MECHANICAL WEED CONTROL IN

CONSERVATION TILLAGE

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of SUZANNE KOPAN find it satisfactory and recommend that it be accepted.

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Chair

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Abstract

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The Northwest Wheat and Range Region is recognized for dryland production of spring and winter wheat, barley, dry peas, lentils, and chickpeas. Although the climate and soil characteristics enhance crop production, most soils are highly susceptible to wind and water erosion. Conservation tillage (CT) reduces soil loss on cropland by retaining crop residue on the soil surface and minimizing deep tillage. Reduced tillage, however, has resulted in a greater dependence on herbicides for weed control, which increases the risk of developing herbicide resistant weeds, and CT promotes soilborne root-infecting fungal pathogens, such as Rhizoctonia root rot. This research investigated the potential use of a pre-plant rotary harrow in conjunction with a high-residue rotary hoe for in-crop weed control and shallow tillage in a CT system. We hypothesized that the tools would enable mechanical weed control without compromising the benefits associated with CT and would reduced the prevalence of Rhizoctonia root rot. The primary objective was to evaluate a Phoenix[1] rotary harrow prototype, pre-plant glyphosate application, and an M&W[2] Minimum Tillage rotary hoe on crop density, weed cover, weed biomass at maturity, and crop yield. It was concluded that despite weed reductions, mechanical weed control with the harrow and hoe is less optimal than chemical control because of low

[1] Phoenix Rotary Equipment Ltd., Nisku, AB, Canada
[2] M&W Gear, Gibson City, IL

efficacy at high weed pressures. The secondary objective was to quantify changes in a population of *Rhizoctonia solani* in response to soil disturbances near the surface of intact soil cores, but results were not obtained because of low inoculation density.

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This thesis is dedicated to my father

whose heart has still to love

CHAPTER ONE

CONTROL OF WEEDS AND DISEASE WITH TILLAGE EQUIPMENT SUITABLE FOR DRYLAND CONSERVATION TILLAGE CROPPING SYSTEMS

INTRODUCTION

The Northwest Wheat and Range Region (NWRR; US Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS), 2006) contains some of the most productive dryland cereal grain and grain legume cropland in the US (Schillinger et al., 2003). The region is recognized for its spring and winter wheat production, but barley, dry peas, lentils, and chickpeas are also important crops in some parts of the region. Soil and weather conditions vary within the NWRR, but areas in dryland crop production are similar in that soils are fine-textured and well-drained and winters are usually wet with mild temperatures. Although these characteristics enhance cereal and legume production, most soils in the NWRR are highly susceptible to wind and water erosion.

Conservation tillage (CT) reduces soil loss on cropland by retaining crop residue on the soil surface and minimizing deep tillage. Reduced tillage has resulted in a greater dependence on herbicides for weed control, which increases costs and the risk of developing herbicide resistant weeds. In addition, reduced tillage and surface residue promote soilborne root-infecting fungal pathogens, such as Rhizoctonia root rot. This research investigated the potential use of a preplant rotary harrow in conjunction with a high-residue rotary hoe for in-crop weed control. We hypothesized that surface tillage will enable us to mechanically control weeds and reduce the prevalence of soilborne diseases without compromising the benefits associated with a mulch tillage system.

THE NORTHWEST WHEAT AND RANGE REGION

The NWRR is one of 28 land resource regions found in the lower 48 states (Figure 1.1). The region, which makes up 210,555 square kilometers, is in Idaho (44%), Washington (29%), and Oregon (27%) with a very small part in Utah (USDA-NRCS, 2006). Flanked by the Cascade Mountains and the Bitterroot Range of the Rocky Mountains, the NWRR is also referred to as the Inland Empire (Martin, 1938), Inland Pacific Northwest (Camara et al., 2003; Schillinger et al., 2003), or the wheat-growing region of the Pacific Northwest.

Geologic History

The cataclysmic floods from glacial Lake Missoula had the greatest geologic impact on the NWRR (reviewed by Norman et al., 2004). During the last Ice Age between 1.81 million to 11,550 years ago, the northern parts of Washington, Idaho, and Montana were covered by an ice mass, known as the Cordilleran ice sheet. As temperatures began to rise, the ice sheet melted into numerous glacial lakes, dammed by large ice fragments. The largest of these ice dams, located on the Clark Fork River near the Idaho-Montana border, created glacial Lake Missoula (Figure 1.2). The lake held 2,500 km^3 of water and was 7,800 km^2, roughly the size of present-day Lake Huron, the third largest freshwater lake in the world. Temperatures continued to rise, and the ice dam holding Lake Missoula failed repeatedly during the last Ice Age, triggering more than 40 massive flood events in the Columbia River Plateau around 18,000 and 15,000 years ago.

Prior to the flood events, windblown materials, called loess, had accumulated across the Columbia River Basin, covering much of the underlying igneous bedrock. The loess, composed of fine sand and silt particles, was blown from the south and southwest during interglacial and interstadial periods since at least 2 million years ago (Busacca, 1991; Busacca and McDonald, 1994). Floodwater pathways carved deep valleys into the landscape, removing the loess and exposing the underlying basalt. Run-off material, left by draining floodwaters provided additional sources of loess, some of which was redeposited to nearby areas (Sweeney et al., 2004). Present-day soils can be as deep as 76 m in areas not eroded by floods, whereas soils can be thinner than 1 m in areas eroded by the floods (Busacca, 1989).

Climate of Dryland Production Areas

The rain shadow from the Cascade Mountains creates a precipitation gradient across the inland Pacific Northwest and divides the region into three precipitation zones. The low precipitation zone receives 150 to 300 mm of mean annual precipitation (MAP) is located on the western edge of the Columbia Plateau and includes much of the Eastern Idaho Plateau (Schillinger et al., 2003). The driest production areas in the low precipitation zone can have a MAP as low as 111 mm in some years, and still produce a harvestable crop (Schillinger and Young, 2004). More than 80% of the MAP occurs between October and March from low-intensity storms (< 2.5 mm hr^{-1}) as rain in fall and spring and as rain or snow in winter (McCool et al., 1978; USDA-NRCS, 2006). The mean annual temperature is 8 to 12ºC in most of the low precipitation zone, and the freeze-free period averages 190 days (USDA-NRCS, 2006).

The intermediate precipitation zone (MAP of 300 to 460 mm) is located on the eastern boundary of the Columbia Plateau and includes much of north-central Oregon (Schillinger et al., 2003). About 80% of the MAP occurs between October and March from low-intensity storms as rain in fall and spring and as rain or snow in winter. The mean annual temperature in the intermediate zone is 8 to 12ºC with cool winters and warm summers, and the freeze-free period averages 190 days and ranges from 130 to 245 days (USDA-NRCS, 2006).

The high precipitation zone (MAP of 460 to 610 mm) is located in the Palouse and Nez Perce Prairies and follows the Idaho-Washington border to the Bitterroot Range in northern Idaho (Bailey, 1995; Schillinger et al., 2003). Little precipitation occurs in summer. The MAP for Pullman, Washington, for example, is 453 mm, but rainfall in July and August averages less than 24 mm. About 60% of the MAP in the high precipitation zone occurs from October to April. Winter precipitation, primarily snow, occurs during low-intensity storms, producing occasional rains that fall on frozen or thawing soil. High-intensity thunderstorms (>10 mm hr^{-1}) can occur during the growing season, but do not significantly contribute to the annual precipitation (McCool et al., 1978; USDA-NRCS, 2006). The mean annual temperature is 8 to 12ºC in the lower altitudes with an average freeze-free period of 165 days (USDA-NRCS, 2006).

Soil Orders Associated with Dryland Crop Production

Soils are classified according to common chemical, physical, and biological properties, which reflect the major course of soil development (Brady and Weil, 2002). Within the hierarchy of soil taxonomy, there are 12 soil orders, 10 of which are found in the NWRR and two of which are found in areas with dryland production (USDA-NRCS, 2006). In most cases, Entisols and Mollisols are associated with a climatic region of a particular moisture and temperature regime.

Entisols are less desirable for dryland crop production. They show little to no soil development and have properties similar to their parent materials: fine-grained sand and silt loess (Brady and Weil, 2002). Found in the low and intermediate precipitation zones, the scarcity of water and vegetation inhibits soil formation. Though these soils are low in fertility, crop production is enabled by adequate storage of winter precipitation (Schillinger et al., 2003).

Mollisols, found in the high and intermediate precipitation zones, are more valued for agricultural production. Known as the soil order of grassland plant communities, they formed from the accumulation of calcium-rich organic matter, largely from the root systems of grasses, and have a thick, dark surface horizon. The surface or A horizon is often 60 to 80 cm in depth, high in calcium and magnesium, and has a cation exchange capacity 50% or more saturated with base cations (Brady and Weil, 2002). These soil properties give Mollisols a naturally high fertility. Below the A horizon, Mollisols have a clayey B horizon, which often has a high water-holding capacity but poor drainage and aeration. Thus, Mollisols with a well-developed B horizon can retain soil moisture for sufficient crop growth.

DRYLAND CROP PRODUCTION IN THE NWRR

Soil Erosion in the Palouse

Soil erosion on cropland can be caused by natural forces, such as wind and water, or by mechanical tillage. Wind erosion is of greater concern in the low and intermediate precipitation zones, whereas, water erosion causes most of the soil loss in the high precipitation zone (Papendick, 1996). The USDA estimated in 1978 that water erosion over the last 100 years has removed all of the original topsoil from 10% of Palouse cropland and has removed ¼ to ¾ of the original topsoil from 60% of the cropland (USDA, 1978).

Water erosion is a four-stage process, initiated by raindrops, that involves the detachment of soil particles, disintegration of aggregates, transport and redistribution of sediments, and deposition in depressions or aquatic ecosystems (Lal, 2003). The energy of falling raindrops causes sand (0.05-2.0 mm), silt (0.002-0.05 mm), and clay (<0.002 mm) particles to detach and fill large pore spaces (Soil Survey Division Staff, 1993). In addition, soil aggregates disintegrate by slaking when immersed in water, resulting in a release of encapsulated carbon and exposure to microbial decomposition (Lal, 2003). Particle detachment and aggregate disintegration form an impermeable crust on the soil surface, which restricts water infiltration (McIntyre, 1958; Mott et al., 1979) and eventually leads to ponding. Accumulated water can move downhill, transporting sediments and further eroding the soil surface.

The silty loam Mollisol soils of the Palouse have an inherent capacity for water erosion. Among the types of soil particles, silt more readily detaches from the soil surface because of its small size (Zhang et al., 2005), thus soils with a high silt and very fine sand content are more prone to soil erosion (Brady and Weil, 2002). Soil organic matter can reduce particle detachment and aggregate disintegration (Oades and Waters, 1991), but as much as 50% of the organic matter content has been lost on cropland in the Palouse during the past 125 years (Stark et al., 1950; Burke et al., 1995; Schillinger et al., 2003). The topography of the Palouse hills also contributes to water-induced rill or inter-rill erosion. Most slopes range from 8 to 30%, but production can take place on slopes greater than 45% (Papendick, 1996). As water and sediment move down the hills, they create narrow channels, called rills. Rill or inter-rill erosion (erosion between irregularly spaced rills) is especially common on bare soil, whether it is newly planted or in fallow. Spring tillage can mask rill development but does not reduce soil erosion.

Tillage erosion, which is caused by tillage implements and results in the downhill redistribution of soil, causes soil loss and deposition on sloping terrain. Kaiser (1961) measured about 1.2 m of soil loss from ridgetops over a 48-year period (1911-1959), and Papendick and Miller (1977) noted 3 to 4 m high soil banks above and below permanent field borders as a result of repeated downslope plowing. Variation in physical soil properties and crop yield potential occur along sloping cropland, but it is unclear as to what extend tillage erosion is responsible (Montgomery et al., 1999) because water causes most of the soil erosion in the Palouse.

Water erosion is most severe in the winter and early spring on frozen or thawing soil (Zuzel et al., 1982; Ramig et al., 1983; McCool et al., 1995). During freezing, water moves from deeper soil layers to the frozen zone, frequently resulting in frost heaves and soil pore expansion, whereas, a period of warm temperatures causes frozen soil to thaw, saturating it with water near the surface. Soils in the Palouse undergo more than 120 freeze-thaw cycles in an average winter (Hershfield, 1974). When rainfall or snowmelt occurs under frozen or thawed conditions, water cannot infiltrate the soil and begins to move sediment downhill, however, runoff and erosion may result solely from thawing soil and snowmelt (Greer et al., 2006). Whether erosion is caused by water or tillage, the loss of topsoil exposes clayey subsoil, which has reduced soil fertility and crop productivity (Mulla and Pierson, 1990; Papiernik et al., 2005)

Surface residue protects soil from water-induced soil erosion. Primarily, it dissipates the energy of raindrops, thereby preventing particle detachment and aggregate disintegration (Unger, 1990; Langdale et al., 1992). Thus, more water is able to infiltrate the soil profile when crop residue is left on the soil surface than when it is removed or incorporated (Bussière and Cellier, 1994; Baumhardt and Lascano, 1996). Surface residue, as well as natural or planted vegetation and crops, also retards the flow of water and allows more time for water to infiltrate the soil profile (Mott et al., 1979; Kemper et al., 1992; Leite et al., 2004). As little as 30% residue cover can reduce interrill erosion by 80% (Brady and Weil, 2002).

Few studies have noted the effects of surface residue on freeze-thaw cycling. Residue helps reduce soil freezing and freezing depth, which can prevent water saturation at the surface of thawing soils (Vomocil et al., 1984; McCool et al., 2000; Flerchinger et al., 2003). Surface residue also reduces heat loss at night and air movement near the soil surface (McCool et al., 2000), which further prevents soil freezing. In addition, different types of residue and its placement within the soil may have a varying effect on heat and water loss. Flerchinger et al. (2003) found that bare soil had the highest evaporation among four study sites and wheat residue, when lying flat, generally had the lowest evaporation. Standing residue, however, may be preferred because it was found to retain heat by 5ºC five to nine days earlier than bare soil and flat residue. Nonetheless, maintaining residue on the surface is most effective in reducing water erosion.

National efforts to reduce soil erosion on cropland were enacted with the Federal Agriculture Improvement Act of 1985 (1985 Farm Bill). The 1985 Farm Bill sought to reduce soil erosion through two methods. It removed highly erodible cropland from production through the Conservation Reserve Program (CRP) and mandated residue management practices on cropland susceptible to soil erosion, mainly through the adoption of conservation tillage (CT) practices. There was a little more than 0.8 million ha in the CRP in 1986, but by 2005, that area had grown considerably to more than 15 million ha (USDA-Farm Service Agency (FSA), 2006). In 1990, about 29.6 million ha were in CT, but within a decade that amount had increased by almost 50% (Conservation Technology Information Center (CTIC), 2006). By reducing crop production on highly erodible land and adopting conservation practices, soil loss on cropland decreased by 39.2% from 1982 to 2003 (USDA-NRCS, 2006).

To date, 40% of US cropland is in CT, but adoption in the NWRR is less than 10% in some areas (CTIC, 2006). More than six decades of scientific research in the Palouse has shown the benefits of CT on reducing soil erosion (Pubols et al., 1939; Horner et al., 1944; Taylor and Baker, 1947), but for a CT system to be economically successful it should maintain reasonable production costs, provide a profitable and stable income flow, and have adequate weed, disease, and insect control (Young et al., 1999).

Adoption of this new technology has been limited by the complexity of CT practices and the individuals adopting the new technology (Carlson and Dillman, 1999). Adoption of some conservation practices, such as contour planting and divided-slope farming, are compatible with existing farm practices and relatively easy to implement. Conservation tillage, however, requires a complex cropping system that causes many changes to existing farm practices. In addition, producers are hesitant to adopt CT if they have little contact with other CT producers and lack information on CT technologies (Carlson and Dillson, 1999). Furthermore, those who have little interest in soil preservation are less likely to adopt CT practices, however, this explanation is confounded by the relationship between landlords and lessees (Carlson and Dillson, 1999). Producers are less likely to adopt CT practices when landlords contest such practices, regardless of their feelings on environmental issues.

Dryland Crop Production

Approximately 4 million ha of small-seeded cereal grains and grain legumes are produced under dryland conditions in the NWRR (Figure 1.2). Dryland, or rain-fed, agriculture refers to non-irrigated cropland that receives less than 610 mm of precipitation annually (Schillinger et al., 2003). Historically, the NWRR is recognized for its wheat (*Triticum aestivum* L.), dry pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.) production, but other cereal grains like barley (*Hordeum vulgare* L.) and grain legumes like chickpeas (*Cicer arietinum* L.) are also important to domestic grain production.

Soft white winter wheat is the most produced cereal grain in the NWRR (USDA-National Agricultural Statistics Service (NASS), 2006). When wheat is planted in the fall, called winter wheat, it yields about twice that of wheat planted in early spring, called spring wheat. Winter wheat yields in the NWRR can reach 4.9 t ha^{-1}, while national winter wheat yields range from 2.5 to 3.1 t ha^{-1} (USDA-NASS, 2006). The soft white wheat, mostly exported to Southeast Asia, is used to make flour for bakery products such as cakes, crackers, cookies, and pastries. The second-leading cereal grain is spring barley, which is mostly used for domestic animal feed. Between 2000 and 2005, barley production in Oregon, Washington, and primarily Idaho accounted for up to 34% of US production (USDA-NASS, 2006).

Since the 1990s, US grain legume production has been centered in the NWRR, but recent increases in production in other parts of the country have shifted dry pea and lentil production to North Dakota and Montana. Idaho and Washington accounted for 75% of US dry pea production in 1996, and the area planted to dry peas increased slightly over the next decade (USDA-NASS, 2006). On the other hand, dry pea production in North Dakota and Montana accounted for 85% of US production in 2005 (USDA-NASS, 2006). A similar trend occurred with lentil production. Idaho and Washington accounted for up to 90% of US lentil production before 1996, but accounted for only 25% in 2005 (USDA-NASS, 2006). The area planted to lentils in these states has remained constant, but production in North Dakota and Montana has increased 7 and 10-fold in a little over seven years, respectively (USDA-NASS, 2006). The increases in production in North Dakota and Montana were the result of the US Farm Security and Rural Investment Act of 2002 (FSRIA), which provided loan payments for the production of dry peas, lentils, and chickpeas (Skrypetz, 2006).

Idaho, Oregon, and Washington continue to be the top producers of chickpeas. Before 1997, production was limited to the California, Idaho, Oregon, and Washington with about half of US production outside of California (USDA-NASS, 2006). In 2005, Idaho, Oregon, and

Washington accounted for 58% of the US production, with 21% in California, and 21% in other states (USDA-NASS, 2006). Chickpea production in the other states, including North Dakota, continues to increase and renewal of the FSRIA in 2007 will most likely cause greater chickpea production outside of the NWRR (Skrypetz, 2006).

Cropping Systems

Dryland cropping systems in the NWRR also vary according to the precipitation gradient. Papendick et al. (1996) describes the common rotation sequences within each precipitation zone of the region (Table 1.1). Most cropping systems in the low precipitation zone are in a winter wheat-summer fallow rotation. This two-year rotation is also found in drier areas of the intermediate precipitation zone. Otherwise, a three-year winter wheat-spring barley-summer fallow rotation is preferred when precipitation is able to sustain spring cereal production. The cropping systems in the high precipitation zone are unique because they include legumes with winter and spring cereal production. In this zone, winter wheat is followed by spring peas or spring lentils in a two-year rotation, or winter wheat is followed by spring peas or spring lentils and spring wheat.

Conventional Tillage Systems

Tillage creates a suitable environment for crop growth and development. Soil disturbances indirectly encourage seed germination and root growth by providing suitable environmental conditions for microbial decomposition, which increases nitrogen availability, by incorporating crop residue and aerating the soil. Furthermore, soil disturbances control the growth and development of weedy plants by burying seeds, which can prevent germination, by uprooting emerging or established weeds and crop volunteers, and by causing physical damage to weedy plants. In addition, the disturbances cause physical harm to insect pests and burrowing animals, such as mice and voles. In conventional tillage systems, primary and secondary tillage operations are used for field preparation, leaving less than 15% of the soil surface covered by crop residue after planting (CTIC, 2006) (Figure 1.3).

