WEED SEEDBANK DYNAMICS AND COMPOSITION OF NORTHERN GREAT PLAINS CROPPING SYSTEMS

by

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ABSTRACT

With a growing concern about sustainability of agricultural production systems, interest in integrated weed management systems has increased. Increasing the understanding of weed seedbank dynamics will improve efficiency of management. The objectives of this study were to 1) quantify weed seedbank dynamics in response to seed density and burial depth, 2) determine weed seedbank decay at varying seed densities and burial depths, 3) quantify weed seed predation in wheat and tilled fallow fields, and 4) characterize and compare weed seedbanks in organic and conventional no-tillage production fields.

Objective 1 was carried out at Montana State University's Arthur H. Post Agronomy Farm. Seedbanks were established at four densities and two burial depths. Weekly seedling counts were taken for two consecutive growing seasons. Data indicated higher density seedbanks had lower proportions of emergence. Individual species responded differently to depth treatments. We concluded that management affecting seed density and depth will affect seedling emergence.

Objective 2 was carried out in the same plots as objective 1. Seedbank samples were used to separate seeds. We found that all studied species declined to low levels over two years with little difference due to depth and density. Wild oat seeds were more germinable in buried treatments. We concluded that seedbanks of these species will decline quickly with lack of seed inputs.

Objective 3 was carried out in four spring wheat and four tilled fallow fields at Montana State University's Arthur Post Agronomy Farm. Surface seed predation was measured at six times during the growing season for four weed species. We observed that predation levels did not differ between wheat and fallow fields for three of four species. We conclude that seed predation can represent an important loss in Montana.

Objective 4 was carried out in spring wheat production fields near Big Sandy, Montana. Weed seedbanks were sampled along a range of aboveground weed diversity points over two years. Weed seedbank composition and characteristics did not differ between cropping systems, but did between years. We conclude that weed seedbank diversity and richness may vary based more upon yearly environmental factors than the management system.

CHAPTER 1

PROJECT BACKGROUND AND OBJECTIVES

Introduction

Agriculture is a worldwide constant and an important part of the global economy. It is, in fact, the largest single industry, employing over a billion people and produces over a trillion dollars of goods annually (Clay, 2004). The United States is a major player in the global agricultural economy. In 2004, agricultural exports exceeded 100 billion dollars (NASS, 2005) and the U.S. share of world cereal production was over 17% (FAOSTAT, 2007).

Weeds have always been a problem in cropping systems. High weed densities reduce crop yield and quality. Although weed management techniques have become more powerful over time, weeds are still present in cropping systems. Weed control was traditionally accomplished by mechanical means (hoe, plow, hand-weeding). The advent of herbicides provided an alternative control method. However, the widespread use of herbicides has led to widespread herbicide resistance in weeds. Recent observations place the number of herbicide resistant species at 183 worldwide, both monocots and dicots (Heap, 2007).

As the numbers of herbicide resistant weeds have increased, the number of conventional pesticides registered with the Environmental Protection Agency has declined. During the last 15 yr, the numbers of biological pesticides registered have increased steadily (USEPA, 2005). Along with the decrease in conventional product registration, there is a trend towards a more ecological view of weed management (Liebman and Gallant, 1997). This is often called “integrated weed management” in that it combines a more traditional view of weed management with an understanding of weed, pest, and crop ecology to increase the efficacy of weed management.

An important part of crop weed ecology is the weed seedbank as it is the most important source of annual weeds in cropping systems and therefore represents a significant point in the weed life cycle for control. The weed seedbank serves as a physical history of the successes and failures of cropping systems and management in a field. Cropping systems have also been shown to affect weed seedbank composition, density, and diversity (Cardina et al., 2002; Tuesca et al., 2004; Murphy et al., 2006; Sosnoskie et al., 2006). These relationships make understanding the weed seedbank even more important for increasing the efficiency of weed management.

Understanding the dynamics of weed seedbanks is an essential first step in improving weed management plans (Buhler et al., 1997). By understanding how long seeds remain viable in the seedbank and how those seeds are related to the aboveground weed community, a producer could tailor weed management programs to increase efficiency and efficacy. Seed predation can also represent an important part of a weed management plan. A number of studies worldwide have shown that weed seed loss to predation can have a significant, if variable, impact on the weed seedbank (Honek et al., 2003; Westerman et al., 2003a; Holmes and Froud-Williams, 2005; Marino et al., 2005; Jacob et al., 2006; O'Rourke et al., 2006; Menalled et al., 2007). A number of these studies have observed how cropping system, canopy cover, and seed density can affect the predation. However, to our knowledge, no work has been done comparing weed seed predation in cropped and fallow fields of the northern Great Plains.

Because of the knowledge that crop, tillage system, weed management, and environmental factors affect weed seedbanks; the lack of seedbank studies in the northern Great Plains represents an important knowledge gap for producers in the area. This project aims to help increase the information on weed seedbank dynamics, composition, and seed predation in the northern Great Plains region.

