonakes and Bjornson 1997; Shaner 2005). As the rapid adoption of herbicide-tolerant crops indicates great market opportunities, agrochemical companies will probably focus on developing transgenic crops that exploit current herbicides (Cobb and Kirkwood 2000). The increased incidence of resistance (over 100 new resistant biotypes in the last decade; Heap 2006) is largely attributable to the use of monocultures, reduced cultivation and persistent chemicals (Cobb and Kirkwood 2000). For agronomic purposes, weeds are naturally occurring plants that are injurious in agricultural systems (Worsham 1991). Weeds may increase insect and disease damage to crops, decrease the quality of the crop, or even harm the health of animals that ingest them (Janick *et al.* 1981).

HERBICIDE AND BEHAVIOR OF EARTHWORM

Herbicides can influence soil community structure and function, both directly through effects on soil organisms and indirectly through effects on supporting plant communities (Griffiths *et al.* 2008). Growth, reproduction and health of earthworms are being increasingly threatened by the excessive application of herbicides to soils (**Table 1**).

Earthworms directly influence the persistence of pesticides by transporting herbicides to depth and increasing the soil bound (non-extractable herbicides) fraction in soil (Farenhorst *et al*. 2000), or by absorbing herbicide residues in their tissues (Edwards and Lofty 1977). Growth and cocoon production were drastically reduced in *Eisenia fetida* exposed to sublethal levels of atrazine (Fisher 1989).

Table 1 Summary of effect of herbicides on earthworms.

Herbicide	Parameter(s) affected	Reference
Butachlor	< Cocoon production	Muthukaruppan*et al*. 2005
Paraquat	> Nuclear swelling (2-fold)	Fisher andMolnár 1992
Glyposate	< Chromatin, loss of the epithelial cell structure, lacking regeneration of the cells	Morowati 2000
1-methyl-3-octylimidazolium bromide	> Catalase activity > glutathione content < malondialdehyde levels > superoxide dismutase activity	Li *et al.* 2010
1-methyl-3-octylimidazolium bromide	> Oxidative stress	Lio*et al*. 1989
Acetochlor	> Glutathione-*S*-transferase activity	Xiao *et al*. 2006
Mecoprop and dicamba	< Biomass	Parfitta 2010
Acetochlor	> Growth rates, >numbers of juveniles per cocoon	Xiao *et al.* 2006
Isoproturon	> Total soluble protein	Mosleh*et al*. 2003
Butachlor	< Cocoon production, < clitellum development	Gobi and Gunasekaran 2010
Paraquat	Nuclear swelling	Fischer and Molńar 1992

> – Increased; < – decreased

As the agrochemical concentration is higher in surface layers, Earthworm activity is very much reduced in the soil surface layer (Keogh and Whitehead 1975; Cock *et al.* 1980). Earthworms are sensitive to the presence of chemicals in the soil due to the chemoreceptors distributed on their body surface (Reinecke *et al.* 2002). This characteristic associated with their locomotory abilities, renders them the chance to avoid contaminated areas where soil habitat function has been affected (Yeardley *et al.* 1996; Reinecke *et al.* 2002).

Herbicides affect the feeding behaviour of earthworms, which was reflected in the weight loss and reproductive capacity (Venter and Reinecke 1988; Bustos-Obregon and Goicochea 2002), reduced cocoon production, due to loss of coelomic epithelium and gametes (Muthukaruppan *et al.* 2005). Parfitt *et al.* (2010) reported that *Aporrectodea caliginosa* biomass was markedly lower in the herbicide mecoprop and dicamba while New Zealand indigenous anecic earthworms increased in abundance under herbicide. Stojanović *et al.* (2007) found epithelial tissue of earthworm *E. fetida*, exposed to butachlor, was severely affected Stojanović *et al*. (2007). Fischer and Molńar (1992) found that extreme nuclear swelling resulting in more than 2-fold volume increase of the average minimum could yet be observed only on the effect of sublethal paraquat toxication.