Most cropping systems in the NWRR utilize moldboard plows, disk harrows, or chisel plows for primary tillage. Although the working depths of these implements vary, the moldboard plow generally causes the most intense soil disturbances. It cuts, lifts, and turns the furrow slice, called inversion tillage, and incorporates crop residue to a depth of 28 cm (Staricka et al., 1991), leaving 5 to 10% of the soil surface covered with residue after each operation (Hofman, 1997). Heavy-duty disk harrows, equipped with rotating, slightly concave disks, cut and mix soil and surface residue. Disk harrows typically bury the residue to a 10-cm depth (Staricka et al., 1991), and when equipped with 58 to 71-cm diameter disks, leave about 50% of surface covered after a single operation (Hofman, 1997). The distinct C or S-shaped shanks on the chisel plow shatter, break, and pulverize the soil without inversion tillage. This plow can operate near the soil surface or down to a 38-cm depth (Buckingham, 1976), while leaving up to 85% of the soil covered with residue after one operation (Hofman, 1997), depending upon the type of soil-engaging tool. When the disk harrow and chisel plow are equipped with larger disks and smaller sweeps, respectively, these implements retain a greater amount of surface residue after each operation (Table 1.2).

Soil and weather conditions dictate the use of the primary tillage implements. In the high precipitation zone, there is a sufficient amount of spring precipitation, which does not limit the use of the disk harrow and chisel plow, but the moldboard plow is preferred because it buries the most crop residue. With little residue remaining on the surface, planting equipment can easily move through soil without clogging and place seed at the appropriate depth for good soil to seed contact. On the other hand, the disk harrow and chisel plow are used for primary tillage in fall prior to winter wheat planting because they are more effective in hard, dry soils. Fall disking and chisel plowing are preferred in the continuous cropping systems of the intermediate precipitation zone, and the moldboard plow is the primary tillage implement in spring. Primary tillage is used to conserve soil water in cropping systems with summer fallow. During the fallow year, fall and spring tillage is used to facilitate soil water infiltration, whereas spring and summer tillage prevents soil water evaporation and promotes soil water storage (Schillinger, 2001; Schillinger and Young, 2004).

Secondary tillage, which cultivates the soil at shallower depths than primary or deep tillage, is used to break large clods, firm and level the soil, and control weeds. In the NWRR, secondary tillage is generally accomplished with field cultivators, medium and light-weight disk harrows, and rodweeders. A typical field cultivator will have several gangs of widely spaced shanks and a single bar attachment, such as a basket roller. The shanks, which operate at a 10-cm soil depth, break up large clods, while the attachment, which operates at a 5-cm soil depth, creates a level soil surface. When equipped with wide sweep blades, the field cultivator is more effective in controlling deep-rooted weeds such as Canada thistle (*Cirsium arvense* L.) and field bindweed (Buckingham, 1976). The disk harrows used for secondary tillage are usually lighter and more maneuverable than those used for primary tillage but function in the same manner. Rodweeders were one of the first secondary tillage tools exclusively designed for weed control (Timmons, 2005). It has a single, rotating bar, which uproots weeds and creates a dry, powdery soil surface above the seeding zone. More common in the lower precipitation zones, rodweeding is effective at sealing in soil moisture during fallow or prior to planting (Payne et al., 2000; Schillinger and Young, 2004).

The sequence of primary and secondary tillage operations varies considerably within each precipitation zone, but the greatest differences occur between cropping systems with and without summer fallow. For example, in the wheat-summer fallow rotation, eight or more tillage operations can occur during fallow, which includes primary tillage with a field cultivators or disk harrow and three to five operations with the rodweeder (Schillinger et al., 2003). In the continuous cropping systems of the intermediate precipitation zone, the chisel plow and disk harrow are used for primary tillage, and secondary tillage consists of two or three operations with a field cultivator and spring-tooth harrow. In fall, deep tillage with a chisel plow after winter wheat harvest is used to promote water infiltration and reduce winter soil loss. Fall chisel plowing also occurs in the high precipitation zone for soil conservation purposes, but moldboard plowing is preferred after winter wheat harvest to better manage the large amount of crop residue. Tillage in spring consists of moldboard plowing, disk harrowing, and chisel plowing, several operations with a field cultivator and disk harrow, and rodweeding or harrowing.

Conservation Tillage Systems

The general principle of CT is to maintain crop residue on the soil surface to reduce soil erosion. Unlike conventional tillage, CT leaves at least 30% of the soil surface covered by crop residue after planting (Soil Science Society of America (SSSA), 1997; CTIC, 2006) (Figure 1.3). Tillage systems that leave 15 to 30% of the surface covered by residue, called reduced tillage, may have similar primary and secondary tillage practices to CT, but at least 30% of the soil surface needs to be covered by residue to significantly reduce soil loss (Schertz and Bushnell, 1993; CTIC, 1997). Even though the term CT implies a certain percentage cover, residue can be maintained on the surface by a variety of methods.

No-tillage refers to tillage systems that are not cultivated from harvest to planting and exclude full-width tillage implements (CTIC, 2006). In other words, primary and secondary tillage practices do not occur, but when tillage does occur, it is only during planting. No-tillage systems also use modified planting equipment, which may involve residue disturbances and soil disturbances but only up to a third of the row width (CTIC, 2006). Nonetheless, no-tillage planters accommodate for a high amount of surface residue, unlike the planters used in conventional tillage systems, primarily so that the residue does not inhibit the placement of seed and fertilizer. These modifications include the addition of single or double disk openers or coulters, which cut into surface residue and enable good seed to soil contact (Erbach et al., 1983).

Full-width tillage implements are used in mulch-tillage systems prior to or during planting for primary and secondary tillage (CTIC, 2006). Crop residue is maintained on the surface after primary tillage operations with chisel and sweep plows. Like the chisel plow, sweep plows have an adjustable working depth and typically operate around a 10-cm depth. Equipped with long, thin blades, the sweep plow lifts and drops soil in a wave-like action to aerate the soil in the seeding zone without burying a large amount of surface residue (Table 1.2). Spike-tooth harrows, rotary harrows, and rotary hoes are used for secondary tillage in mulch-tillage systems. With shallow operating depths, these implements penetrate the soil to a 5-cm depth yet do little to bury surface residue.

Direct seeding is another term used to describe CT systems. Like no-tillage systems, direct seeding excludes primary and secondary tillage prior to planting (Veseth and Karow, 1999), however, some fall tillage is allowed to control immediate weeds problems, reduce soil moisture, and alleviate heavy clay soil conditions (Green, 1999). Nevertheless, most of the crop residue remains on the surface with at least half the stubble remaining upright and anchored to trap snow and conserve soil moisture (Green, 1999).

Descriptions of direct seed systems incorporate the number of field operations necessary to seed the crop and place fertilizer and the relative amount of soil disturbance caused by seeding equipment. For example, in a one-pass direct seed system, the crop is seeded and fertilizer is placed in one operation, whereas in a two-pass direct seed system, the crop is seeded and fertilizer is placed in two separate operations (Veseth and Karow, 1999). Low-disturbance planters, fitted with narrow knives or single or double disks openers, disturb less than 40% of the soil surface to form the furrow for seed placement, whereas high-disturbance planters, fitted with hoe or sweep openers, disturb more than 40% of the soil surface, sometimes disturbing the entire soil surface (Green, 1999). Basically, a one or two-pass, low-disturbance direct seed system is most similar to no-tillage.

Reducing Soil Erosion

Numerous studies have shown that CT reduces soil loss compared to conventional tillage. Soileau et al. (1994) conducted a 3-year study of sediment discharge into a watershed from no-tillage and conventional cotton production on a silt loam soil. Although the no-tillage system resulted in a higher proportion of annual rainfall as runoff than the conventional tillage system, the no-tillage system reduced sediment loss by 50%. The authors attributed most of the soil loss in the conventional tillage system to a few intense storms between late winter and early spring before closure of the cotton canopy. Under simulated rainfall conditions, Gaynor and Findlay (1995) reported a similar percent reduction of soil loss in no-tillage compared to conventional tillage on a clay loam soil, and Truman et al. (2005) measured at least two times less runoff and four times less soil loss in no-tillage compared to conventional tillage on a loamy sand soil.

WEED MANAGEMENT IN THE NWRR

Predominant weeds

Weeds are undesirable plants that interfere with the management of a production system. In general, they produce a large number of seeds, which may remain dormant in the soil seedbank for several years, exhibit great plasticity, and have specialized seed dispersal mechanisms. Moreover, they have the ability to invade recently disturbed areas and compete with crops for moisture, nutrients, and light. The most prominent weeds in the cropping systems of the NWRR are spring and winter annuals, although field bindweed (*Convolvulus arvensis* L.), a perennial, can also be a problem (Swan, 1980; Degennaro and Weller, 1984; Anderson, 1999).

Annuals mostly reproduce by seed, and in temperate climates with cold winters, these weeds are further distinguished as summer and winter annuals. Seeds of summer annuals germinate in spring or early summer, and plants emerge in the early part of the growing season, flowering and setting seed during the year of emergence (Håkansson, 2003). When seeds of summer annuals germinate in fall, young plants rarely survive the winter. Russian thistle (*Salsola iberica* (Sennen & Pau) Botsch. ex Czerepanov), common lambsquarter (*Chenopodium album* L.) and *Amaranthus* spp., including redroot pigweed (*A. retroflexus* L.), Powell amaranth (*A. powellii* S. Wats.) and smooth pigweed (*A. hybridus* L.), are some of the more common summer annual broadleaf weeds found in the NWRR (Holm et al., 1977; Weaver and McWilliams, 1980; Ogg and Dawson, 1984; Stallings et al., 1995; Schillinger and Young, 2000; Costea et al., 2004). In addition, the biology and phenology of wild oat (*Avena fatua* L.) contribute to its pervasiveness as a grassy weed in regional cropping systems (Muzik, 1970; Chancellor, 1976; Morishita and Thill, 1988; Cudney et al., 1991).

Seeds of winter annuals germinate in any season under suitable temperature and moisture conditions (Håkansson, 2003). Spring-germinating winter annuals flower and set seed like summer annuals, but those that germinate in late summer and fall survive the winter and flower and set seed in the following growing season. The most problematic winter annual weeds in the NWRR include prickly lettuce (*Lactuca serriola* L.), mayweed chamomile (*Anthemis cotula* L.), downy brome (*Bromus tectorum* L.), and jointed goatgrass (*Aegilops cylindrica* Host.), which are known for highly plastic growth and reproduction when in competition with agricultural crops (Rydrych, 1974; Mack, 1981; Marks and Prince, 1982; Thill et al., 1984; Grealy et al., 1985; Donald and Ogg, 1991; Mikulka and Chodová, 2003; Weaver and Downs, 2003; Schillinger, 2001; Stougaard et al., 2004). Soil tillage stimulates seed germination of many annual weeds, particularly if seeds are sensitive to light and soil gases and nutrients, as is the case for many winter annuals (Håkansson, 2003).

Integrated Weed Management

Integrated weed management (IWM) uses a combination of effective, environmentally safe, and sociologically acceptable control tactics to reduce weed infestations to levels below economic injury (Swanton and Weise, 1991; Thill et al., 1991). Consistently limiting weed control to one or two agronomic practices may be highly effective on a weed population for a relatively short period of time, but such control measures, acting as selective agents, only reduce a particular group of weeds within an entire community. On the contrary, it is more difficult for a weed community to adapt to a production system with dynamic selection pressures from a variety of weed control practices. Liebman and Gallandt (1997) describe an ideal IWM system where “many little hammers” are working together to reduce weed populations to acceptable levels. Such a program balances cultural, mechanical, and biological control practices with chemical control.

Numerous CT studies show the importance of crop rotation as an effective weed management practice (Blackshaw et al., 1994; Légère et al., 1997; Kegode et al., 1999). In a crop rotation study by Young et al. (1996), they found that a spring barley-spring pea-winter wheat rotation as opposed to continuous wheat production systems eliminated downy brome, a winter annual, in the spring crops and dramatically reduced the weed population in winter wheat, resulting in a more profitable cropping system. Rotation between spring and winter wheat is also useful for jointed goatgrass control because few post-emergence herbicides are available in wheat and delayed spring planting allows for non-selective, pre-plant herbicide applications (Young et al., 2003). As a cultural management practice, crop rotation may be more feasible in the intermediate and high precipitation zones, where winter rainfall does not limit crop production and rotation options.

Other cultural practices, such as paired-row planting, banded fertilizer application, and increased seeding rate and seed size, can be implemented to increase crop competitiveness and reduce weed populations (Young et al., 1999; Mesbah and Miller, 1999; O'Donovan et al., 2000; Xue and Stougaard, 2002). Kirkland et al. (2000), however, reported that increased seeding rates of wheat, barley, and lentils led to greater crop-to-crop competition, and concluded that reduced herbicide rates were a more effective alternative to reducing herbicide use.

Mechanical weed control practices are most often implemented as a partial replacement of chemical weed controls in CT. Swanton et al. (2002) reported similar levels of weed control in a no-tillage corn-soybean-winter wheat rotation with minimum and conventional management programs consisting of a pre-plant glyphosate application followed by shallow inter-row tillage and a pre-plant glyphosate application followed by a post-emergence herbicide application, respectively. They concluded that the minimum management level, which integrated mechanical and chemical controls, was the better option because gross returns did not differ with the treatments. Other studies in corn production systems showed that inter-row weed control with field cultivators caused reductions in herbicide applications (Mt. Pleasant et al., 1994; Buhler et al., 1995).

Biological weed control refers to the use of an organism as a control agent against a weed species or population of weeds (Müller-Schärer and Frantzen, 1996). The control agent can be a native or exotic plant, pathogen, or insect that provides protection for a continuous or limited time period. Legumes, for example, have been used as winter cover crops to reduce weed density and growth in no-till corn production (Fisk et al., 2001). Biological control with weed pathogens has also proven a feasible component of an IWM program (Charudattan, 2001). Rhizosphere-inhabiting bacteria, characterized as non-parasitic rhizobacteria, colonize plant root surfaces and can suppress growth and development (Kremer and Kennedy, 1996). Several weed-specific rhizobacteria, particularly *Pseudomonas* spp., have been shown to reduce the survival, growth, and reproduction of Canada thistle in soybeans (Hoeft et al., 2001; Gronwald, 2002), downy brome in winter wheat (Cherrington and Elliott, 1987; Kennedy et al., 1991), and velvetleaf (*Abutilon theophrasti* Medik.) in corn (Adam and Zdor, 2001). Many rhizobacteria are plant-specific (Kennedy et al., 1991), but seed predators can provide broad-spectrum control of weeds, reducing weed seed populations by as much as 32% (Cromar et al., 1999).

Chemical Weed Management

The use of chemicals for crop protection began after the Second World War with the commercialization of the selective broadleaf herbicides, 2,4-dichlorophenoxyacetic acid (2,4-D) in 1945 and 2-methyl-4-chlorophenoxyacetic acid (MCPA) in 1946 (Cobb and Kirkwood, 2000). Effective at low doses and inexpensive to manufacture, these herbicides stimulated the growth of the crop protection industry in Europe and North America. Currently, herbicides are available for all major crops, especially in Western Europe and the US, and recent estimates value the US market for crop protection herbicides at $4.25 billion (Gianessi and Reigner, 2006).

An herbicide is a chemical substance used to kill or control weeds, including crop volunteers and undesirable plants, by disrupting an essential physiological process. They are grouped according to their primary site of action, which, for many herbicides, is accomplished by binding to a single target protein, and according to chemical families of similar sites of action. The mechanism by which an herbicide kills a plant is known as its mode of action (MOA). For example, Group 1 herbicides inhibit the production of acetyl-coenzyme A carboxylase (ACCase), an enzyme used in the production of fatty acids, and include the cyclohexanedione and aryloxyphenoxypropanoate chemical families. However, not all weeds are controlled by Group 1 herbicides. In grasses, the physical properties of ACCase make these weeds susceptible, whereas ACCase in broadleaf plants is structurally different and tolerates applications (Sasaki et al., 1995). Thus, selection of the appropriate herbicide must consider the biology and phenology of the crop and weed species (William et al., 2005).

Table 1.3 describes in detail the specific modes of action and herbicide products used to control grassy and broadleaf weeds in the NWRR. Grassy weeds are selectively controlled in cereal grains mostly by herbicides in Groups 1, 2, and 8 and in grain legume crops and canola by herbicides in Groups 1 and 8. Broadleaf weeds are controlled in cereal grains with herbicides from Groups 2, 4, 6, and 14. Among these groups, most chemical control programs rely on herbicides in Group 2, the acetolactate synthase (ALS) inhibitors, and a limited number of herbicides from Groups 6 and 14 are used in the NWRR (personal communication, J. P. Yenish, WSU Extension). In addition, Group 7 herbicides, which inhibit Photosystem II but have a different binding behavior than Group 6 herbicides, are registered for use in winter wheat. Selectively controlling broadleaf weeds in peas, lentils, and canola is problematic because so few herbicides are available, but there are at least two modes of action registered for use in each of the crops that do not cause a significant amount of crop injury.

Pre-plant non-selective herbicides control grassy and broadleaf weeds without significant residual damage to the crop, or the herbicides can be used as a harvest aid late in the growing season. Non-selective control is provided by herbicides in Groups 3, 5, and 15, but glyphosate and paraquat are more commonly applied. Paraquat, a Group 22 herbicide, can be used in barley, winter peas, and chickpeas as a harvest aid and in winter wheat as a rescue treatment. Glyphosate, a Group 9 herbicide, can be used in barley, wheat, and herbicide-tolerant canola as a pre-plant and pre-emergence herbicide or, less frequently, as a harvest aid or rescue treatment in cereals and winter peas.

Herbicide Resistance

Herbicide resistance (HR) refers to the heritable ability of a weed to survive an herbicide application that would otherwise be lethal. When a single mechanism for HR confirms resistance across chemical families, it is called cross-resistance, whereas weeds with two or more distinct mechanisms for HR have multiple resistance (Heap, 1997). Herbicides do not directly cause HR but act as selective agents within a population of weeds (Jasieniuk et al., 1996; Diggle and Neve, 2001). In annual weeds several biological characteristics are favorable to the development of HR, such as prolific seed production, low seed mortality, and large populations, but, most herbicides are applied at rates that result in 90 to 99% weed mortality. Thus, the selection pressure imposed by the herbicide is the most important factor contributing to the development of HR within a weed population (Jasieniuk et al., 1996).

Rotating herbicide modes of action (Stanger and Appleby, 1989; Gronwald et al., 1989; Holt, 1992), use of less effective herbicides (Jasieniuk et al., 1996), and non-chemical weed control practices (Diggle and Neve, 2001) reduce the risk of developing HR. Rotating between herbicide modes of action delays the development of HR because selection for resistance is generally restricted to the growing seasons during which the herbicide is applied (Jasieniuk et al., 1996). Except for herbicides with long residual activity, the frequency of resistant weeds is unlikely to increase at a higher rate than that of susceptible plants during "herbicide-off" periods. Furthermore, the efficacy of the herbicide during "herbicide-on" periods affects the development of HR. In annual ryegrass simulation models, resistant weed biotypes accounted for 55% of the weed population after three generations with the use of highly effective herbicides, which controlled 99% of the population, but it took an additional three and seven generations for the resistant biotypes to reach this frequency when herbicides with 90 and 75% efficacy rates were applied (Jasieniuk et al., 1996). Although less effective herbicides delay the development of HR, the remaining weeds can replenish the soil seedbank and increase weed infestations.

Substituting cultural practices for herbicide applications also delays the onset of HR. During "herbicide-off" periods, the frequency of resistant weed biotypes does not increase and may even decline because most herbicide resistant weeds have reduced fitness levels (75%) relative to susceptible weeds (Jasieniuk et al., 1996). Besides implementing many of the non-chemical control practices previously discussed, Stone et al. (1999) suggested scouting fields for weed populations, which could result in reduced herbicide rates and smaller areas of applications.

Herbicide Resistance Potential in the NWRR

Herbicide resistance has been reported in many of the predominant weeds of the NWRR (reviewed by Heap, 2006). Herbicide resistant wild oat has been reported in only eight countries but is widespread throughout the cereal, legume, and canola production systems in Australia, Canada, and the US. Resistance to Group 1, 3, and 8 herbicides has been reported in the NWRR, and there are many populations of wild oat in Canada that are resistant to up to four modes of action (Beckie et al., 1999). Outside of Australia, wild oat is the most important species for developing HR. Herbicide resistant common lambsquarter has been reported in 18 countries, including the US, to Group 2, 5, and 7 herbicides, and the weed is considered the 4th most important species for developing HR. *Amaranthus* spp. are also known for developing herbicide resistance; redroot pigweed is among the most important species for developing HR, as well as the closely related smooth pigweed. Herbicide resistant redroot pigweed has been reported in 14 countries to Groups 2, 5, and 7 with multiple resistance in Germany and the US. Herbicide resistant prickly lettuce is not widespread, however, resistance to Group 2 herbicides is found throughout the NWRR. Likewise, Group 2 herbicide resistant Russian thistle is limited to Canada and the Northwestern US with widespread infestations throughout Idaho, Oregon, and Washington. Herbicide resistant downy brome has been reported in France, Spain, and the US to Group 2, 5, and 7 herbicides, and infestations in Oregon are increasing. Group 2 resistant mayweed chamomile has only been reported in Idaho, and the only report of herbicide resistant field bindweed was in Kansas in the 1960's to Group 4 herbicides, but the weed has shown varying responses to glyphosate (Degennaro and Weller, 1984).

Weed resistance in herbicide-resistant crops has been of increasing concern, especially in glyphosate-resistant cropping systems. Glyphosate was considered to be a low risk for developing HR weeds because the herbicide has little residual activity and no weeds had become resistant after extensive use (Heap, 1997). However, since the first glyphosate-resistant weed was identified under field conditions in 1996, glyphosate-resistant weeds have spread to soybean (*Glycine max* L.), corn, and cotton (*Gossypium hirsutum* L.) production and are widespread in some orchards and vineyards (Heap, 2006). In the US, glyphosate-resistant horseweed (*Conyza canadensis* (L.) Cronq) developed 3 years after the adoption of glyphosate-resistance soybean (VanGessel, 2001), and resistance continues to increase in other glyphosate-resistant crops in the eastern US. Glyphosate resistance in the western US is limited to roadsides, orchards, and vineyards (Heap, 2006), as a relatively small amount of cropland is devoted to corn and soybean production. The development of glyphosate-resistant wheat, initiated in 1997, was discontinued in 2004 mainly because of the opposition from US producers and oversea wheat importers (Stokstad, 2004). Nonetheless, imazamox-resistant wheat and canola varieties, developed though mutagenesis, has been developed for the NWRR. Rainbolt et al. (2004) noted that imazamox-resistant crops could increase Group 2 herbicide resistant weeds, especially if producers continued to utilize Group 2 herbicides.

Chemical weed control options become more limited when herbicide resistant weeds infest cropland. Producers can opt to apply older, less effective herbicides, but these chemistries may not be available or cost effective (Morrison and Devine, 1994; Shaner, 1995). Although industrialized agriculture discourages field burning and mechanical cultivation, these practices may be reconsidered with the onset of HR (Pannell and Zilberman, 2001). The external costs associated with field burning (i.e. reduced air and water quality) have led to strict legislative regulation (Steiner et al., 2006). Thus, it is doubtful that the practice will be implemented to control herbicide resistant weeds. The costs associated with mechanical cultivation, namely soil erosion, may pose a less obvious threat to non-crop areas, but water and wind erosion does, nonetheless, reduce the sustainability of crop production.

Soilborne Fungal Pathogens in Conservation Tillage

The soil and surface residue environments of CT systems promote certain soilborne root-infecting fungal pathogens. Residue provides a suitable over-wintering habitat for *Cephalosporium gramineum* Nisikado & Ikata, the cause of Cephalosporium stripe, and *Gaeumannomyces graminis* (Sacc.) Arx & D. Olivier var. *tritici* J. Walker, the cause of wheat take-all (Cook et al., 2000; Bockus and Shroyer, 2000). *C. gramineum* infects plant roots and systematically travels through the vascular system, causing the appearance of leaf stripes and restricting the transport of water and nutrients. Mycelia survive in diseased straw, and spores produced in fall and winter infect young crops in spring. Similarly, *G. graminis* var. *tritici* survives in diseased straw, and mycelia grow from residue to infect the roots and basal stem of young crops in spring, causing stunted growth, chlorosis of leaf and stem tissue, and reduced seed production.

Pythium root rot, caused by *Pythium* spp., is favored by increased soil moisture, a result of greater surface residue (Bockus and Shroyer, 2000). Although the pathogen produces sclerotia for long-term survival in soil, many *Pythium* species have motile spores, which swim through soil water to infect young crop roots. Symptoms of Pythium root rot include stunted crop growth with discolored, under-developed roots, chlorosis of leaf and stem tissue, and reduced seed production.

Rhizoctonia root rot was first diagnosed in a CT system in the NWRR in the late 1980s within a couple of years of adoption (Weller et al., 1986). The disease is favored by a reduction in tillage practices and is normally associated with spring cropping systems (Bockus and

Shroyer, 2000). Symptoms of Rhizoctonia root rot are commonly recognized as circular patches of stunted, chlorotic crops (Smiley and Wilkins, 1992). *Rhizoctonia solani* Kühn and *R. oryzae* Ryker & Gooch both play a role as disease agents, but it is generally thought that *R. solani* is of greater importance (Smiley and Uddin, 1993; Mazzola et al., 1996; Paulitz et al., 2002; Paulitz et al., 2003). Adequate control of Rhizoctonia root rot is limited because seed treatments and fungicides are ineffective under field conditions, and genetic resistance has not been identified in existing locally-adapted cereal cultivars (Smith et al., 2003). Cook et al. (2000) reported that disease severity can be reduced in CT systems when tillage disrupts soil within the crop rooting zone and fertilizer is placed below the seed.

CONCLUSIONS

Mechanical weed control is not common is conservation tillage systems, but considering the risk of herbicide resistance and possible control of Rhizoctonia root rot, it would be a valuable component within a spring crop production system. The rotary harrow is a suitable primary tillage tool because it loosens the soil in preparation for planting but does not completely bury crop residue, thereby enabling its use within a mulch tillage system. The tool also serves as a non-selective weed control against grassy and broadleaf weeds without increasing the herbicide resistant weed population. We hypothesized that the rotary harrow could be as effective in controlling weeds as a pre-plant glyphosate application.

On the contrary, the rotary harrow may promote weed growth and development by fracturing the soil surface, which enables greater soil-to-weed seed contact, and increasing available soil nitrogen through greater microbial decomposition. Germination could further be encouraged if the soil had a sufficient amount of moisture or if rotary harrow operations were followed by a sufficient amount of rainfall. In such cases, post-plant mechanical weed control would be needed after initial rotary harrow operations.

The rotary hoe is a suitable tool for pre-emergence and in-crop weed control in cropping systems which maintains residue on the soil surface. It provides non-selective control of grassy and broadleaf weeds without increasing the herbicide resistant weed population and could be used throughout the spring to control weed flushes. We hypothesized that the greater the number of rotary hoe operations, the more effective it could be in controlling weeds.

On the contrary, the rotary hoe may also be an ineffective weed control because of poorly timed operations. If spring rainfall followed a rotary hoe operation, then uprooted weeds would continue to grow and weed seeds could germinate. Therefore, rotary hoe operations should be timed so that rainfall does not occur within a couple of days of its use. Furthermore, the final rotary hoe operation should occur shortly before the crop has a well-established canopy, which reduces the competitive ability of young weeds for space, nutrients, and soil moisture against the spring crops.

The secondary objective of this research was to investigate the effect of tillage on soilborne root-infecting fungal pathogens in a conservation tillage system. In a controlled environment, which mimics a spring cropping system, soil disturbances can alter *Rhizoctonia solani* populations. Seeing that volunteer crops could provide a green bridge for infection, we hypothesized that soil disturbances could reduce *R. solani* populations, thereby controlling the spread of Rhizoctonia root rot in spring wheat.

On the contrary, soil disturbances may have no effect on disease infection. If the disturbances do not effectively break the hyphal network of *R. solani*, infection could occur even after weeds have been controlled with a systemic herbicide. Therefore, populations of *R. solani* would need to be measured throughout the soil profile. Furthermore, several disturbances may be needed to break the hyphal network of the pathogen before infection is reduced. Therefore, populations of *R. solani* would need to be measured after each disturbance. In addition, soil disturbances could increase disease infection because of crop injury. Injury sites on young plant roots could provide a suitable site for fungal penetration even if the pathogen population was reduced by soil disturbances. Therefore, crop roots would need to be evaluated for physical damage.

The results from this research will demonstrate the importance of the rotary harrow and rotary hoe for weed and disease control in a mulch tillage cropping system. The tools may be suitable replacements to chemical weed control practices or supplement existing IWM programs. Nonetheless, mechanical tillage tools could provide an effective, environmentally safe, and sociologically acceptable method of weed control in both conventional and conservation tillage systems.

Figure 1.1. Map of Land Resource Region B, the Northwest Wheat and Range Region with its relative location in the US (USDA-NRCS, 2006).

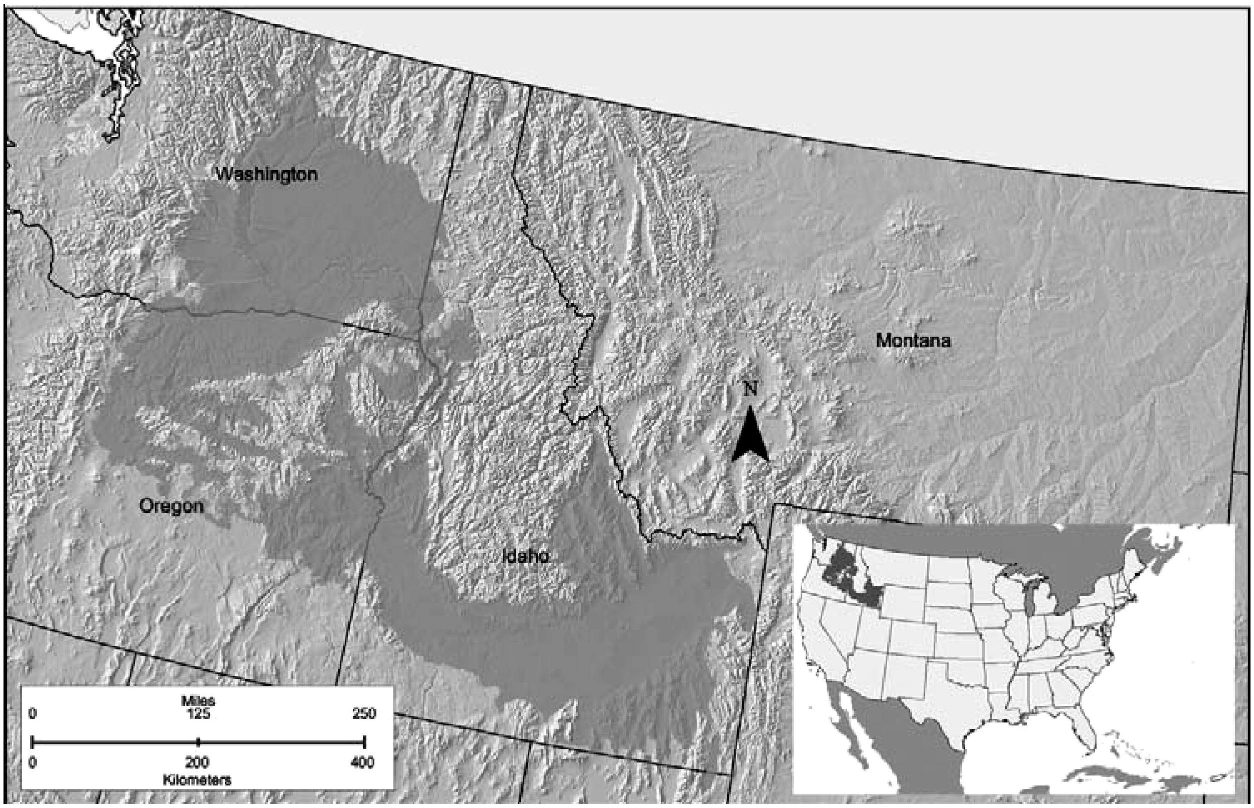

Figure 1.2. Loess distribution is shown in relationship to the Cordilleran ice sheet with the pathways of the glacial outburst floods and the prevailing southwesterly winds during the Last Glacial Maximum in North America (Sweeney et al., 2004).

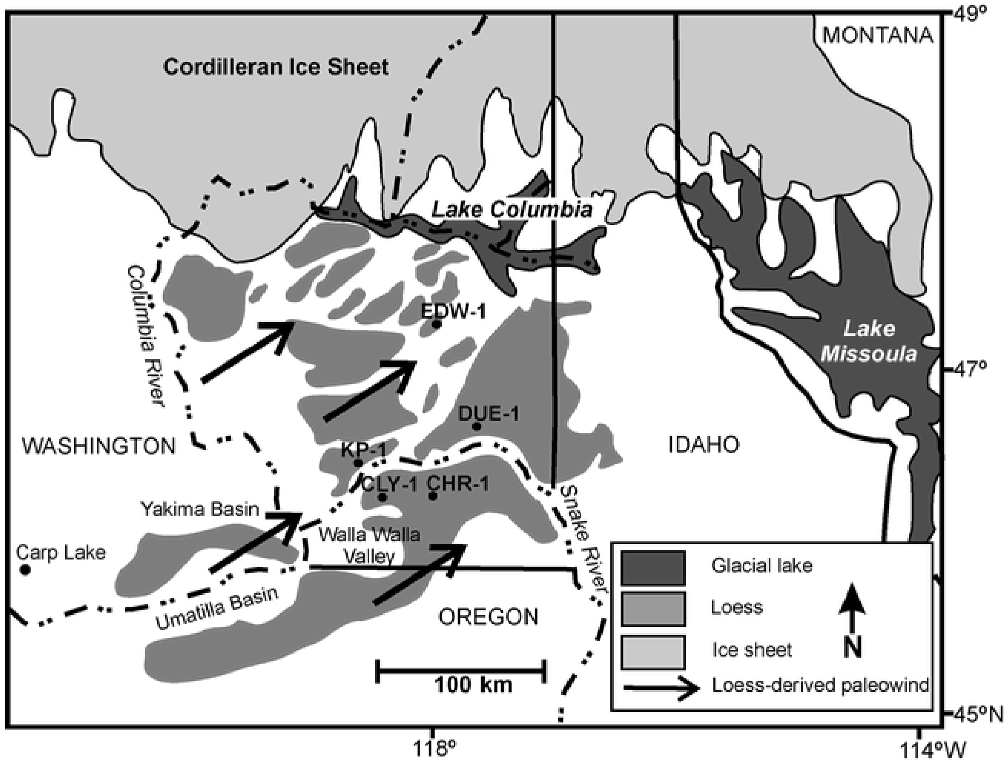

Figure 1.3. Dryland grain producing areas of the Northwest Wheat and Range Region. Wheat, barley, canola, and legumes are produced in northern and southern Idaho, northern Oregon, and eastern Washington without the use of irrigation on approximately 4 million ha of cropland.

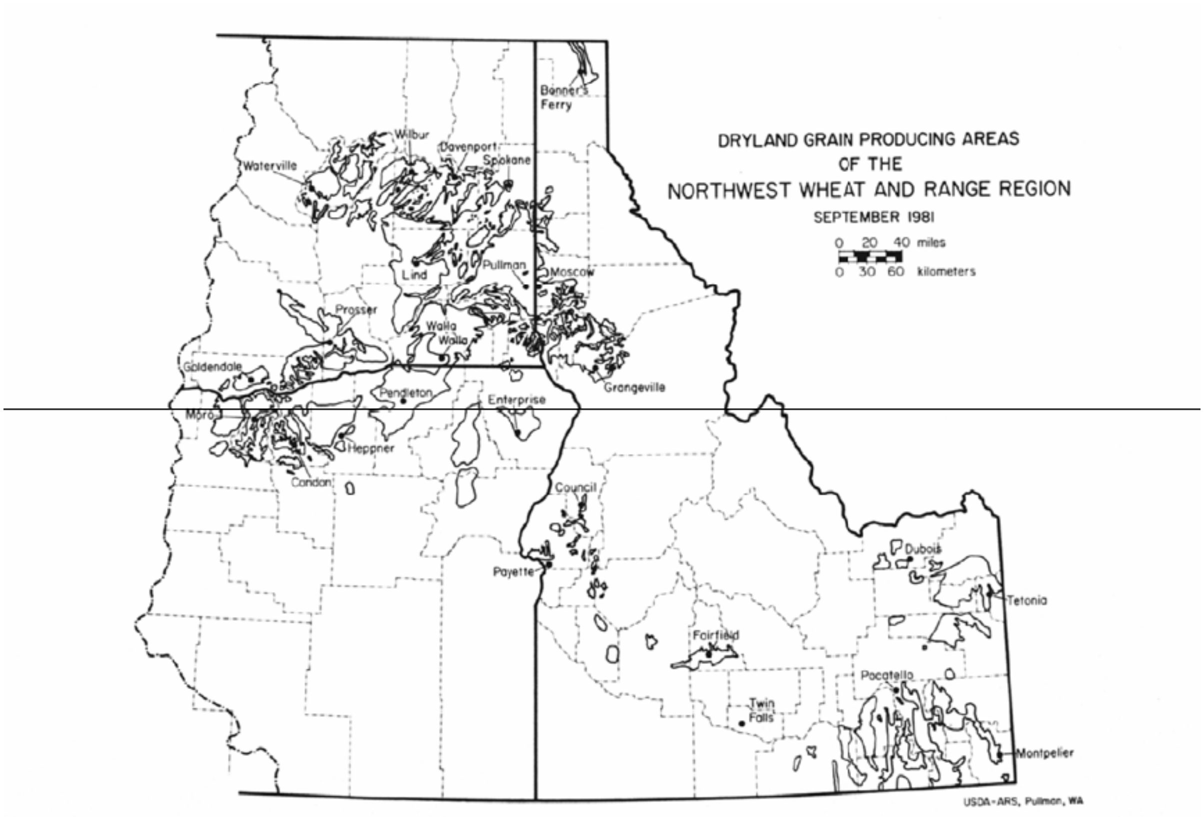

Table 1.1. Crops grown in rotation with winter wheat according to the low, intermediate, and high precipitation zones of the NWRR (Papendick, 1996).