Li *et al.* (2010) and Di Giulio *et al.* (1989) found that 1-methyl-3-octylimidazolium bromide, [C8mim]Br, leads to oxidative stress in the worm. Catalase is an important enzyme in the anti-oxidant system of organism. It eliminates $^{-}$OH and protects cells from damage. Alteration in cellular catalase activity reflects change in oxidative stress on biological cells, which may be induced by pollutants (Li *et al.* 2010). As another key anti-oxidant enzyme, superoxide dismutase removes the O_2^- produced during biological oxidation (Li *et al*. 2010). It is also an important enzyme involved in the removal of ROS. Therefore, SOD activity was considered an important biomarker for the effects of pollutants on ecosystems (Reddy and Sreenivasula 1997). Li *et al.* (2010) found that *Eisenia fetida* SOD activity exposed to [C8mim]Br treatment was increased. Glutathione-*S*-transferase (GST) can catalyze the reaction of the –SH group of glutathione with the electrophilic groups of endogenous and extraneous harmful substances (Li *et al.* 2010). It plays an important role in anti-oxidation (Dallinger 1993) and is thus regarded as an important anti-oxidant enzyme. Li *et al.* (2010) observed a high increase in activity of GST in *Eisenia foetida* exposed to [C8mim]Br. Xiao *et al*. (2006) also found that GST activity in *E. foetida* increased when worms were exposed to acetochlor. Gao *et al.* (2007) reported that GST activity in the whole worm, the anterior region, the mid-part and the posterior region of *E. foetida* was inhibited to different degrees after exposure to albendazole and that this inhibition was enhanced by prolonged exposure. Glutathione is an important water-soluble anti-oxidant. It can directly combine with cellular electrophilic reagents for anti-oxidation or detoxification (Li *et al.* 2010). Glutathione *E. fetida* increased when worms were exposed to [C8mim]Br (Li *et al.* 2010) and induced a decrease when worms were exposed to high dose of mercury (Nielsen *et al.* 1991). Cellulase activity of earthworms indicates their role in the decomposition of plant litter and other cellulosic materials (Xiao *et al.* 2006). It was used as a biomarker of a pesticide contamination on earthworms (Luo *et al.* 1999). Xiao *et al.* (2006) showed that when *E. fetida* was exposed to different concentrations of acetochlor (5-80 mg kg^{-1}), the cellulase activity was significantly inhibited which indicates that acetochlor may bring harmful effects on the biochemical metabolism of *E. fetida*.

TIME AND CONCENTRATION EFFECTS OF HERBICIDES

The mortality of earthworm also depend on time that earthworm exposure to the herbicide. Xiao *et al.* (2004) reported that the mortality of earthworm increased with increased exposure time for any given concentration of acetochlor. These authors reported that up to 6-day exposure, no deaths of the tested earthworms took place if the concentration of acetochlor was lower than 296 mg kg^{-1}. The post-emergence herbicides tend to require lower application and are less persistent chemicals in the environment (Scott and Pollak 2005). The weight change rate of the earthworms was a more sensitive to the toxic effects of acetochlor than changes in the mortality. Chlorpyrifos in compared to atrazine and Cyanazine resulted in slightly higher mean LC_{50} (Lydy and Linck 2003). The mean earthworm biomass was found to be decreased with increasing herbicide concentration. Cocoon production was reduced by the increasing herbicide concentration (Gobi and Gunasekaran 2010). Growth, cocoon production and clitellum development of *E. fetida* exposed to butachlor was decreased (Stojanović *et al.* 2007).

The joint toxicity of acetochlor and urea to earthworms was apparently less than toxicity of acetochlor alone (Xiao *et al.* 2004). Triazine herbicides such as atrazine, cyanazine, and simazine are commonly applied in most agriculture areas of the world. Several recently published studies have demonstrated that organophosphate insecticides and phosphorothionate group in binary combination with triazine herbicides, exhibit greater-than-additive toxicity (Lydy and Linck 2003). Atrazine concentrations (>40 μg/L) in combination with chlorpyrifos, methyl parathion, and diazinon caused a significant increase in mortality to the earthworm *E. fetida* (Lydy and Linck 2003). Lydy and Linck (2003) reported when *E. fetida* were exposed to chlorpyrifos in combination with atrazine or cyanazine, the resulting toxicity was greater than additive. Jin-Clark *et al.* (2002) reported cyanazine enhanced the toxicity of chlorpyrifos 2.2-fold in 48-h acute toxicity tests with *Chironomus tentans*.