Precipitation zone	Cropping System
Low	Two-year rotation
	Winter wheat-summer fallow
Intermediate	Two-year rotation
	Winter wheat-summer fallow
	Winter wheat-spring barley-summer fallow
High[1]	Continuous cereal cropping
	Winter wheat-winter wheat (minor)
	Winter wheat-spring cereal
	Two-year rotation
	Winter wheat-pea (or lentil)
	Three-year rotation
	Winter wheat-spring cereal-pea (or lentil)
	Winter wheat-spring cereal-spring canola
	Winter wheat-fallow-winter rapeseed

[1] Occasionally, fall barley is substituted for winter wheat

Figure 1.4. Zero (a) and ten percent (b) residue cover in spring wheat and forty percent (c) residue cover in spring pea. (Photos taken by S. Kopan)

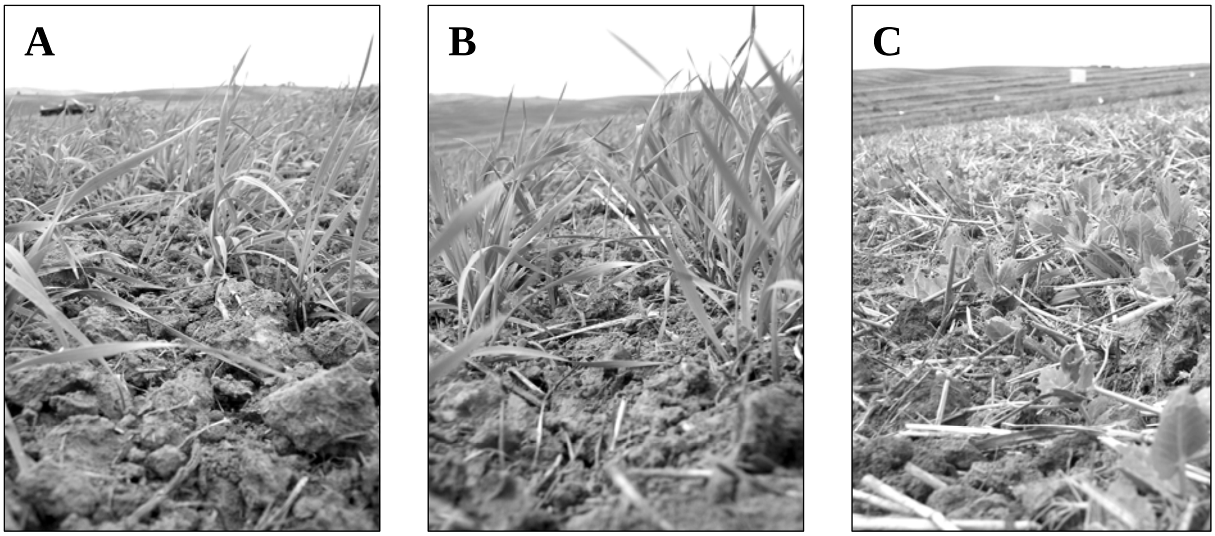

Table 1.2. Influence of tillage implements and other practices on surface residue (adapted from Woodruff et al., 1966; Hofman, 1997).

Operation	Surface residue remaining after each operation (%)
Spraying (chemical fallow)	100
Rodweeder	
Plain rod	90
With semi-chisels	85
Sweep plow	
Sweep blade 61 cm or wider	90
Chisel plow	
36 – 46 cm sweeps	85
20 – 31 cm sweeps	80
Straight spikes	75
Twisted spikes	50
Disk (tandem or offset)	
Less than 58-cm diameter blade	70
58 to 71-cm diameter blade	50
Greater than 71-cm diameter blade	30
Field cultivator	60
Moldboard plow	5 to 10
Overwinter weathering	70 to 80

Figure 1.5. The rotary harrow, typically a secondary tillage tool used for residue management, has potential use as a primary tillage tool in mulch-tillage conservation tillage. The Phoenix© model has two adjustable axles (a), each made of interwoven, blunt-ended metal rods (b). (Photos taken by S. Kopan)

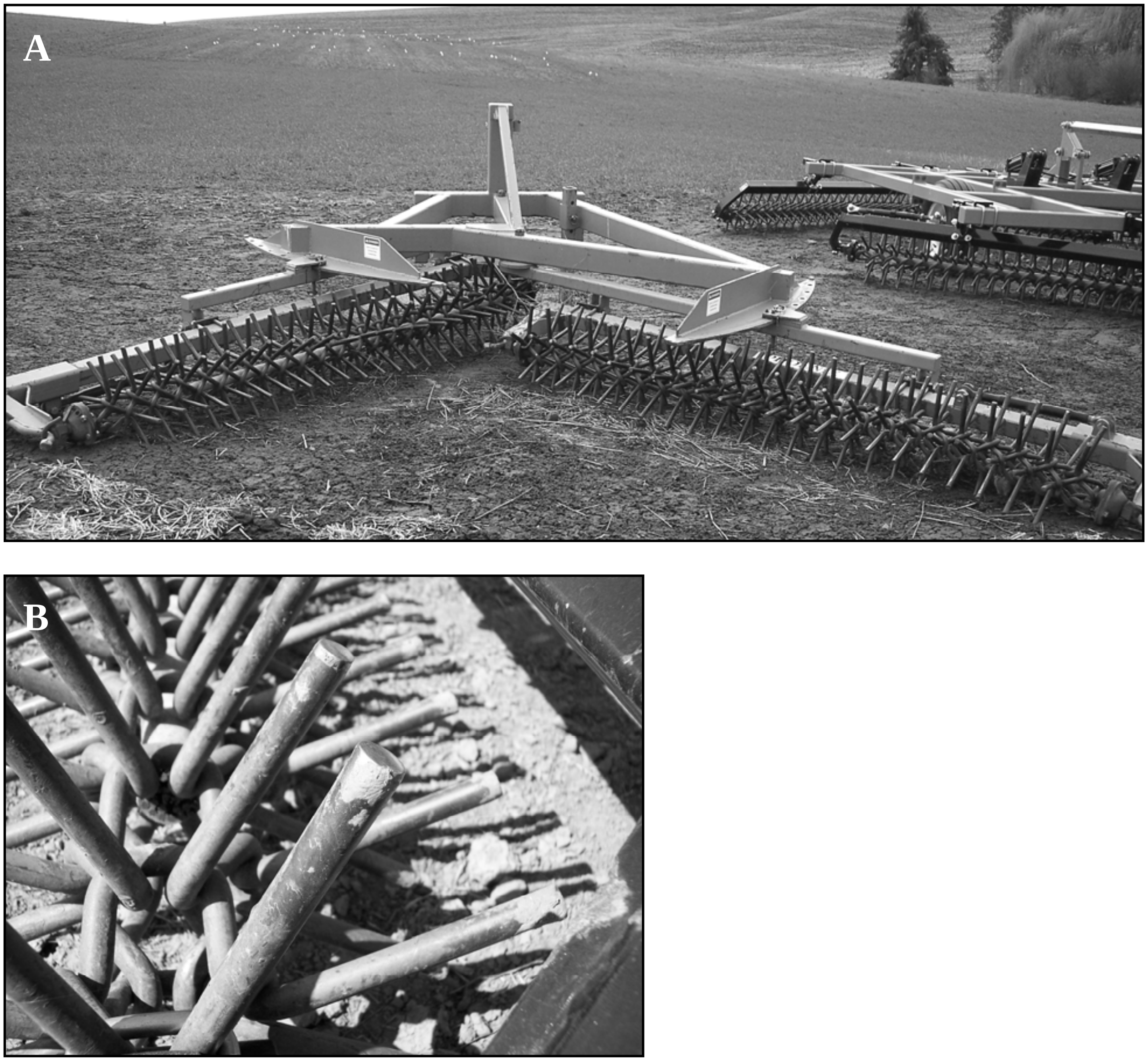

Figure 1.6. The rotary hoe is used for secondary tillage operations. The M&W© Minimum Tillage rotary hoe has two rows of spinning wheels, offset to prevent residue clogging (a). Each wheel has a spooned ends, which uproots emerging weeds within 5 cm of the soil surface (b). (Photos taken by S. Kopan)

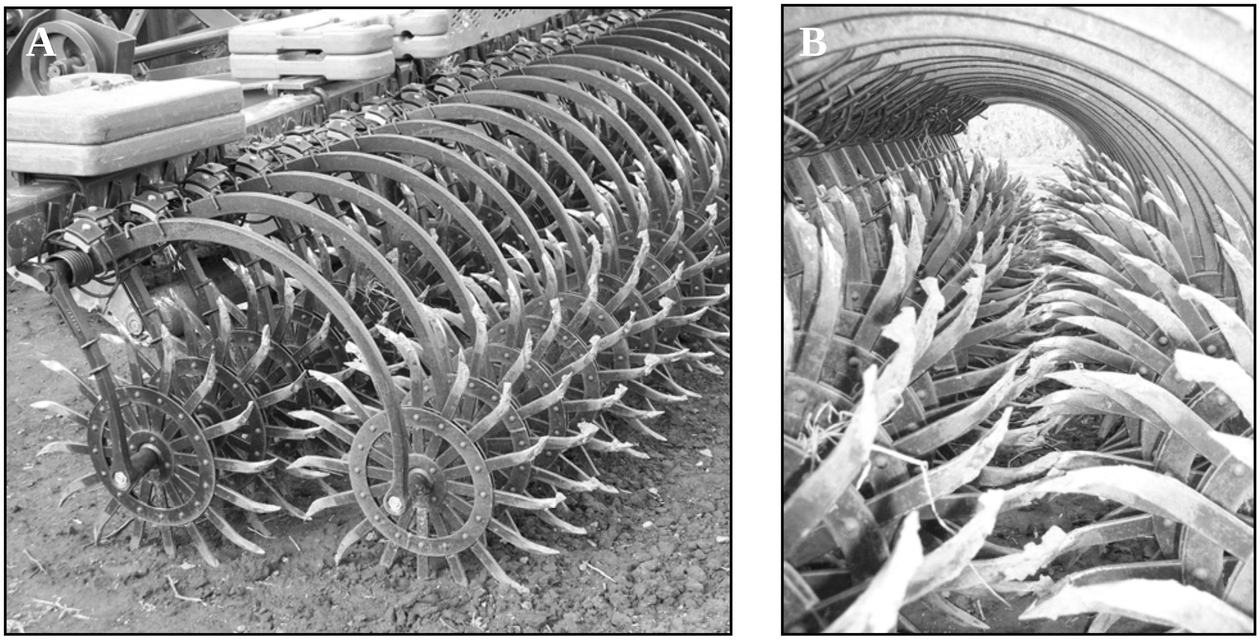

Table 1.3. Summary of herbicide modes of action, common names, and trade names registered for use in Idaho, Oregon, and Washington for selective control of grassy and broadleaf weeds in cereals, legumes, and canola (adapted from William et al., 2006).

		Selective chemical control		
Weed type	Mode of action (Group number)	Common name	Trade name	Crop
Grassy	ACCase inhibitors (1)	diclofop	Hoelon	cereals
		fenoxaprop	Puma	cereals
		quizalofop-P	Assure II	legumes, canola
		sethoxydim	Poast	legumes, canola
		tralkoxydim	Achieve	cereals
	ALS inhibitors (2)	chlorsulfuron, metsulfuron	Finesse	wheat
		imazamethabenz	Assert	wheat
		propoxycarbazone	Olympus	wheat
		sulfosulfuron	Maverick	wheat
	Microtubule assembly inhibitors (3)	trifluralin/triallate	Buckle	legumes
	Lipid synthase inhibitors (8)	triallate	Far-Go	cereals, legumes, canola
Broadleaf	ALS inhibitors (2)	chlorsulfuron, metsulfuron	Finesse	cereals
		chlorsulfuron	Glean	cereals
		metsulfuron	Ally Extra	cereals
		thifensulfuron, tribenuron	Harmony Extra	cereals
		triasulfuron	Amber	cereals
		imazethapur	Pursuit	lentil
	Microtubule assembly inhibitors (3)	pendimethalin	Prowl	lentil
	Synthetic auxins (4)	2,4-D	various	cereals, pea
		MCPA	various	cereals, pea
		MCPB	Thistrol, others	cereals, pea
		dicamba	Banvil, Clarity	cereals, pea
	PS II inhibitors (5)	metribuzin	Sencor	lentil
	PS II inhibitors (6)	bentazon	Basagran	pea
		bromoxynil	Buctril	cereals
	Protox inhibitors (14)	carfentrazone-ethyl	Aim	cereals
	PS II inhibitors (7)	diuron	Karmex, Direx	winter wheat
		linuron	Lorox, Linex	winter wheat

Table 1.4. Summary of herbicide modes of action, common names, and trade names registered for use in Idaho, Oregon, and Washington for non-selective control of grassy and broadleaf weeds in cereals, legumes, and canola (adapted from William et al., 2006).

Non-selective chemical control				
Weed type	Mode of action (Group number)	Common name	Trade name	Crop
Grassy, broadleaf	ALS inhibitors (2)	imazamox	Beyond	wheat*, canola*
	Microtubule assembly inhibitors (3)	ethalfluralin	Sonalan	pea
		trifluralin	Treflan, Trilin	wheat, legumes
	PS II inhibitors (5)	metribuzin	Sencor	winter wheat, barley, legumes
	EPSP synthase inhibitors (9)	glyphosate	various	cereals, pea, canola*
	Long-chain fatty acid synthesis inhibitors (15)	metolachlor	Dual	lentil, chickpea
		dimethenamid	Frontier	lentil, chickpea
	PS I inhibitors (22)	paraquat	Gramoxone	barley, winter wheat, winter pea, chickpea

* herbicide-tolerant crops

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CHAPTER TWO

EVALUATION OF A ROTARY HARROW AND ROTARY HOE FOR WEED CONTROL IN A CONSERVATION TILLAGE SYSTEM

ABSTRACT

Data from a spring wheat (*Triticum aestivum* L.)/spring dry pea (*Pisum sativum* L.) rotation, in southeastern Washington, were used to evaluate a Phoenix[1] rotary harrow prototype, pre-plant glyphosate application, and an M&W[2] Minimum Tillage rotary hoe on crop density, weed cover and biomass at maturity, and crop yield. The experiment consisted of two pre-plant treatments [glyphosate (control) or rotary harrow], two post-emergence chemical treatments (control or herbicide application), and five in-crop tillage treatments (control, 2-5 rotary hoe operations) in the 2004 growing season. Hoe operations did not cause a significant reduction in crop density. When the post-emergence herbicide was applied to the wheat and peas, weed cover was significantly reduced by at least 45 and 27%, respectively. Weed biomass was significantly reduced when glyphosate and the post-emergence herbicide were applied in wheat. Weed biomass was similar for all weed control treatments in pea, although the post-emergence herbicide tended to reduce weed biomass. Wheat and pea yields were not affected by the weed control treatments and were no less than 1.1 and 2.5 t ha^{-1}, respectively. In the 2005 growing season, the experiment consisted of four pre-plant treatments (control, glyphosate, rotary harrow, glyphosate + rotary harrow) and four in-crop tillage treatments (control, 2, 3, or 4 rotary hoe operations). Rotary hoe operations did not cause a significant reduction in crop density. Weed biomass of the control treatments were about five times those of the previous year. Rotary

[1] Phoenix Rotary Equipment Ltd., Nisku, AB, Canada
[2] M&W Gear, Gibson City, IL

harrowing reduced weed biomass by 38 and 34% in wheat and pea, respectively, whereas the glyphosate application reduced weed biomass by about 75% in both crops compared to the pre-plant control. There was no evidence that harrowing further reduced weed biomass when glyphosate had been applied. Wheat yield was at least 2.0 t ha^{-1} when glyphosate was applied and at least 0.9 t ha^{-1} in harrowed treatments. Results demonstrated that despite weed reductions, mechanical weed control with the harrow and hoe are less optimal than chemical control because of low weed control at high weed pressures.

INTRODUCTION

Reducing herbicide use in conservation tillage (CT) cropping systems should delay the development of herbicide resistant weeds and improve environmental quality. This can be accomplished with an integrated weed management program that uses mechanical control as an alternative to chemical control. Conservation tillage practices, defined as non-inversion cultivation, leave more than 30% of the soil surface covered by crop residue after planting (Soil Science Society of America, 1997; Conservation Technology Information Center (CTIC), 2004) and are accomplished by eliminating (no-tillage) or reducing (mulch-tillage and ridge-tillage) conventional tillage operations. In general, CT cropping systems substitute tillage with herbicides to control weeds, although other weed management practices, including crop rotation and fertilizer placement, are also implemented (Young et al., 1994; Blackshaw et al., 2001; Cardina et al., 2002; Acciaresi et al., 2003). Compared to conventionally tilled cropping systems, no-tillage systems use a greater amount of herbicides (Hinkle, 1983; Veseth, 1986), which has been justified by increased profits and lower economic risks (Young et al., 1994), but weather, soil type, tillage system experience, and endemic weed problems are potentially more important than the tillage system used in determining herbicide use (Uri, 2000).

Herbicide resistance is known in all areas where herbicides are used intensively (Powles et al., 1997). To date, there are 183 herbicide-resistant weed species worldwide, and 114 herbicide resistant weed species in the US (Heap, 2006). Notable herbicide resistant weed species in the Pacific Northwest include Russian thistle [*Salsola iberica* (Sennen & Pau) Botsch. ex Czerepanov], prickly lettuce (*Lactuca serriola* L.), and wild oat (*Avena fatua* L.), which infest dryland cereal production systems. In the southeastern US, glyphosate-resistant horseweed (*Conyza canadensis* L.) is of growing concern in soybean [*Glycine max* L. (Merr.)] and cotton (*Gossypium hirsutum* L.) production, where most crop varieties are glyphosate-tolerant (Koger, 2004).

Several biological and agronomic factors affect the selection and development of herbicide resistance (Jasieniuk et al., 1996). Herbicide resistance is more likely to develop in a population of weeds with prolific seed production, high densities, and low seed mortality, dormancy, and persistence in the seedbank (Cavan et al., 2001; Hanson et al., 2002; Rainbolt et al., 2004). In addition, herbicide resistance develops more readily in populations with a high initial gene frequency that confers resistance (Jasieniuk et al, 1996). Nonetheless, herbicide use is the single most important factor in the development of herbicide resistance in weeds (Jasieniuk et al., 1996). Acetolactate synthase (ALS) inhibitors, for example, are prone to selecting for herbicide resistance because these herbicides have been used widely for weed control, are highly effective against susceptible weeds, and have residual soil activity (Tranel and Wright, 2002). The first ALS-resistant weed, prickly lettuce (*Lactuca serriola* L.), was reported in 1987, only 5 years after the commercialization of ALS herbicides (Mallory-Smith et al., 1990).

The impact of chemical weed control extends beyond field boundaries, as detectable amounts of herbicides can be found in surface and ground water, which pose a direct threat to aquatic organisms and may indirectly harm humans (Unterreiner and Kehew, 2005; Green and Young, 2006). Herbicide transport occurs with sediment or water flow by subsurface drainage or surface runoff. Most herbicides have intermediate soil adsorptions ($0.1 < K < 100$) and are primarily transported by runoff (Carlisle and Trevors, 1988; Fawcett et al., 1994). Notable exceptions with very high adsorption rates ($K > 100$) include trifluralin, paraquat, and glyphosate, which are primarily transported by sediment (Fawcett et al., 1994). Reduced herbicide application rates reduce herbicide loss by surface runoff (Hall et al., 1972; Baker and Mickelson, 1994; Hansen et al., 2001), but herbicide concentrations can be very high when runoff events occur within 30 days of an herbicide application, regardless of the tillage system (Fawcett et al., 1994; Shipitalo et al., 1997; Hansen et al., 2001; Leu et al., 2004). Typically, however, CT systems reduce herbicide loss because these systems often reduce sediment loss and runoff and increase water infiltration (Soileau et al., 1994; Gaynor and Findlay, 1995; Truman et al., 2005).

Alternatively, mechanical tillage can be as effective in controlling weeds as herbicides or reduce reliance on herbicide applications in CT systems (Mt. Pleasant et al., 1994; Buhler et al., 1995; Swanton et al., 2002). Under high weed densities, rotary hoes and reduced herbicide rates provide excellent weed control, and the tool can substituted for 50 to 75% of the herbicide (Buhler et al., 1992; Mulder and Doll, 1993; Hooker et al., 1997). Few studies have shown mechanical tools as complete replacements for chemical control, however, Mohler et al. (1997) reported that the flex tine harrow was comparable to the use of herbicides in some years.

The efficacy of weed control with mechanical tillage tools, such as rotary hoes, flex-tine harrows, and spike-tooth harrows, can be inconsistent. Numerous studies have reported the importance of timely field operations when weed seedlings have germinated but not emerged from the soil and soil conditions are optimal (Lovely, 1958; Gunsolus, 1990; Mattsson et al., 1990; Mohler et al., 1997). Bond and Grundy (2001) found that mechanical tools worked well in dry soil conditions, but fields were often wet in spring when timely weed control was critical. In-crop mechanical weed control can promote crop injury when soil is tilled within or below the seeding zone, especially if roots are not well-developed (Rasmussen, 1994; Mohler et al., 1997). At later growth stages, however, the crop can overcome soil burial (Kurstjens and Perdok, 2000). Crop injury and reductions in stand density have been reported in corn (Gunsolus, 1990; Mulder and Doll, 1993) and soybeans (Gunsolus, 1990; Buhler et al., 1992) but not in fresh beans (VanGessel et al., 1995). Nonetheless, mechanical tools can provide greater benefits by removing weeds even when crop densities are reduced (Rasmussen and Rasmussen, 2000) or seeding rates can be adjusted to accommodate mechanical tillage.