KIND OF HERBICIDE

The mortality of earthworms in soils and excessive use of herbicides is still vague. Brown (1978) reported that some herbicides are directly toxic to earthworms while others

Table 2 The LC_{50} values of several herbicides toxic to earthworms.

Herbicide	Earthworm sp.	LC_{50}	References
Butachlor (2-chloro-2', 6'-diethyl-*N*-(butoxymethyl) acetanilide) (label content Butachlor)	*Eisenia fetida*	0.515 mg kg^{-1}	Stojanović*et al.* 2007
Atrazine	*E. fetida*	2.9 µg/cm^2	Lydy and Linck 2003
Cyanazine	*E. fetida*	4.9 µg/cm^2	Lydy and Linck 2003
Chlorpyrifos	*E. fetida*	8.3 µg/cm^2	Lydy and Linck 2003
Acetochlor	*E. fetida*	0.307 mg/kg	Liang and Zhou 2003a
Isoproturon	*E. fetida*	>1 g/kg soil	Tomlin 2000
Chlorpyrifos	*E. fetida*	15.6 µg/cm^2	Roberts and Dorough 1984
Malathion	*E. fetida*	13.5 µg/cm^2	Roberts and Dorough 1984
Parathion	*E. fetida*	14.8 µg/cm^2	Roberts and Dorough 1984
1-Methyl-3-octylimidazolium bromide	*E. fetida*	206.8 mg/kg	Li *et al.* 2010
1-Methyl-3-octylimidazolium bromide	*E. fetida*	159.4 mg/kg*	Li *et al.* 2010
Acetochlor	*E. fetida*	198.7 mg/kg	Xiao *et al*. 2004
Urea	*E. fetida*	1065.9 mg/kg	Xiao *et al* 2004
Methamidophos	*E. fetida*	0.708 mg/kg	Liang and Zhou 2003a
2,4-D	*E. fetida*	> 100 mg/kg	Correia and Moreira 2010
Sulcotrione	*Eisenia andrei*	1,000 mg a.i./kg	Marques *et al.* 2009
Penoxsulam	*E. andrei*	1,000 mg a.i./kg	Marques *et al.* 2009
Isoproturon			

* 7 d-LC_{50} and 14 d-LC_{50}, respectively

have virtually no effects. The LC_{50} values for several herbicides are presented in **Table 2**.

Herbicides in general show low toxicity toward worms, although there are some exceptions. However, herbicides have a drastic indirect effect on earthworms through their influence on the availability of organic matter (Edwards and Thompson 1973). The triazine classes of herbicides have a moderate impact on earthworm numbers. There have been several reports that chlorpropham, propham, dinoseb, and triazine herbicides such as simazine have moderate effects on earthworm population (Edwards and Thompson 1973). Chio and Sanborn (1978) reported that *Lumbricus terrestris* could metabolize atrazine, chlorambar and dicamba. Numerous studies support the conclusion that normal use of glyphosate formulations such as the original Roundup will not adversely affect earthworms. A comprehensive review of the effects of agricultural chemicals on earthworms reviewed the effects of glyphosate on earthworms (Edwards and Bohlen 1996). Glyphosate was ranked as 0 on a scale of zero (relatively non-toxic) to 4 (extremely toxic). Monsanto (manufacturer of Roundup) as well as several independent researchers have conducted studies in which no adverse effects were observed when earthworms were exposed to glyphosate residues in soil at rates equal to or greater than labeled rates (Giesy *et al.* 2000). Lydy and Linck (2003) reported simazine caused no toxicity to the worms and did not affect chlorpyrifos toxicity in binary mixture experiments. Studies have shown that triazine herbicides have toxic effects on *E. fetida* populations (Edwards and Thompson 1973; Fisher 1989; Lydy and Linck 2003). Atrazine is more toxic than the organophosphate insecticide turbufos to *E. fetida* (Haque and Ebring 1983). Edwards and Bohlen (1992) found that most organophosphates are not very toxic to *E. fetida*. Acetochlor has become one of the three herbicides most widely used in Chinese phaiozem area for agricultural production in view of its effective control of weeds (Aga *et al.* 1999) which lead to earthworms in some agricultural soils of this area are becoming extinct. Muthukaruppan *et al.* (2005) showed inhibitory effects of herbicides on the growth of the earthworm *P. sansibaricus*, when exposed to Butachlor. Both Mikado and sulcotrione impacted the behaviour of *E. andrei* only slightly (Marques *et al.* 2009). Acetochlor to *E. fetida* is more toxic than methamidophos (Liang and Zhou 2003a). However, it is less toxic than methamidophos (Liang and Zhou 2003b). Several toxicity studies indicate that paraquat is relatively less toxic to earthworms (Edwards and Bohlen 1992). A widely used herbicide in agriculture, which is known to be toxic to both animals and man, is paraquat (Bullivant *et al.* 1966; Halley 1976). Isoproturon is used for pre- and post-emergence control of monocot and dicot weeds in winter wheat. No lethal effect of isoproturon on earthworms (*Lumbricus terrestris* L.) was observed even at the highest concentration tested (1.4 g/kg soil) after 60 days of exposure (Mosleh *et al.* 2003).