Mechanical weed control may be well suited to the CT systems of the Pacific Northwest (PNW), where soils are prone to wind and water erosion (Papendick and Miller, 1977; Moldenhauer et al., 1983; Young et al., 1994). In the Palouse Prairie Region of southeastern Washington, water erosion accounts for most of the soil loss on cropland (Papendick and Miller, 1977). This region encompasses 750,000 ha of dryland production, and many cropping systems include spring and winter wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), dry peas (*Pisum sativum* L.), or lentils (*Lens culinaris* Medik.) in the crop rotation (US Department of Agriculture (USDA)-Soil Conservation Service, 1968). As much as 85% of the annual soil loss occurs during winter, when the Palouse receives 60% of its annual precipitation (Zuzel et al., 1982). Residue management practices that leave the soil surface exposed during winter, intermittent freezing and thawing of soils, and steep slopes contribute to the high rates of soil loss (Papendick et al., 1983; Jennings et al., 1990). Rates of soil loss on cropland often exceed the tolerable limit of 11 t ha^{-1} yr^{-1} (USDA, 1978; Renard et al., 1997; Greer et al., 2006).

This study investigated the use of a rotary harrow for pre-plant weed control and a rotary hoe for in-crop weed control in a spring wheat and spring dry pea mulch-tillage system. We hypothesized that problem weeds could be controlled with pre-plant rotary harrow operations using a Phoenix[3] harrow prototype and with multiple in-crop rotary hoe operations using an M&W[4] Minimum Tillage hoe. The effects of the rotary harrow, a pre-plant glyphosate application, and rotary hoe on crop density, total weed biomass at weed maturity, and crop yield were investigated.

MATERIALS & METHODS

Field Location

Field experiments were conducted at Boyd Research Farm (46°44’59’’ N, 117°05’00’’ W) in Pullman, WA in 2004 and 2005 as part of a larger research program in conservation tillage cropping systems. The 16-ha research farm is approximately 790 m in elevation with a 7 to 25% western-facing slope, and the soil is classified as a Palouse silt loam (fine silty, mixed, mesic Pachic Ultic Haploxeroll). Spring wheat was the prior crop for the 2004 field site, while winter pea, mulched and used as a green manure, was the prior crop in the adjacent 2005 field site.

Though inland, the area is described as having a Mediterranean climate with cool, wet winters and hot, dry summers. Daily temperatures vary, and monthly mean daily minimums and maximums during the year can vary by as much as 17°C. The daily minimum and maximum temperatures in January, the coldest month, are -5.5 and 1.2°C, and the daily minimum and

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[3] Phoenix Rotary Equipment Ltd., Nisku, AB, Canada
[4] M&W Gear, Gibson City, IL, USA

maximum temperatures in July, the hottest month, are 9.7 and 27.7°C (Figure 2.1). Pullman receives 544 mm of annual precipitation, 67% of which occurs between October and March, inclusive (Figure 2.2). December is the wettest month with 78 mm of precipitation, and July is the driest month with less than 15 mm of average precipitation.

2004 Field Season

The 2004 experiment was arranged in a randomized complete block split-split plot design with four replications. Replications were blocked to reduce variability along the slope. The whole plots consisted of pre-plant weed controls with rotary hoe operations as the subplots and post-crop emergence herbicides as the sub-subplots. The pre-plant weed controls were randomly assigned to each main plot, and the sub-plots were randomly assigned within each main plot. The subplots were split into sub-subplots treatments, which measured 4.57 m^2.

The pre-plant weed control treatments consisted of 1) two rotary harrow operations or 2) a glyphosate application. Plots were rotary harrowed traveling at a speed of 3.4 m s^{-1} on April 2 and 3 using a Phoenix[5] rotary harrow with gangs set at 45° for a 3.7-m operating width. Glyphosate [N-(phosphonomethyl)glycine] was applied at 1.1 kg active ingredient (AI) ha^{-1} five days before planting. The rotary harrow and glyphosate, a foliar-applied, non-residual herbicide, were used to control early spring emerged grassy and broadleaf weeds with additional control of emerging weeds with the rotary harrow.

A Fabro[6] double disk drill with a 17.8-cm row spacing was used to seed the crops and place fertilizer. Spring wheat (*Triticum aestivum* L. cv. Wawawai) was seeded on April 12 at 202 kg ha^{-1}, and spring dry pea (*Pisum sativum* L. cv. Lifter) was seeded on April 13 at 112 kg ha^{-1}. The drill also placed starter fertilizer (N:P:K) (16:20:0) at 112 kg ha^{-1}, urea (N:P:K)

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[5] Phoenix Rotary Equipment Ltd., Nisku, AL, Canada
[6] Fabro Enterprises Ltd., Swift Current, SK, Canada

(46:0:0) at 247 kg ha^{-1}, and gypsum (anhydrous calcium sulfate, which contained 20% Ca and 16.5% S) at 16.3 kg ha^{-1} with the wheat seed to meet the anticipated N and S needs of the crop.

Post-plant weed control practices consisted of 0, 2, 3, 4, or 5 rotary hoe operations for wheat and 0, 2, 3, or 4 rotary hoe operations for pea with or without a post-crop emergence herbicide application. An M&W[7] Minimum Tillage (MT) rotary hoe was used for in-crop weed control of recently emerged and emerging weeds. The rotary hoe had a 4.6-m operating width and was operated at a speed of 5.4 m s^{-1} with an additional 90 kg of weight for increased soil penetration. Rotary hoeing was initiated about 10 days after rotary harrowing and attempted every 10 days, weather permitting (Table 2.2). Grassy weeds were controlled with Assure II[8] (quizalofop-ethyl) in the peas and Discover[9] (clodinofop-propargyl) in the wheat on June 4, which are foliar-contact herbicides. The former was applied at 584 ml AI ha^{-1}, and the later was applied at 292 ml AI ha^{-1}.

Measurements from each sub-subplot included crop density, an early season estimate of weed control, late season weed biomass, and crop yield (Table 2.1). Pea and wheat density was evaluated on June 17 and 18 as the average number of plants per meter row in three sub-subplot measurements, respectively. Weed control was estimated on July 6 to determine visual differences in the pre-plant and post-plant weed controls. The amount of weed cover in each sub-subplot was estimated as the average of three values between 0 (no weed cover) and 100% (completely covered by weeds). Aboveground weed biomass at weed maturity was collected on August 2 in the peas and on August 3 in the wheat, oven-dried for at least 48 hours, and bulk

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[7] M&W Gear, Gibson City, IL, USA
[8] E. I. du Pont de Nemours and Company, Wilmington, DE, USA
[9] Syngenta Crop Protection, Inc., Greensboro, NC, USA

massed. The peas were harvested on August 5 and 6, and the wheat was harvested on August 20 using a Hege[10] 140 plot combine with 1.5-m wide cutting platform.

Analysis of variance (ANOVA[11]) was conducted using a fixed model to evaluate the effects of pre-plant weed controls, rotary hoe operations, and post-crop emergence herbicides on the dependent variables. Each crop density, estimate of weed control, and weed biomass observation consisted of the mean between three subsamples within a sub-subplot, and crop yield was the total of each sub-subplot. Pairwise comparisons of all treatments were performed using Bonferroni's method of multiple comparisons with a 0.05 level of significance, and standard errors were calculated using a mixed model.

2005 Field Season

The 2005 experiment was arranged in a randomized complete block split-split plot design with four replications. Replications were again blocked to reduce variability along the slope. Main plots consisted of rotary harrow operations with pre-plant herbicide applications as the subplots and in-crop rotary hoe operations as the sub-subplots. The rotary harrow treatments were randomly assigned to each main plot, and the subplot and sub-subplot treatments were randomly assigned within each main plot. Sub-subplots measured 4.57 by 9.14 m.

Main plots were rotary harrowed zero or two times on March 14 with a Phoenix prototype rotary harrow. This rotary harrow prototype, designed by Carl Gabriel at Phoenix Rotary Equipment Ltd. and Robert Gallagher at Washington State University, had four gangs of working tools unlike the typical Phoenix rotary harrow, which has two gangs. The additional gangs were incorporated into the equipment design to double the number of operations in a single pass and provide additional weight for greater soil penetration. The two pairs of gangs

[10] Hans-Ulrich Hege Maschinenbau, Waldenburg, Germany
[11] Statistical Analysis Systems, SAS Institute Inc., Cary, NC, USA

were set at 45° angles for a 3.7-m operating width, and the rotary harrow traveled at a speed of 3.4 m s^{-1}. Like a typical rotary harrow, it controls recently emerged and emerging weeds.

The subplots received either no or a full rate pre-plant herbicide application. Similar to the previous year, glyphosate was used for non-selective control of weeds, but 2,4-D (2,4-dichlorophenoxyacetic acid) also provided increased control of broadleaf weeds. The former was applied at 1.1 kg AI ha^{-1}, and the latter was applied at 0.6 kg AI ha^{-1} three days before planting.

The same Fabro double-disk drill from the previous year was used to seed the crops and place fertilizer in 2005. Spring wheat ('Alpowa') was seeded at 112 kg ha^{-1}, and spring dry pea ('Stirling') was seeded at 179 kg ha^{-1} on April 25. Alpowa soft white wheat was chosen to replace the wheat variety from the previous year because of its increased popularity among regional producers and similar yields (Kidwell et al., 2002), while Stirling was chosen to replace the pea variety from the previous year because of its increased biomass (McPhee and Muehlbauer, 2004). The drill also placed starter fertilizer (N:P:K) (16:20:0) at 112 kg ha^{-1}, urea (N:P:K) (46:0:0) at 247 kg ha^{-1}, and gypsum (anhydrous calcium sulfate, which contained 20% Ca and 16.5% S) at 16.3 kg ha^{-1} with the wheat seed to meet the anticipated N and S needs of the crop.

The M&W MT rotary hoe was the only post-plant weed control. Like the previous year, the rotary hoe was operated at a speed of 5.4 m s^{-1} with an additional 90 kg of weight for increased soil penetration. Rotary hoeing was initiated about 10 days after rotary harrowing and attempted every 10 days, weather permitting, for 0, 2, 3, or 4 operations in each crop (Table 2.2). The post-crop emergence herbicide treatment was omitted from the 2005 experiment, since the high weed control efficacy of this factor precluded an interaction with the rotary hoe treatments as previously expected.

Measurements from each sub-subplot included crop density, an early season estimate of weed control, late season weed biomass, and crop yield (Table 2.1). Crop density was measured on July 3 as the average number of plants per meter row in three sub-subplot measurements. Aboveground weed and crop biomass at weed maturity was collected on August 2 and 3 in the peas and wheat, respectively, oven-dried for at least 48 hours, and bulk massed. Stirling suffered significant reductions in seed set due to the Pea Enation Mosaic Virus (McPhee, USDA-ARS, Pullman, WA, personal communication), and these plots were not harvested. The wheat was harvested on August 22 using the Hege 140 plot combine.

ANOVA[12] was conducted using a fixed model to evaluate the effects of rotary harrow operations, pre-plant herbicides, and rotary hoe operations on the dependent variables. Each crop density and weed and crop biomass observation consisted of the mean between three subsamples within a sub-subplot, and crop yield was the total of each sub-subplot. Pairwise comparisons of all treatment means were performed using Bonferroni's method of multiple comparisons with a 0.05 level of significance, and standard errors were calculated using a mixed model.

RESULTS & DISCUSSION

2004 Field Season

The temperatures in Pullman in 2004 were much like the 30-year average, but precipitation was uncharacteristically high in May. Daily minimum and maximum temperatures in January were -4.5 and 1.7°C, respectively, which were about average, and daily minimum and

[12] Statistical Analysis Systems, SAS Institute Inc., Cary, NC, USA

maximum temperatures in July were 10.8 and 29.4°C, respectively, which were slightly higher than average (Figure 2.1). Spring temperatures were above average with daily maximum temperatures in March and April 5.3 and 3.4°C higher than expected, respectively (Figure 2.1). The precipitation for the 2004 rain year, which occurred from October 2003 to September 2004, was 515 mm, which was 26 mm below normal even though precipitation in May was almost twice the average amount (Figure 2.2).

Crop density

The pre-plant and in-crop weed controls had no significant effect on crop density in both years (Table 2.3). Pea density ranged between 18.5 and 20.5 plants m^{-1} in glyphosate treatments and between 18.6 and 19.8 plants m^{-1} in harrow treatments (data not shown). Wheat density ranged between 24.4 and 27.4 plants m^{-1} in glyphosate treatments and between 26.4 and 27.0 plants m^{-1} in harrow treatments (data not shown). There was no evidence that a greater number of hoe operations significantly reduced crop density. These results conflict with other studies that measured reductions in crop density with the rotary hoe (Gunsolus, 1990; Buhler et al., 1992; Mulder and Doll, 1993; Rasmussen and Rasmussen, 2000). Mohler and Frisch (1997), however, reported the when oats (*Avena sativa* L.) were planted at a greater planting depth, rotary hoeing caused a smaller reduction in crop density relative to when the oats were planted at a normal planting depth.

Early season estimate of weed control

The chemical weed controls significantly reduced weed cover (Table 2.3). Glyphosate reduced weed cover in pea from 28 to 20% compared to the rotary harrow treatments but had no significant effect on wheat cover (data not shown). The use of the post-emergence herbicide reduced weed cover in pea from 35 to 5% in the glyphosate treatments and from 45 to 10% in the harrow treatments (Figure 2.3). When the post-emergence herbicide was applied in wheat, weed cover was reduced from 42 to 7% in the glyphosate treatments and from 36 to 17% in the harrow treatments (Figure 2.3).

Late season weed biomass

Wild oat and prickly lettuce were most frequently identified in the weed samples, and these weeds accounted for most of the biomass. Wild oat or prickly lettuce were identified in about 80% of the samples, but Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], field bindweed (*Convolvulus arvensis* L.), and cheatgrass (*Bromus tectorum* L.) were also frequently found, although in smaller quantities (data not shown). The weed species collected from the crops were similar, but the peas had about twice the weed biomass than the wheat field.

Few differences in weed biomass were found between the pre-plant weed controls. Although the pea cover of the early season weed estimate was significantly greater in the glyphosate treatments, data indicated that there were no significant differences in the weed biomasses of the pre-plant weed controls in either crop (Table 2.3). The post-plant treatments tended to cause greater reductions in weed biomass than the pre-plant treatments, with the herbicide having less weed biomass than the hoe operations (data not shown).

The effects of hoeing on weed biomass were variable. Even though hoeing reduced weed biomass from 26 to 42% in the glyphosate treatments and at least 62% in the harrow treatments, four operations were needed in the harrow treatments to cause a significant reduction compared to the non-hoed control treatments (Figure 2.4). Although there was no significant trend towards a greater reduction in weed biomass with a greater number of hoe operations, two or more operations reduced weed biomass. Other studies reported similar rank reductions of weed biomass with the rotary hoe, but in most years, the hoe was not significantly different from the untreated weedy check (Mohler and Frisch, 1997; Mohler et al., 1997).

The post-emergence grassy herbicide significantly reduced weed biomass in both crops (Table 2.3). The herbicide reduced weed biomass in peas from 58.7 to 26.4 g m^{-2} when glyphosate was applied and from 119.2 to 39.8 g m^{-2} in the harrow treatments (Figure 2.4). The post-emergence herbicide reduced weed biomass in wheat by 70% when glyphosate was applied and by 28% in the harrow treatments (Figure 2.5). Only the post-emergence herbicide-glyphosate treatment combination significantly reduced weed biomass. Nonetheless, the mechanical and chemical pre-plant weed control treatments had similar effects on weed biomass when the post-crop emergence herbicide was not applied (Figure 2.5). The weed biomass values, which give an estimate of the weed pressure, are within the same magnitude of values reported by Mohler et al. (1997) but are more than twice those reported by Mohler and Frisch (1997).

Crop yield

Crop yield was affected only by the post-emergence herbicide (Table 2.3), which caused a 15% reduction in pea yield from 1.4 to 1.2 t ha^{-1} in the glyphosate treatments and a 9% reduction from 1.3 to 1.2 t ha^{-1} in the harrow treatments (Figure 2.6). These yields are much less than those reported by Young et al. (1994), but more than two times the pea yields reported by Yenish and Eaton (2002). Pea injury can be significant after application of broadleaf post-emergence herbicides and result in yield reductions (Yenish and Eaton, 2002). Although quizalofop, a graminicide, has not been known to cause injury to peas, another herbicide within the aryloxyphenoxypropanoate chemical family was reported to cause injury to a broadleaf weed

(Luo and Matsumoto, 2002). The mechanism for the yield reduction in this study is unknown but could be the result of herbicide injury.

2005 Field Season

Temperatures were uncharacteristically warm in the early part of the year with little precipitation. The daily minimum and maximum temperatures in July were 10.6 and 29.1°C, which were about the 30-year average (Figure 2.1). On the contrary, between November 2004 and May 2005, inclusive, the daily minimum and/or maximum temperatures were at least 1°C higher than the average. During this time, the greatest deviation from the daily minimum and maximum monthly temperature occurred in January, which was 2.6°C higher than the average, and in March, which was 4.8°C higher than the average, respectively (Figure 2.1). The precipitation for the 2005 rain year, which occurred from October 2004 to September 2005, was 371 mm, which was 173 mm below the 30-year average (Figure 2.2). This reduction can be attributed to the relatively dry winter, when the precipitation between October 2004 and March 2005 was 167 mm less than the average (Figure 2.2). Nonetheless, precipitation in May was about twice the average with 70 mm (Figure 2.2), as was the case in the previous year.

Crop density

Similar to the results of the first study year, the mechanical weed control practices had no significant effect on crop density in 2005 (Table 2.4). Pea density ranged between 7.5 and 10.9 plants m^{-1} in pre-plant glyphosate and 2,4-D herbicide treatments (HERB) and between 8.2 and 11.4 plants m^{-1} in harrow treatments (data not shown). Wheat density ranged between 10.4 and 16.7 plants m^{-1} in HERB treatments and between 13.3 and 17.5 plants m^{-1} in harrowed treatments (data not shown). There was no evidence that a greater number of hoe operations significantly reduced crop density, which conflicts with other studies that measured reductions in crop density with the rotary hoe (Gunsolus, 1990; Buhler et al., 1992; Mulder and Doll, 1993; Rasmussen and Rasmussen, 2000).

Late season weed biomass

Prickly lettuce was the most frequently identified weed species and was found in nearly 80% of biomass samples. Wild oat was not as frequently collected compared to the previous year but was the most commonly identified grassy weed (data not shown). Mayweed chamomile (*Anthemis cotula* L.), the second most frequently collected broadleaf weed, was identified in almost 20% of biomass samples (data not shown). Weed species and biomass values were similar between the crops, but when the weed biomass values of the years were compared, the values in the peas and wheat were two and four-times those from 2005, respectively, and about the same as those reported by Mohler et al. (1997).

Under the higher weed pressure, any weed control treatment seemed to reduce weed biomass in peas (Table 2.4). When the pre-plant weed control treatments where not rotary hoed, the HERB only treatment caused the greatest reduction in weed biomass, reducing it from 393.6 to 35.8 g m^{-2} (Figure 2.7). The rotary harrow treatment and harrow- HERB treatment combination also significantly reduced weed biomass compared to the non-hoed control but to a lesser extent. The weed biomass of the HERB only treatment was 77 and 68% less than that of the rotary harrow and harrow- HERB treatments, respectively (Figure 2.7). Weed biomass of the rotary harrow, HERB, and harrow- HERB treatments were not significantly different, regardless of the number of hoe operations, indicating that there was no benefit to using both pre-plant weed controls.

The rotary hoe tended to reduce weed biomass in peas, but only when it was used in combination with another pre-plant weed control was the reduction significant. Hoeing alone reduced the weed biomass by 23 to 34% when no pre-plant weed controls were used, but any hoe- HERB treatment combination further reduced weed biomass by at least 95% (Figure 2.7). When the harrow was used as the pre-plant weed control, three hoe operations caused a significant reduction in weed biomass compared to rotary hoeing in the pre-plant control treatment, but the reduction in weed biomass was at most 68% (Figure 2.7). There were no significant reductions in weed biomass with a greater number of hoe operations, but each rotary hoe operation consistently reduced weed biomass after harrowing.

Rotary hoe operations had no significant effect on weed biomass in wheat (Table 2.4), but there were notable results. Four hoe operations reduced weed biomass by 80% from 156.3 to 31.3 g m^{-2} within the harrow treatment (data not shown). Conversely, three operations increased weed biomass by 44% compared to the non-hoed pre-plant control treatment. This was attributed to a single subsample which contained a 10-fold increase in weed biomass relative to the two other weed biomass subsamples.

As in the peas, several pre-plant weed control treatments reduced weed biomass in wheat. The rotary harrow caused a significant reduction in weed biomass from 302.4 to 114 g m^{-2} compared to the pre-plant control treatment. The additional application of glyphosate and 2,4-D further reduced weed biomass to 27.0 g m^{-2}, although this harrow- HERB treatment combination was marginally significant compared to rotary harrowing alone (Figure 2.8). Very few weeds were found in the HERB treatments.

Crop biomass

All weed control practices had a significant effect on pea biomass at pod development (Table 2.4). Few pea plants were collected in the pre-plant control treatments regardless of the number of hoe operations. The pea biomass values in the HERB, rotary harrow, and HERB-harrow treatments were 84.4, 40.8, and 64.1 g m^{-2}, respectively, when not rotary hoed, and the values increased by about 25 g m^{-2} after weeds were controlled with three rotary hoe operations (Figure 2.9). Although hoeing did not significantly increase pea biomass by controlling weed growth, each operation resulted in a consistent increase in biomass after rotary harrowing.

Only the pre-plant weed controls had a significant effect on wheat biomass at flowering (Table 2.4). Few plants were collected in the pre-plant control treatment. Wheat biomass in the HERB, harrow, and HERB-harrow treatments were 207.0, 103.1, and 193.6 g m^{-2}, respectively, and applying glyphosate and 2,4-D increased biomass by about 94% compared to rotary harrowing alone (Figure 2.10). Although rotary harrowing did not perform as well as the glyphosate and 2,4-D application, it significantly increased wheat biomass from 18.4 to 103.1 g m^{-2} compared to the pre-plant control treatment.

Crop yield

The results from the 2005 crop yield were lost due to disease as the peas were devastated and none were harvested, and none of the pre-plant control treatments were harvested due to a high weed pressure in the wheat. In the rotary harrow only treatment, wheat was harvested from only one plot when 0 and 3 rotary hoe operations occurred. Despite these setbacks, the weed controls tended to increase wheat yield (Table 2.4). Yield was highest when glyphosate and 2,4-D was applied, which was followed by the HERB-harrow treatment combination and the rotary harrow treatment, regardless of the number of rotary hoe operations (Figure 2.11). In the non-hoed treatments, glyphosate and 2,4-D increased wheat yield by 82 and 40% compared to rotary harrowing or the HERB-harrow treatment combination, respectively, and among the pre-plant weed control treatments, wheat yields were highest (at least 1.7 t ha^{-1}) with four rotary hoe operations (Figure 2.11). Two and three operations did not necessarily increase the yield compared to non-hoed treatments. Given that there were large differences in the variability among treatments, it is more difficult to make further assumptions of treatment means. Generally, spring wheat yields in Pullman are about 2.5 t ha^{-1} but can be as high as 3.3 t ha^{-1} (Young, 2004).

CONCLUSIONS

In this study, mechanical weed control in a CT system provided adequate weed control that was, at times, as effective as glyphosate and 2,4-D. However, the performance of the harrow and hoe are inconsistent in different crops and between growing seasons. The greatest reduction in weed biomass and increase in crop yield was obtained when glyphosate and 2,4-D were used in conjunction with the rotary hoe, but the rotary harrow was a suitable replacement for the pre-plant herbicide at low weed pressures.

The results from this study could be used to increase the effectiveness of the harrow and hoe in a CT system. Untimely operations, which coincided with unusually high precipitation, could be the cause of reduced weed control. Precipitation can increase weed seed germination and emergence during the period of mechanical weeding, although the impact of soil moisture on germination and emergence is highly variable among weed species (Fernandez-Quinantilla et al., 1990; Boyd and Acker, 2003). In regards to crop yield, mechanical weed control appears to be more suitable in spring wheat, probably due to more rapid seedling growth and earlier establishment of crop canopy relative to spring peas. In addition, optimal performance of the harrow and hoe may be more conducive in larger plot areas, where tools can operate at more uniform speeds and soil depths. Further research is needed to determine how mechanical weed control can be effective in a diverse CT cropping system.

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Figure 2.1. Mean daily maximum and minimum air temperatures for Pullman, WA for 2004, 2005, and the 30-year average (Courtesy of J. Barry, USDA-ARS, Pullman, WA).

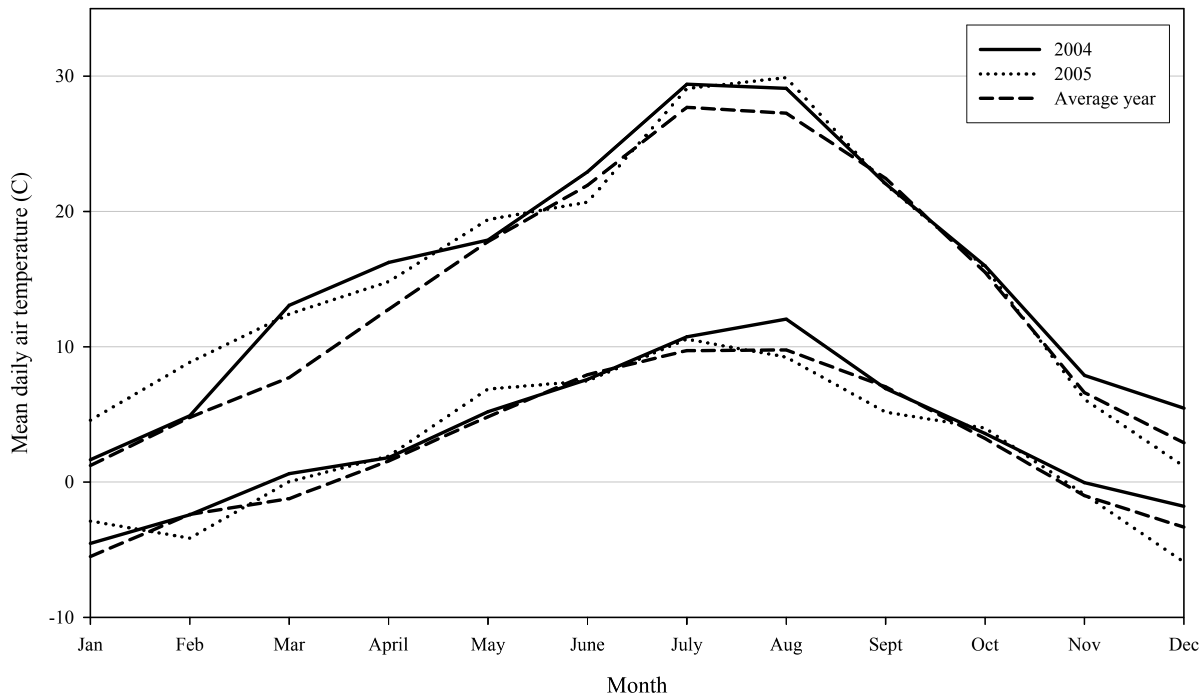


Figure 2.2. Average monthly precipitation in Pullman, WA for 2004, 2005, and the 30-year average (Courtesy of J. Barry, USDA-ARS, Pullman, WA).

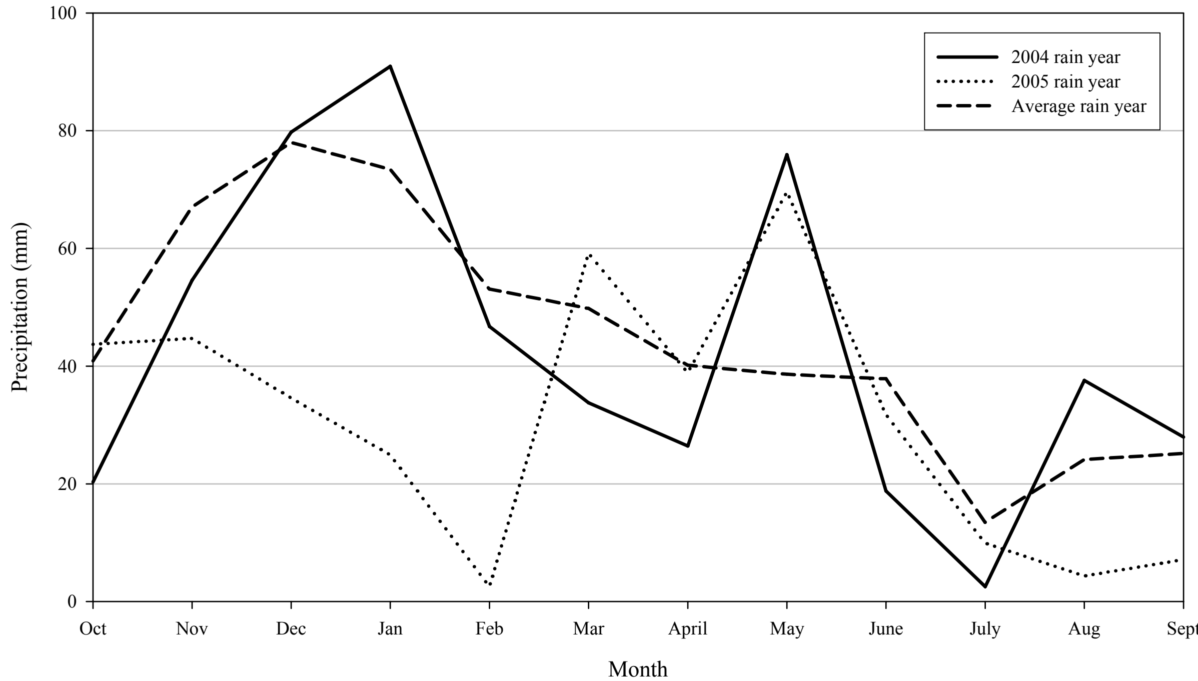


Table 2.1. Summary of data collected in 2004 and 2005 by crops.

Data collected	2004	2005
Crop density		
Pea	17 June	3 July
Wheat	18 June	3 July
Early season estimate of weed control		
Pea	6 July	-
Wheat	6 July	-
Late season weed biomass		
Pea	2 August	2 August
Wheat	3 August	3 August
Crop yield		
Pea	5, 6 August	-
Wheat	20 August	22 August

Table 2.2. Summary of rotary hoe operations in spring dry pea and spring wheat for 2004 and 2005 with date of each operation and timing after planting.

Number of rotary hoe operations	Spring pea		Spring wheat	
	Date	Days after planting	Date	Days after planting
		2004		
1	19 April	6	19 April	7
2	3 May	20	23 April	11
3	14 May	31	3 May	21
4	1 June	49	14 May	32
5			1 June	50
		2005		
1	13 May	18	13 May	18
2	24 May	29	24 May	29
3	3 June	39	3 June	39
4	13 June	49	13 June	49

Table 2.3. Analysis of variance for data collected in 2004.

Source of variation[1]	Spring pea			Spring wheat		
	df	Mean square	P-value	df	Mean square	P-value
			Crop density			
Block	3	17.8781	0.0893	3	142.8811	< 0.0001
PRE	1	2.2600	0.5938	1	8.7781	0.2621
Error block * PRE	3	5.9531	0.5224	3	20.6531	0.0375
POST (PRE)	2	2.4208	0.7360	2	10.7781	0.2159
HOE (PRE)	6	3.9078	0.8078	8	6.7953	0.4510
POST * HOE (PRE)	6	12.3078	0.1734	8	5.1141	0.6489
Residual error	58	7.8573		54	6.8341	
			Early season estimate of weed control			
Block	3	2144.2792	< 0.0001	3	5317.2787	< 0.0001
PRE	1	1239.8616	0.0260	1	50.0298	0.7544
Error block * PRE	3	1586.3458	0.0006	3	1006.4194	0.1275
POST (PRE)	2	9626.0045	< 0.0001	2	7627.7792	< 0.0001
HOE (PRE)	6	394.6146	0.1466	8	329.3515	0.7306
POST * HOE (PRE)	6	264.5063	0.3653	8	215.6408	0.8994
Residual error	58	237.3491		49	505.4492	
			Late season weed biomass			
Block	3	600.6712	0.7014	3	1357.7222	0.0005
PRE	1	1452.9922	0.2885	1	20.5234	0.7461
Error block * PRE	3	3136.7253	0.0703	3	113.0422	0.6285
POST (PRE)	2	5504.7383	0.0174	2	1610.9558	0.0008
HOE (PRE)	6	3364.5731	0.0240	8	177.8365	0.5096
POST * HOE (PRE)	6	1505.8791	0.3249	8	126.3994	0.7296
Residual error	58	1266.4106		49	193.6423	
			Crop yield			
Block	3	0.1697	0.1185	3	1.8891	0.0041
PRE	1	0.0403	0.4893	1	0.0064	0.8970
Error block * PRE	3	1.1669	< 0.0001	3	0.2682	0.5487
POST (PRE)	2	0.2684	0.0470	2	0.3681	0.3828
HOE (PRE)	6	0.1417	0.1369	8	0.2819	0.6475
POST * HOE (PRE)	6	0.0871	0.4051	8	0.0982	0.9754
Residual error	58	0.0832		49	0.3759	

[1] PRE = pre-plant weed controls (glyphosate or rotary harrow), POST = post-emergence herbicide, HOE = rotary hoe

Figure 2.3. Estimate of weed control by pre-plant weed controls and post-crop emergence herbicide in pea and wheat, 2004. Data represent means ± standard errors, and bars with the same letter within the crops are not significantly different based on Bonferroni's LSD (0.05).

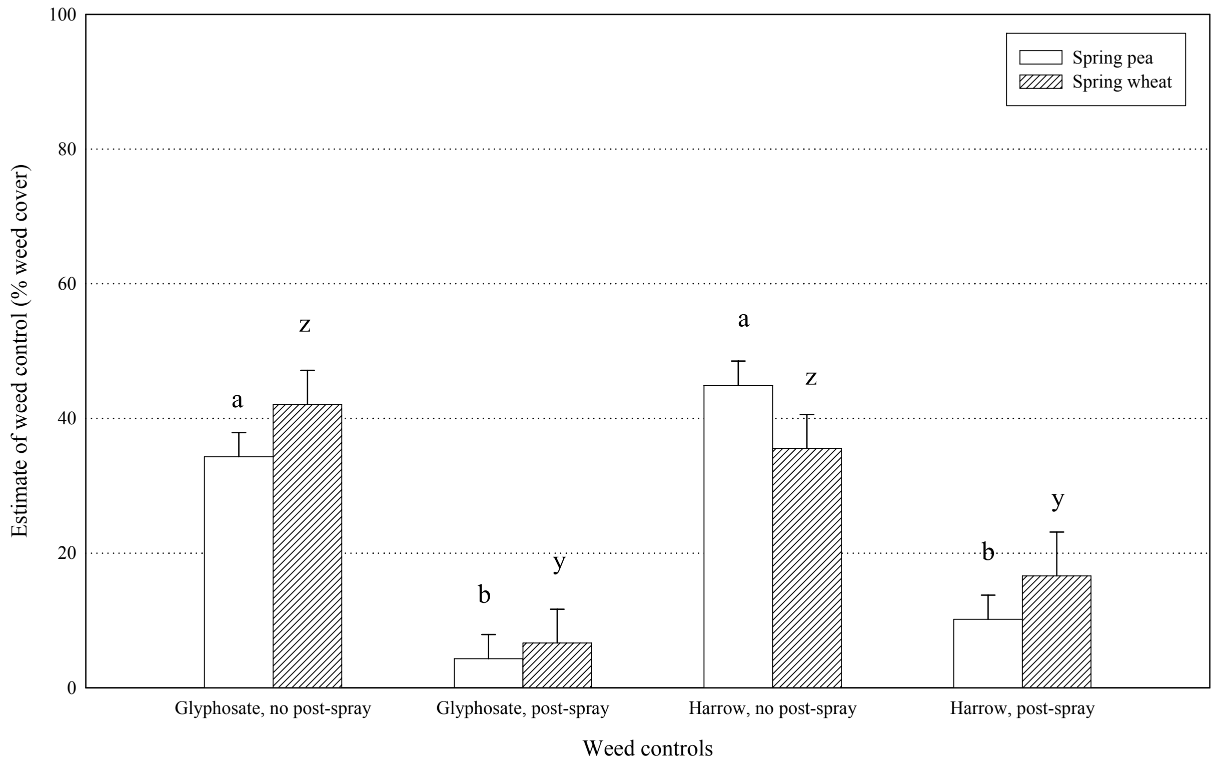


Figure 2.4. Weed biomass in peas by pre-plant and post-plant weed controls, 2004. Data represent means ± standard errors, and bars with the same letter are not significantly different based on Bonferroni's LSD (0.05).

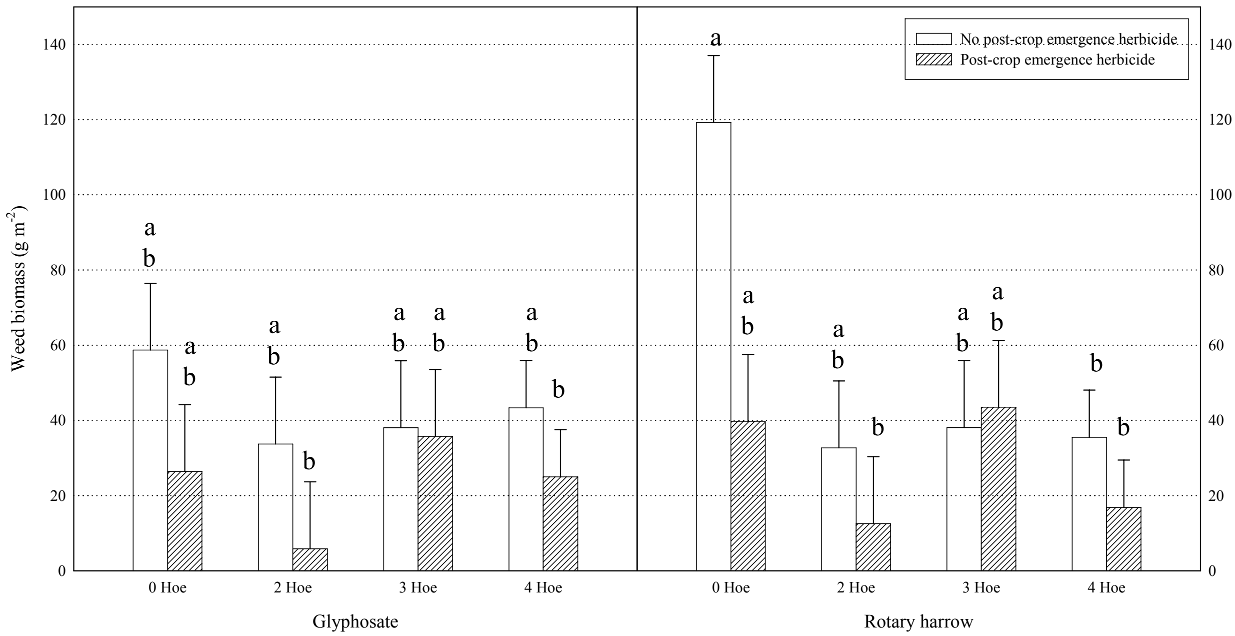


Figure 2.5. Weed biomass in wheat by pre-plant weed control and post-crop emergence herbicide, 2004. Data represent means ± standard errors, and bars with the same letter are not significantly different based on Bonferroni's LSD (0.05).