CONSERVATION TILLAGE, WEED PROBLEM, EARTHWORM

The adoption of conservation tillage (CT) has increased worldwide over the past few decades. Weeds may become a problem, both in no-tillage systems and in reduced tillage systems (Zarea 2010). In Norway, Tørresen and Skuterud (2002) showed that both post-emergence herbicide and glyphosate application were necessary to control different weed groups when tillage was reduced. Over 95% of weed control is achieved by broad spectrum herbicides like glyphosate and glufosinate, which is a level not attained by their traditional counterparts (Westwood 1997).

Under no-tillage (NT), weed seeds are no longer distributed throughout the soil profile but tend to accumulate in the topsoil layer. Densities of weed populations may increase because most weed seeds are in a condition favoring germination (Zarea 2010). The large quantity of plant residue left on the soil surface may affect the performance of herbicides by intercepting up to 70% of the active ingredients (Sadeghi *et al.* 1998). NT has been shown to increase bulk density, lower total porosity and penetration resistance of soil. Many studies have demonstrated the important role that earthworm burrows play in affecting infiltration and runoff in agricultural soils (Zarea 2010).

Tillage increases the bioavailability of chemicals that have been sequestrated in soil aggregates. Without tillage, herbicide degradation may be decline. Radosevich *et al.* (1997) found without tillage, atrazine degradation decline and atrazine became unavailable because of soil sequestration. Earthworm borrows enhance leaching of herbicide. However, Larsbo *et al.* (2009) showed that reduced tillage (RT) has the potential to reduce pesticide leaching. The presence of the earthworm *L. terrestris* L., doubled the leaching rate of herbicides in soil, clearly demonstrating enhanced preferential flow resulting from presence of earthworm burrows (Farenhorst *et al.* 2000). Conventional or traditional tillage (TT) is generally considered to reduce pesticide leaching in soils where preferential flow and transport is significant (Isensee *et al.* 1990; Elliot *et al*. 2000) by cutting continuous macropores that may act as preferential flow paths in RT and NT soils (Edwards *et al.* 1988). No-till soil often shows higher pesticide concentrations in percolate, shallow groundwater or drainage than tilled soil (Isensee *et al.* 1990; Kanwar *et al.* 1997; Masse *et al*. 1998; Elliot *et al.* 2000). The reason(s) for this, however, are uncertain. Possibly, tillage completely destroys macropores, changes macropore properties (more or less macropores, change in tortuosity, change in macropore continuity, etc.) and/or changes soil matrix soil properties (e.g., change in soil matrix hydraulic conductivity) (Malone *et al.* 2003). Malone *et al.* (2003) reported that differences in soil properties other than macroporosity such as a lower soil matrix saturated hydraulic conductivity and porosity in subsurface soil (8–30 cm) can cause percolate to occur sooner through macropores on NT than on moldboard plowed and cause higher herbicide concentrations in percolate on NT, even when macro does not differ between till and no-till.

The herbicides are more highly sorbet in high moisture soil. TT has been reported to increase pesticide leaching compared to NT and RT (Gish *et al.* 1995; Sadeghi *et al.* 1998) or have insignificant effects (Gaynor *et al.* 1995). In cases where TT increased leaching, this was attributed to weaker sorption due to lower soil organic carbon content (Sadeghi *et al.* 1998) or slower microbial degradation (Gish *et al.* 1995) although no direct measurements of sorption strength or degradation rates were reported (Larsbo *et al.* 2009). Soil microorganisms are normally most active where optimum moisture exists (Brock *et al.* 1994). Humidity seems to favor degradation and volatilization of the chemical in the soil (Klein 1989). Crop residue on the soil surface reduces soil temperature and increases soil moisture (Van Wijk *et al.* 1959; Chaudhary and Prihar 1974). If soil moisture is enchased in soil, maybe herbicide degradation festered. The high temperature and humidity seem to favor degradation and volatilization of the chemical in the soil (Klein 1989). On the other hand, humid and warmer conditions might enhance the toxicity of some pesticides by increasing the penetration through the skin of animals, and these might be taken up more quickly by tropical biota (Viswanathan and Murti 1989).

Tillage effects on sorption have been studied by Gaston *et al.* (1996) who found no differences in bentazone sorption strength between TT and NT soils. Tillage effects on degradation have been studied by Gaston *et al.* (1996), Otto *et al*. (1997), and Zablotowicz *et al*. (2007). Otto *et al.* (1997) found NT effects on isoproturon dissipation rates while Gaston *et al.* (1996) reported faster degradation of bentazone in the top 10 cm of TT plots compared to RT plots and Zablotowicz *et al.* (2007) reported faster degradation of fluometuron at the 2–10 cm depth in TT compared to NT soils. It has been suggested that the degradation rate of pesticides should be related to the microbial activity of the soil (Kah *et al.* 2007; Borggaard and Gimsing 2008). Stenberg *et al.* (2000) showed that, for RT, both the organic carbon content and the microbial activity were higher in the soil layer affected by shallow tillage activities compared to the soil layer just below the depth of shallow tillage while there were no differences in microbial activity and organic carbon content between the two depths for CT. Larsbo *et al*. (2009) sorption was stronger and degradation was faster in the top five centimeters in RT systems where the soil organic carbon contents generally were higher. This shows that RT has the potential to reduce pesticide leaching (Gish *et al.* 1995; Sadeghi *et al.* 1998).

Fox (1964) found that earthworm numbers decline after atrazine applications, not due to toxicity, but because the vegetation cover is reduced by herbicide use. Binet *et al.* (2006) suggested that earthworm (*L. terrestris* and *Aporrectodea calignosa*) activity would promote atrazine mineralisation by altering the size and diversity of microbial communities. Farenhorst (2003) fond that earthworm weight with corn residues increased in spite of all atrazine dose. Earthworm biomass was less affected by herbicide application rates relative to crop management (Tomlin *et al.* 1995) and crop residues (Farenhors 2003). Farenhors (2003) reported that Earthworms more affected by the kind of crop residue than by herbicide rates. In no-till weight of earthworm biomass and numbers are less affected by herbicide application and more depend on kind of crop residue. However, Edwards and Bohlen (1996) reported that Earthworms numbers increase after herbicide application as the result of an increasing availability of dead plant material at the soil surface. It is well-known (e.g. Holmstrup 2000), that due to surface activity anecics like *L. terrestris* will be exposed to high concentrations of pesticides on the soil surface while searching for food, etc. (Laitinen *et al.* 2006).

The high temperature and humidity seem to favor degradation and volatilization of the chemical in the soil (Klein 1989). Thereby, may humid and warmer conditions might enhance the toxicity of some pesticides by increasing the penetration through the skin of animals, and these might be taken up more quickly by tropical biota (Viswanathan and Murti 1989). However results from Römbke *et al.* (2007) showed that the effects of benomyl were, on average, lower under tropical conditions (LC_{50}: 450–630 mg active ingredient (a.i.)/kg; EC_{50}: 0.8–12.9 mg a.i./kg) than under temperate conditions (LC_{50}: 61–67 mg a.i./kg; EC50: 1.0–1.6 mg a.i./kg). In a higher temperature might higher number and growth of micro-organisms more rapidly degradation the chemicals in soil and thereby enhanced the toxicity of some pesticides.