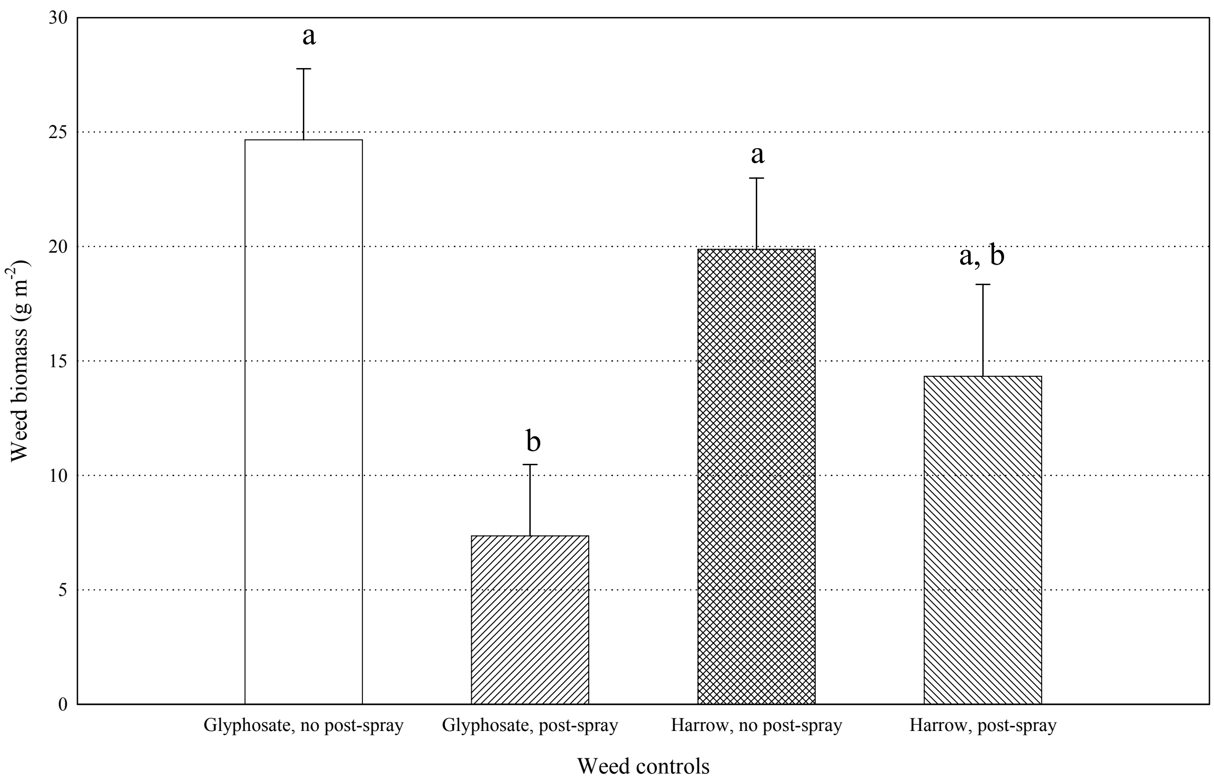


Figure 2.6. Crop yields by pre-plant weed control and post-crop emergence herbicide. The pea (a) and wheat (b) yields are shown from 2004. Data represent means ± standard errors, and bars with the same letter within the crops are not significantly different based on Bonferroni's LSD (0.05).

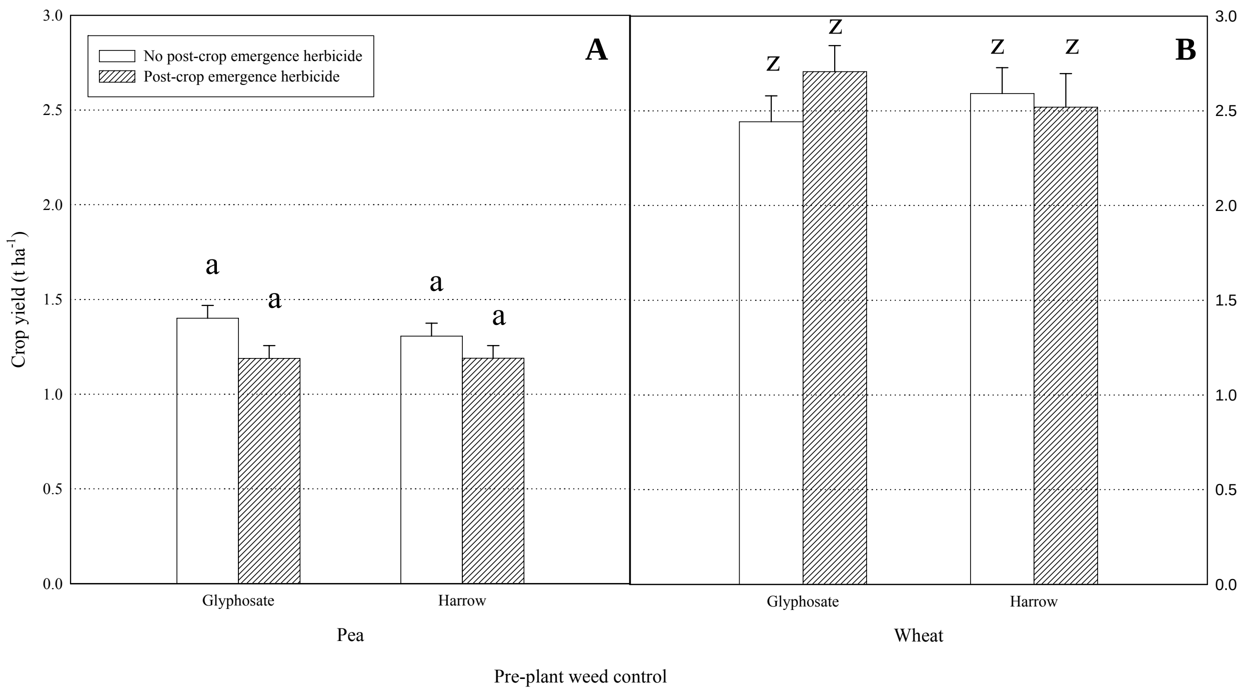


Table 2.4. Analysis of variance for data collected in 2005.

Source of variation[1]	Spring pea			Spring wheat		
	Df	Mean square	P-value	df	Mean square	P-value
			Crop density[2]			
Block	3	14.7707	0.1703	3	21.3007	0.0469
HAR	1	2.6486	0.5637	3	1.9149	0.8338
Error block * HAR	3	21.9880	0.0744	5	3.8283	0.7187
HERB (HAR)	1	4.6861	0.4448			
HOE (HAR)	6	6.4452	0.5519	9	13.7292	0.0884
HERB * HOE (HAR)	3	3.3304	0.7274			
Residual error	13	7.5462		19	6.6612	
			Late season weed biomass			
Block	3	5255.3542	0.2108	3	5382.2083	0.4351
HAR	1	69028.0000	< 0.0001	1	56786.0000	0.0039
Error block * HAR	3	13216.0000	0.0155	3	9143.2095	0.2128
HERB (HAR)	2	339800.0000	< 0.0001	2	186383.0000	< 0.0001
HOE (HAR)	6	11090.0000	0.0107	6	7609.1459	0.2781
HERB * HOE (HAR)	6	3575.0522	0.3945	6	6490.1077	0.3697
Residual error	34	3314.3274		28	5732.8946	
			Crop biomass at pea pod development and wheat flowering			
Block	3	4496.5254	< 0.0001	3	1634.8048	0.4158
HAR	1	1680.3614	0.0316	1	13192.0000	0.0089
Error block * HAR	3	467.3481	0.2602	3	165.7663	0.9596
HERB (HAR)	2	38747.0000	< 0.0001	2	82910.0000	< 0.0001
HOE (HAR)	6	765.3674	0.0580	6	3562.3012	0.0803
HERB * HOE (HAR)	6	418.8792	0.3047	6	485.0186	0.9362
Residual error	34	334.2667		28	1666.3869	
			Crop yield			
Block				5	0.3024	0.0169
PRE				1	1.9929	0.0001
Error block * PRE				3	0.2768	0.0381
HOE (PRE)				9	0.3686	0.0034
Residual error				16	0.0778	

[1] HAR = rotary harrow, HERB = pre-plant glyphosate and 2,4-D herbicides, HOE = rotary hoe, PRE = rotary harrowed treatments with or without glyphosate and 2,4-D.

[2] The sources of variation of the wheat density for the rotary harrow included rotary harrowed treatments with or without glyphosate.

Figure 2.7. Weed biomass in pea by pre-plant weed controls and rotary hoe operations, 2005. The pre-plant weed control treatments labeled with 'herbicide' refers to glyphosate and 2,4-D. Data represent means ± standard errors, and bars with the same letter are not significantly different based on Bonferroni's LSD (0.05).

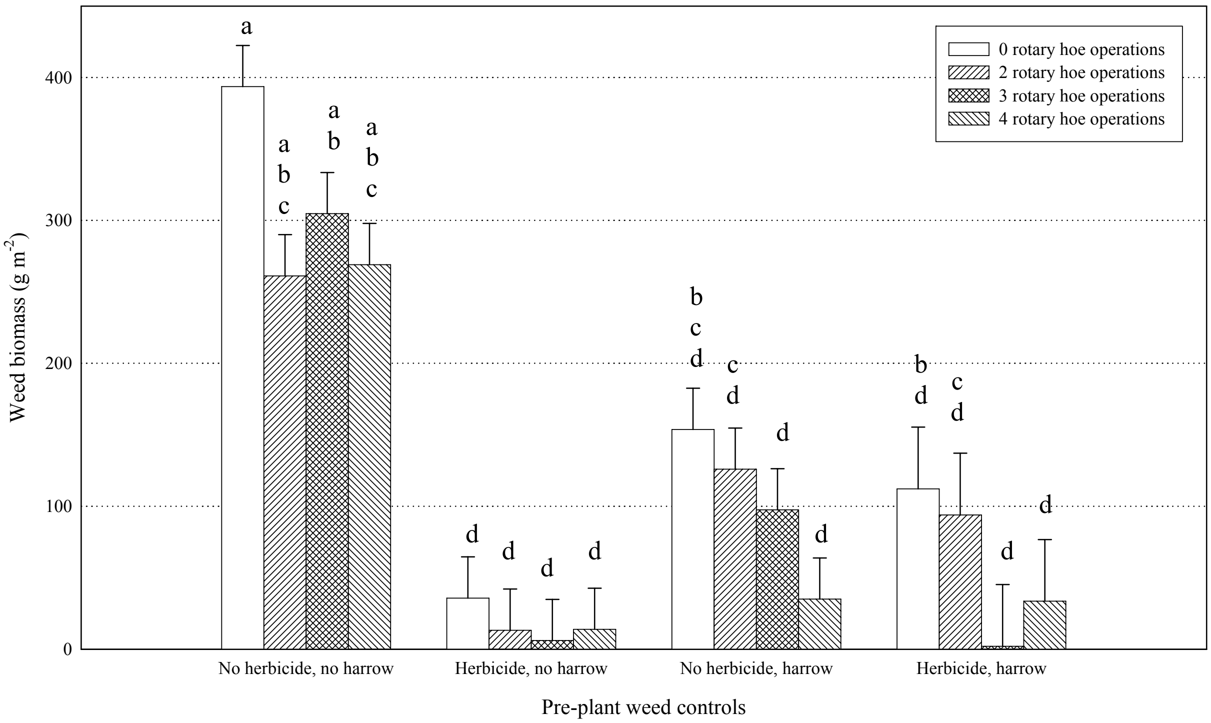


Figure 2.8. Weed biomass in wheat by pre-plant weed controls and rotary hoe operations, 2005. The pre-plant weed control treatments labeled with 'herbicide' refers to glyphosate and 2,4-D. Data represent means ± standard errors, and bars with the same letter are not significantly different based on Bonferroni's LSD (0.05).

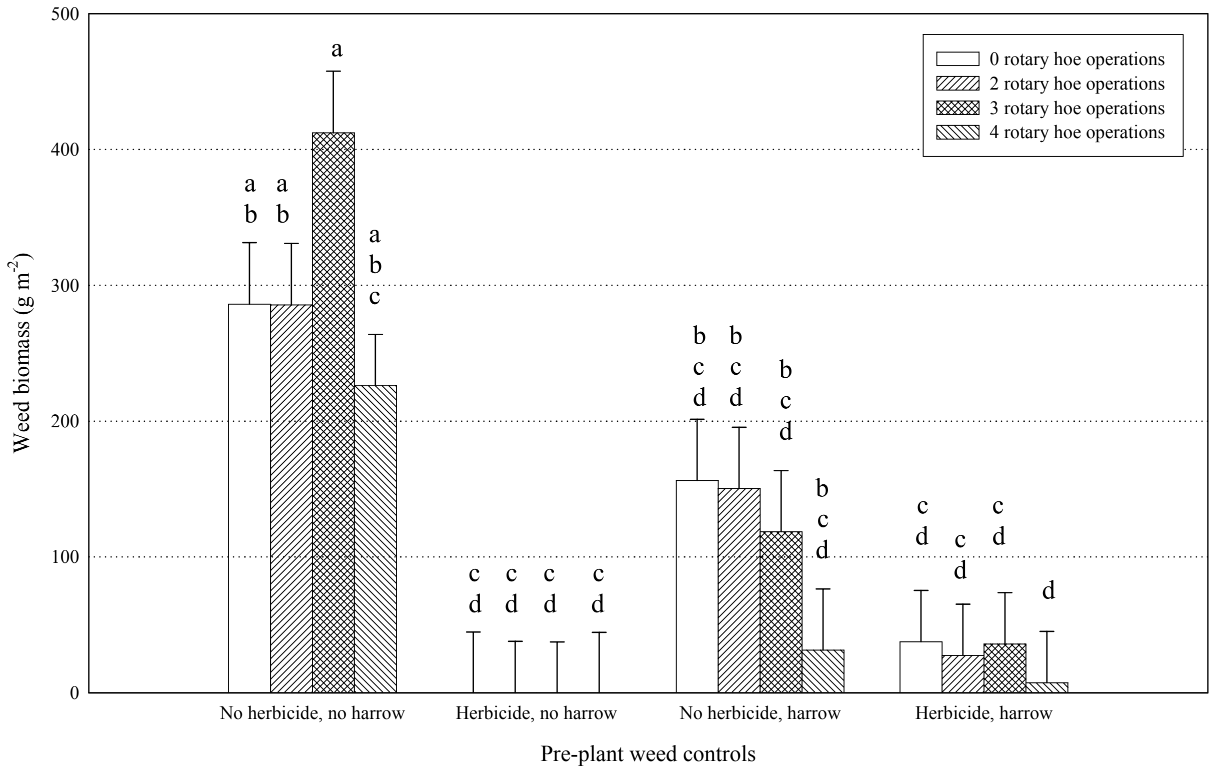


Figure 2.9. Pea biomass at pod development by pre-plant weed controls and rotary hoe operations, 2005. The pre-plant weed control treatments labeled with 'herbicide' refers to glyphosate and 2,4-D. Data represent means ± standard errors, and bars with the same letter are not significantly different based on Bonferroni's LSD (0.05).

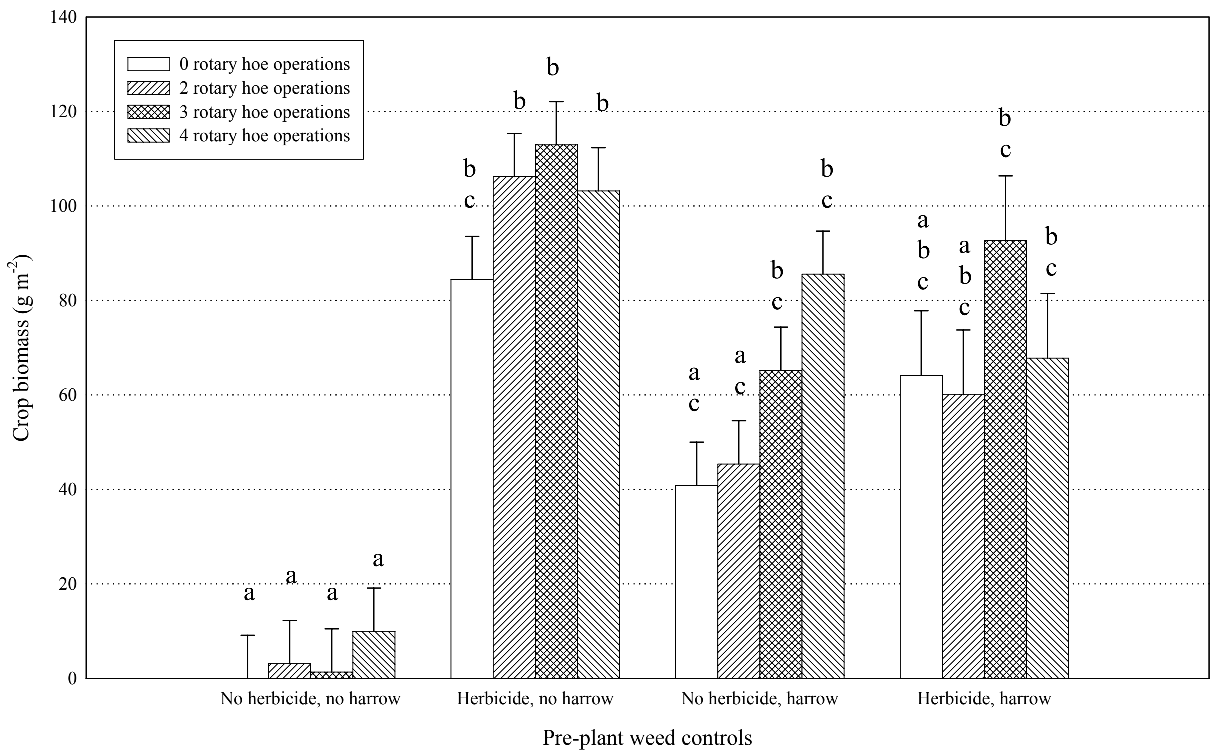


Figure 2.10. Wheat biomass at flowering by pre-plant weed controls, 2005. The pre-plant weed control treatments labeled with 'herbicide' refers to glyphosate and 2,4-D. Data represent means ± standard errors, and bars with the same letter are not significantly different based on Bonferroni's LSD (0.05).

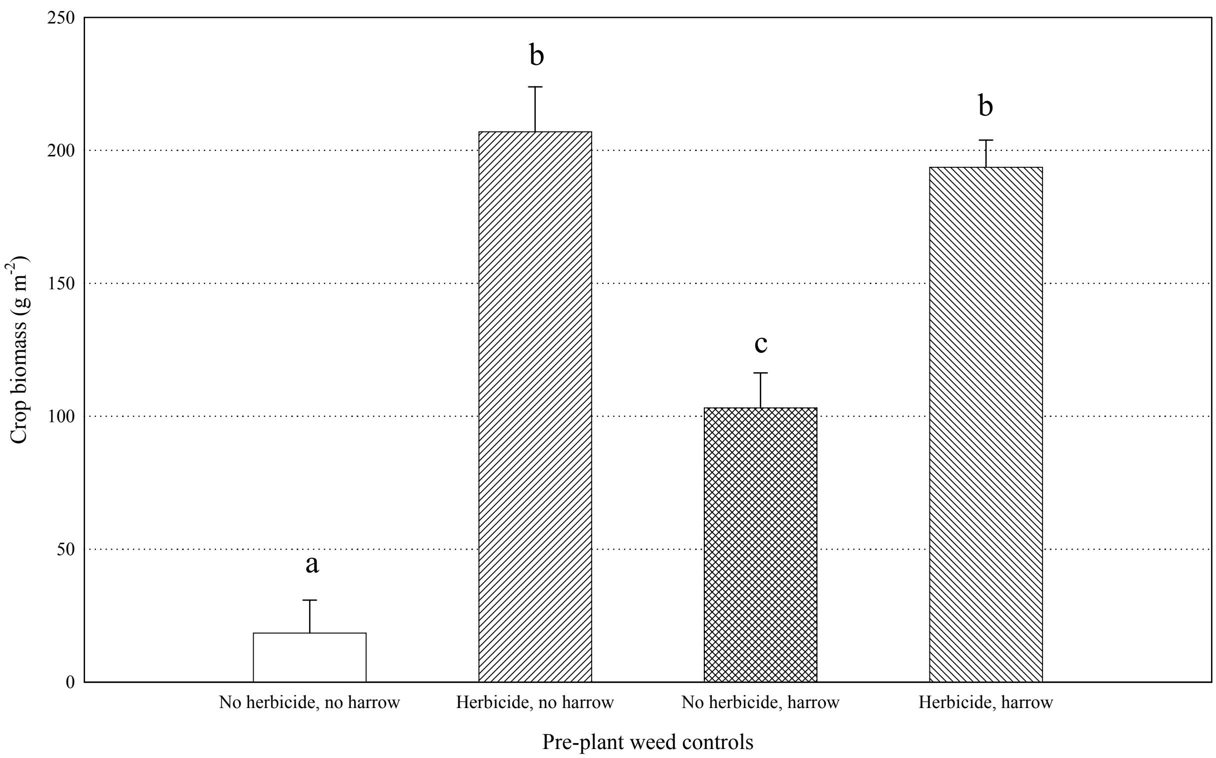
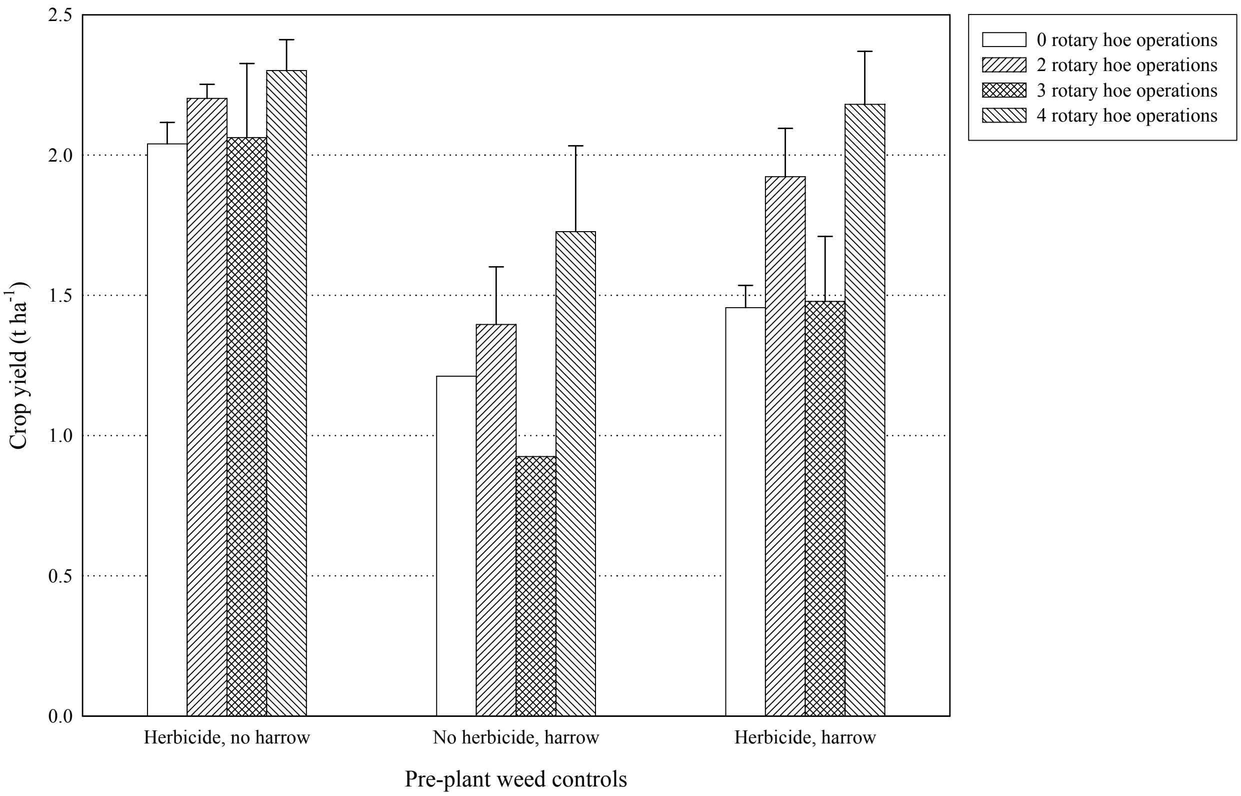


Figure 2.11. Wheat yield by pre-plant weed controls and rotary hoe operations, 2005. The pre-plant weed control treatments labeled with 'herbicide' refers to glyphosate and 2,4-D. Data represent means ± standard errors.



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CHAPTER THREE

CONTROL OF *RHIZOCTONIA SOLANI* IN INTACT SOIL CORES USING SOIL DISTURBANCES

INTRODUCTION

Rhizoctonia root rot is one of the most important cereal diseases delaying adoption of conservation tillage cropping systems in the wheat-growing region of the Pacific Northwest (PNW) (Smiley, 1996). *Rhizoctonia solani* Kühn (telemorph: *Thanatephorus cucumeris* Frank) and *R. oryzae* Ryker & Gooch (teleomorph: *Waitea circinata* Warcup & Talbot) have both been isolated from plant roots affected by Rhizoctonia root rot, but it is unclear which of the species is the primary incitant of disease in the field (Ogoshi et al., 1990; Smiley and Uddin, 1993; Mazzola et al., 1996; Paulitz et al., 2003). Nevertheless, a wide range of virulence exists within *Rhizoctonia* species, and *R. solani* and *R. oryzae* both contribute to disease incidence.

The symptoms of Rhizoctonia root rot first appear as individually stunted plants within rows of healthy, productive plants. As infection progresses, aboveground circular patches of stunted and chlorotic plants develop, and the patches can coalesce until large portions of a field appear uniformly affected. In a chronic form, patch symptoms do not appear, although moderate root damage, seen as lesions and pruning of seminal and crown roots, can cause up to a three week delay in wheat maturation (Smiley and Wilkins, 1992). Winter wheat yields of severely infected plants can be 50% less than those of surrounding disease-free plants (Weller et al., 1986).

Reduced tillage and weed management practices contribute to the severity of Rhizoctonia root rot. *Rhizoctonia solani* and *R. oryzae* overwinter in soil, inside of roots, or on residue as sclerotia, a source of primary inoculum. Sclerotia germinate, and hyphae grow towards seedlings, stimulated by root exudates. Infection of the epidermis and cortex causes tissue degeneration, which appears as dark-colored lesions, and pruning of crown and seminal roots, which result in black or brown "spear tips" at the ends of severed roots (MacNish, 1985). As facultative saprophytes, *Rhizoctonia* spp. overwinter on the roots of living plants, such as weeds and crop volunteers, that survive post-harvest and pre-plant weed control, providing an important source of inoculum. The fungi then grow from the weeds to newly planted crops, a process referred to as green bridging (Smiley and Wilkins, 1992).

Pre-plant herbicides, however, may not necessarily be effective in controlling the spread of disease. When wheat or barley is seeded 2 or 3 days after fields have been sprayed with glyphosate, a non-selective, systemic herbicide, Rhizoctonia root rot can still cause reductions in crop yield and quality (MacNish, 1985; Pumphrey et al., 1987; Roget et al., 1987). Waiting 2 to 3 weeks before seeding wheat or barley may reduce disease severity and crop damage (Roget et al., 1987; Smiley et al., 1992), but, a 2-week delay in planting can also cause a yield reduction and may not be a suitable control option under a low disease pressure.

Few management options are available for the control of Rhizoctonia root rot. In over a decade of research, genetic resistance to Rhizoctonia root rot has not been identified in locally adapted wheat and barley varieties, but some show varying degrees of susceptibility (Smith et al., 2003). Seed treatments and fungicides are not effective against Rhizoctonia root rot because commercially available seed treatments do not move systemically to the root and fungicides do not prevent infection in the field, even though some show control of *R. solani* in laboratory conditions. Declines in Rhizoctonia root rot have been found in long-term continuous cereal production systems (MacNish, 1988; Lucas et al., 1993; Roget, 1995), but it is unclear which management practice can be adopted in the cereal and legume conservation tillage production systems of the PNW to reduce disease severity. Seeing that Rhizoctonia root rot has been identified in many broadleaf crops, including peas, lentils, and canola, crop rotation may not be an effective technique to reduce disease (Paulitz, 2002).

It is thought that tillage breaks the hyphal network and fragments the inocula of *Rhizoctonia* spp., reducing its inoculum potential, which has been investigated in other fungal pathogens (Evans and Miller, 1990; Kabir et al., 1997). Cook et al. (2000) reported that disruption of soil within the seed zone during planting reduced the severity of disease, and Roget et al. (1996) found that placement of fertilizer below the seed, which increases crop growth and competitiveness, can be used to eliminate the green bridge. Tillage may also stimulate microflora that are suppressive to *Rhizoctonia*, since it is well known that tillage causes a burst of respiration in the soil due to increased microbial activity. The objective of this research was to investigate how soil disturbances affect *R. solani* when inoculated in intact soil cores in a controlled environment. We hypothesized that soil disturbances can reduce the inoculum potential of *R. solani* by breaking the hyphal network of the pathogen even if wheat is seeded within two days of applying a non-selective, systematic herbicide to control weeds. A reduction in the inoculum potential of *R. solani* would limit disease infection and reduce the severity of disease.

MATERIALS & METHODS

The experimental design was a repeated measure with two treatments and 6 replications. The first treatment consisted of 0 (control), 1, 2, or 3 soil disturbances, and the second treatment consisted of 4 repeatedly measured 4-cm intervals within the soil core profile. In addition to the

6 replications, 6 samples were used for procedural purposes, but were not planned to be included in the statistical analysis.

Rhizoctonia solani *Inoculum Preparation*

Rhizoctonia solani inoculum was prepared according to the methods described by Paulitz and Schroeder (2004). One-liter Erlenmeyer flasks were filled with 250 ml of oat kernels and equal parts water and autoclaved two times within 48 hours. The kernels were inoculated with *Rhizoctonia solani* that had been growing in a 90 mm petri dish on potato dextrose agar (PDA) growth medium (made of 24 g potato dextrose broth, 20 g agar, and 1 l water) for 2 weeks. The flasks were shaken once a week to increase aeration and kept at 23°C in the dark. After 4 weeks, the inoculated oat kernels were spread on dry, clean paper, air dried in a laboratory fume hood to reduce contamination, and stored at 4°C until needed.

Inoculated oat kernels were evaluated for *R. solani* propagule density and fungal contamination according to the methods described by Schroeder (2004). Three separate 100-mg samples of inoculated oat kernels were ground for several seconds in an electric coffee grinder and sieved through 1 mm^2 and 250 μm^2 screens. Each sample was used to make a 1 to 10, 1 to 100, or 1 to 1000 dilution of ground inoculum and deionized water. Two hundred µl of each dilution was plated onto *R. solani* selective growth media [100 mg chloramphenicol (3.3 ml of 30 mg ml^{-1} stock), 1 mg benomyl (1 ml of 1000X stock), 20 g nutrient agar, and 1 l water] in 90-mm petri dishes. The number of *R. solani* colonies in each dish was recorded after 24 hours to estimate the number of propagules on the inoculated oat kernels so that the inoculum density of the soil cores was consistent to previous research (Paulitz and Schroeder, 2004, Schroeder 2004).

To evaluate the oat grain for fungal contamination, one kernel was placed in five 90 mm petri dishes on PDA media (Figure 3.1). The dishes were kept at 23°C in the dark for 48 hours and examined for fungal contamination based on hyphal morphology using a dissecting microscope (Olympus SZ 10-40 X). If contamination was prevalent, the entire batch of oat kernels was not used for soil inoculation.

Creating a Green Bridge

Soil cores were taken on November 5, 2004 from field plots on Boyd Farm (46°44’59’’ N, 117°05’00’’ W) in Pullman, WA where conservation tillage had been practiced for 3 years. Soil was extracted into 4 mm thick, 14.8 cm diameter, and 25.5 cm tall PVC (polyvinyl chloride) piping using a tractor-mounted Giddings[1] hydraulic soil sampling and coring machine and stored dry until needed.

A temperature and light-controlled environment was used to facilitate volunteer crop growth and *R. solani* infection. Soil cores were placed into a 15°C growth chamber with a long day cycle (14 hours light/10 hours dark) under 44 W high output fluorescent lights and watered to field capacity. After 5 days, a spring barley seed (‘Morex’) was sown into one of ten 9-cm deep holes, which were uniformly spaced on the surface of each core. After seeding, the cores were watered about every other day and fertilized weekly with 150 parts per million N of 15-5-15 (N-P-K) solution until the barley reached the three-leaf stage (Zadok growth state of 13) approximately 3-weeks after barley seeding (Figure 3.2).

On the first and second run of the experiment, 5 and 10 grams of inoculated oat kernels were added to seven randomly placed holes on the surface of each core, respectively. Each hole was 18-cm deep, and a small amount of 1 to 2 mm^2 sieved field soil was added between each inoculated oat kernel. Sieved field soil was added to the seven holes of three additional soil cores without the inoculated oat kernels so that the natural population of *R. solani* in the field soil could be assessed.

[1] Giddings Machine Company, Fort Collins, CO

The final steps allowed for the pathogen, which was living in the soil and on the barley roots, to infect newly planted wheat. Glyphosate (2.3385 l ha^{-1}) was applied to the barley soon after tillering (Figure 3.3), and a single wheat seed ('Alpowa') was sown into four 9-cm deep holes 48 hours after herbicide application. The *R. solani* population was estimated when the wheat was at the three-leaf stage (Zadok growth stage of 13) approximately 2 weeks after seeding, 5 weeks after inoculation, and before the treatments were initiated.

Measuring the* R. solani *Population

A toothpick bioassay was used to estimate the population of *R. solani*, which was measured as the number of colony forming units per gram of soil. The methods developed by Paulitz and Schroeder (2004) were used in this experiment as well as a modified procedure, which enabled evaluation of *R. solani* deeper in the soil core. In both experimental runs, the *R. solani* population was evaluated before and after inoculation and in the soil cores that were not inoculated.

With this method, five flat wooden toothpicks were inserted into each pot to intersect the growth of fungal hyphae. After 48 hours, the toothpicks were placed onto RS media in 90-mm petri dishes, which were left at room temperature for 24 hours, and the toothpicks were examined for the presence of *Rhizoctonia spp.* using an Olympus SZ 10-40 X dissecting microscope[2]. Colonies of *R. solani* and *R. oryzae* were distinguished based on hyphal morphology, and the number of *R. solani* colonies growing from the toothpicks was estimated using a 5-mm grid beneath the dish. If the grid square contained *R. solani* hyphae, it was counted as one colony, and the total number of colonies per five toothpicks was recorded.

Five weeks after inoculation of the soil cores, the five toothpicks were inserted directly into the soil cores along a random transect. In addition, five 15-cm long bamboo skewers were

[2] Olympus America, Inc., Center Valley, PA

used to measure *R. solani* deeper in the soil core. The skewers were also inserted along a random transect within the soil core. After 48 hours in the growth chamber, the toothpicks and skewers were removed from the soil cores, the latter were cut into 4-cm segments, and both were placed onto RS media in 90-mm petri dishes for 24 hours at room temperature. Similar to the pre-inoculation procedures, the toothpicks and skewers were examined under the dissecting microscope, and the number of *R. solani* colonies were counted using the 5-mm grid square system.

RESULTS & DISCUSSION

Poor green bridge colonization prevented the experiment form being completed, since without high populations of *R. solani* in the cores, I could not measure the effect of the disturbance treatments. In the first run, the toothpick assay measured few or no colony forming units of *R. solani* before the treatments were initiated. Consequently, the inoculum density was doubled in the second run, however, few or no colony forming units were detected in the toothpick bioassay conducted 5 weeks after inoculation.

Several factors could have prevented soil inoculation. This same inoculation technique has been used previously on large soil cores, with oat seeds added to the center of the core and the spread of *R. solani* and *R. oryzae* were measured over time radiating out from the center (Schroeder, 2004). However, in one of his runs, the fungus failed to spread (Schroeder, 2004). Most likely, poor kernel to soil contact hindered the growth of *R. solani*, thus few colony forming units were detected by the toothpick bioassay. Another possibility was that a suppressive microflora was present in the soil, which prevented the spread of *Rhizoctonia*, but colony forming units were detected in one of five non-inoculated soil core samples in the first run of the experiment, which indicates that the environmental conditions were appropriate to encourage the growth of the natural populations of *Rhizoctonia*. Another possibility was that not enough time was allowed for the fungus to colonize the roots of barley and then colonize the wheat after the barley was killed. A higher density of inoculated oat kernels may have allowed for greater infection of the barley. In any case, without a high level of *Rhizoctonia* activity in the core, the effect of disturbance could not be analyzed.

CONCLUSIONS

Despite the results of this study, it still remains uncertain whether tillage tools can be used to control Rhizoctonia root rot effectively. Research has shown that inoculum of Rhizoctonia is present in the top 10 cm of soil, which would be affected by the tillage systems evaluated in this thesis (Paulitz et al., 2003), and soil disturbances can reduce Rhizoctonia disease in a sandy soil (Gill et al., 2001). Nonetheless, there may be more acceptable alternatives in a production system, such as the selection of cultivars with disease resistance, proper fertilizer placement, and use of biological control agents in seed treatments (Howell et al., 2000). Nonetheless, more research is needed under field conditions to determine the extent to which mechanical tillage tools can be used for disease and pest control.

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Figure 3.1. Petri dishes indicating the presence of fungal contamination on inoculated oat kernels. (Photos taken by S. Kopan)

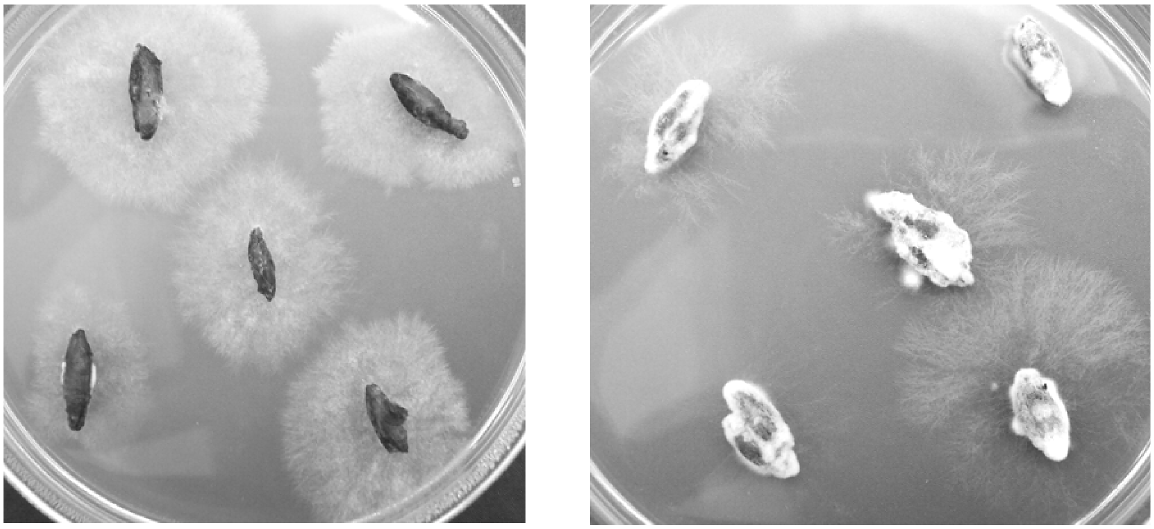

Figure 3.2. Young barley plants prior to inoculation. (Photo taken by S. Kopan)

Figure 3.3. Inoculated barley plants prior to glyphosate application. (Photo taken by S. Kopan)

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