The effect of tillage on earthworm abundance is usually negative because of physical damage and adverse environmental conditions caused by the burial of residues (Zarea 2010). Conservation tillage, which leaves crop residues on the soil surface as a food source for soil biota, may encourage earthworm populations (Zarea 2010). Schmidt *et al.* (2003) and Chan (2004) demonstrated that both absence of tillage and an increased food supply were necessary for a significant increase in earthworm numbers. In many studies, absence of tillage has been found sufficient to increase the population of *L. terrestris* (Edwards and Lofty 1982; Nuutinen 1992; Edwards and Shipitalo 1998; Pitkänen and Nuutinen 1998; Chan 2001). Significant increases in earthworm numbers have occurred even 2–3 years after turning intensively cultivated field into pasture (Haynes *et al.* 1995). Schmidt *et al.* (2003), in turn, demonstrated that absence of tillage is not enough to increase earthworm numbers significantly when a lack of food is limiting their growth. Earlier, Lofs-Holmin (1983) had concluded that a yearly supply of crop residues is needed to promote earthworm activity.

Some researchers have examined the option of using herbicides at less than recommended rates. There are some good indications of potential for reducing herbicide rates (Lundkvist 1997; Fernandez-Quintanilla *et al.* 1998; Navarrete *et al.* 2000; Boström and Fogelfors 2002; Barros *et al.* 2008). Weeds may often be satisfactorily controlled when herbicides are used at lower doses than those normally recommended while maintaining satisfactory crop yield (Steckel *et al.* 1990; Hamill and Zhang 1995; Fernandez-Quintanilla *et al*. 1998; Navarrete *et al.* 2000).

Moomaw and Burnside (1979) reported that weed control and soybean yield did not significantly differ between 0.5× and 1.0× rates of preplant-incorporated or pre-emergence herbicide systems in use at that time. Bradley *et al.* (2001) showed that adequate weed control and soybean yields were maintained using reduced rates (0.5×) of herbicides (mix of glyphosate plus 2,4-D). Barros *et al*. (2008) showed that lower herbicide doses than those recommended by the manufacturer were sufficient to achieve a high *Avena sterilis* L. and *Lolium rigidum* G. control efficiency in no-till wheat under Mediterranean environment. When the herbicide application was delayed (complete tillering) it was necessary to increase the herbicide dose in order to achieve the highest grain yield (Barros *et al.* 2008). Prostko and Meade (1993) and Steckel *et al.* (1990) found that, although weed control was less effective in reduced-rate post emergence treatments, soybean yields from these treatments were equal to yields from full-rate treatments. Defelice *et al.* (1989), however, found that single applications of reduced-rate post emergence herbicides in soybean resulted in less weed control and lower yields than from full-rate treatments, but there is need for more confirmation with current herbicides. Evaporation of stored soil moisture is reduced by residue crop which can enchase soil microorganisms in soil, and thereby maybe increase degradation herbicide. No-till spring cropping is proposed as an alternative to traditional winter wheat *Triticum aestivum* L./dustmulch fallow (WWF) on agricultural lands in the semi-arid (<300 mm year^{-1}) Columbia Plateau region of the Pacific Northwest. The results from Young and Thorne (2004) show that weed management within no-till spring crop and (WWF) rotations can significantly reduce weed population density in the semi-arid region of the Pacific Northwest USA.

WEED MANAGEMENT STRATEGIES TO REDUCE HERBICIDES APPLICATION IN NO-TILLAGE SYSTEMS AND IN REDUCED TILLAGE SYSTEMS

Fertilizer and herbicides are major input costs in any cropping systems worldwide (Raun and Johnson 1999; Derksen *et al.* 2002). Farmers are cognizant of these costs and thus are interested in alternative approaches to supplying crops with nutrients and to managing weeds. Managing for increased competitive ability of crops with weeds is an important means of achieving improved weed management programs (Liebman *et al.* 2001). Integrated weed management systems have the potential to reduce herbicide use (and associated costs) and to provide more robust weed management over the long term (Swanton and Weise 1991).

In NT and in reduced tillage systems, weeds are often recognized as the most serious threat to crop production. An alternative to herbicides is the use of cover crops, which can suppress the growth of weeds by competition for light (Teasdale and Mohler 2000), soil moisture and nutrients (Barberi 2002), and by producing allelopathic compounds (White *et al.* 1989; Reberg-Horton *et al.* 2005). Cover crops are useful tools for weed control in vegetable cropping systems (Ngouajio and Mennan 2005). The ability of cover crops to suppress weeds depends on many factors and residues of some cover crops have selective effects on weed species (Putnam *et al.* 1983; Barnes and Putnam 1987; Weston 1990; Teasdale 1996; Nagabhushana *et al.* 2001). Crop rotation including both spring-sown and autumn-sown crops is an important management tool to control weeds. For example inclusion of a spring-sown crop will suppress winter annuals, while autumn-sown crops will suppress summer annuals (Melander *et al.* 2005). One of the most successful systems is the use of cereal and/or legume cover crops for physical and allelopathic weed control (Teasdale 1996; Ngouajio and Ennan 2005; Mennan *et al.* 2006; Norsworthy *et al.* 2007; Isik *et al.* 2009). Isik *et al.* (2009) confirm that hairy vetch, ryegrass, rye, and common vetch can be used to reduce weed emergence in organic pepper production.

Manipulation of crop fertilization is a promising agronomic practice in reducing weed interference in crops (Di Tomaso 1995). Fertilization alters soil fertility, which affects not only crop growth but also composition and growth of associated weeds (Banks *et al.* 1976; Pysek and Leps 1991; Mountford *et al.* 1993; Theaker *et al.* 1995; Jørnsgård *et al.* 1996; O'Donovan *et al.* 1997).

Nitrogen (N) is the major nutrient added to increase crop yield (Raun and Johnson 1999; Camara *et al.* 2003) but it is not always recognized that altered soil N levels can affect crop-weed competitive interactions. Nitrogen fertilizer, as well as fresh and composted manure, can affect weed germination and establishment (Egley and Duke 1985). Many weeds are high N consumers (Qasem 1992; Hans and Johnson 2002), thus limiting N for crop growth. Weeds not only reduce the amount of N available to crops but the growth of many weed species also is enhanced by higher soil N levels (Supasilapa *et al.* 1992; Blackshaw *et al.* 2003). Research has shown that crop–weed competitive interactions can be altered by N dose (Cathcart and Swanton 2003), source (Davis and Liebman 2001), application timing (Angonin *et al.* 1996), and application method (Kirkland and Beckie 1998; Mesbah and Miller 1999), indicating that many agricultural weeds are equally or more responsive than crops to higher soil N levels (Lintell-Smith *et al.* 1992; Supasilapa *et al.* 1992; Blackshaw *et al.* 2003, 2005). The organic system had a greater aboveground weed biomass at harvest compared to other systems (Poudel *et al.* 2002). The lower potential risk of N leaching from lower N mineralization rates in the organic and low-input farming systems appear to improve agricultural sustainability and environmental quality while maintaining similar crop yields (Poudel *et al.* 2002).

Soil available P affects the weed community more than N and K (Yin *et al.* 2005). Yin *et al.* (2005) showed that changes in the weed community composition were first due to soil available P, followed by light intensity on soil surface. Nutrient source whether of organic or chemical origin had little influence on weed community composition (McCloskey *et al.* 1996).

CONCLUSION

Environmental concern has arisen from potential negative impacts of herbicides on non-target organisms, beneficial species, spray drift of residues in food, ground water contamination, weed resistance and poisoning hazards, especially mammalian toxicity (Schroeder *et al.* 1993; Kropff and Walter 2000). As people learn more about possible adverse effects of herbicide exposure, they become more interested in alternative farming systems. Because of these potential problems and increased public pressure on conventional agriculture, there is increasing interest in organic farming systems (Isik *et al.* 2009). Earthworms affect by herbicide. Herbicides in general show low toxicity towards earthworms, although there are some exceptions.

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