Literature Review

The seedbank is the main source of propagules for annual weeds and a very important one for biennials and perennial species. Because agricultural weeds may remain viable in the seedbank for many years, seedbank dynamics and seed persistence can have long-lasting effects on crop yields (Cavers and Benoit, 1989). Moreover, changes in emergence times, persistence, and over-winter dormancy and survival can be affected by both the crop rotation (Bellinder et al., 2004) and weed management practices (Cardina et al., 2002), making an understanding of seedbank characteristics more complicated. This section summarizes previous studies assessing the composition and dynamics of seedbanks with special emphasis on agricultural systems.

Weed seedbank assessment strategies

There are two approaches to estimate seedbank composition and density: first, separation of seeds from a soil sample and second, counts of emerged seedlings from soil samples (Luschei, 2003). While seed separation is time consuming and expensive in terms of labor; counts of emerged seedlings do not give a full picture of the seedbank, leaving out dormant and dead seeds as well as seeds that may need special vernalization. In a statistically based modeling study, Luschei (2003) determined that in most cases data gathered with seedling counts gave a better picture of seedbank density than soil sampling. However, with higher seedbank variation, soil sampling could give a better picture of the seedbank.

Sample size and distribution also plays an important role in the efficiency of seedbank characterization. Ambrosio et al. (2004) compared systematic and random sampling of the seedbank. When seedbank spatial variability was taken into account, systematic sampling with a square grid was more efficient than random sampling. Seedbank density also has an affect on the precision of sampling methods (Mickelson and Stougaard, 2003), with denser seedbanks more precisely quantified with any sample size than lower density seedbanks. However, at low seedbank densities, a smaller number of large size samples give a more precise picture of the seedbank (Mickelson and Stougaard, 2003).

There are several ways of separating seeds from soil samples. In the modified floatation method (Buhler and Maxwell, 1993), seeds are separated from soil using a K_2CO_3 solution and centrifugation. This method gives good recovery of several species of seeds, but affects their ability to germinate. Gross and Renner (1989) used a modified root elutriator to remove seeds from soil samples. Although this method gave good recovery rates for the three species tested and had no effect on the seed viability, it is rather time consuming.

To estimate seedbank density and community composition, Gross (1990) compared germination efficacy with a cold treatment, germination without a cold treatment, and elutriation. She found that while germination with a cold treatment can give the most complete estimation of the composition of the seedbank, separating seeds by elutriation gives a higher estimate of the density of seeds because of the inclusion of non-viable seeds in the samples. Germination without cold treatment did not give as complete an estimation of the seedbank composition as the cold treated samples.

In light of these results, the objectives of the study should be considered when choosing a method of extracting seeds. If viability is an important factor, elutriation may be the best method. If time is a constraint, K_2CO_3-centrifugation may be a better method. Direct germination would be the best option if a picture is needed of which seeds were most likely to be a part of the aboveground community.

Impact of Management Decisions on Weed Seedbanks

Field management practices affect weed seedling emergence patterns (Mohler and Galford, 1997; Bond et al., 1998; Spandl et al., 1998; Spandl et al., 1999; Cardina et al., 2002; Bullied et al., 2003; Peachey et al., 2004; Van Acker et al., 2004), weed seedbank diversity (Mayor and Dessaint, 1998), seed dormancy and viability (Mohler and Galford, 1997; Davis and Liebman, 2003), and seed placement (Cardina et al., 2002; Mohler et al., 2006). All of these factors can have important impacts on seedbank management decisions. As these factors and their impacts are taken into account, the efficiency and efficacy of management can be increased.

For example, tillage can change weed seed dormancy status by exposing seeds to short pulses of light needed as germination triggers (Milberg et al., 1996). This can cause a flush of emergence after tillage and has been used as a control measure with preparation of a stale seedbed to deplete the weed seedbank (Carroll and Mullinix, 1995; Juroszek and Gerhards, 2004; Rasmussen, 2004). In this case, a field is tilled and the flush of weed seedlings is managed before planting of the crop (Swanton and Booth, 2004). The relationship between tillage and seedling emergence has also led to research on night tillage to avoid germination triggers (Scopel et al., 1994; Gallagher and Cardina, 1998). However, the effectiveness of dark tillage for reducing tillage triggered germination is not considerable (Scopel et al., 1994; Gallagher and Cardina, 1998). In a review of night-time tillage trials, Juroszek and Gerhards (2004) found a wide range of efficacy. This ranged from a 97.5% reduction in weed cover to an 80% increase in weed seedling emergence. A number of factors caused this range of variability, including the type of tillage implement used, the light sensitivity of the weed species, the variation in soil water content, and the dormancy status of the weed seeds.

In a study conducted in the UK, Froud-Williams et al (1983) found that seeds were not distributed uniformly in the soil by tillage and that this distribution fluctuated annually. In a later study conducted in Ohio, Cardina et al. (2002) found that in no-tillage systems, seedbank density tends to be higher that in tilled systems with most of the seeds concentrated near the soil surface. Mohler et al. (2006) used ceramic beads as seed surrogates to get a more complete picture of the affects of tillage types on vertical seed distribution. They found that chisel, disk, and rotary tillage buried at least 70% of seeds below 2 cm, but caused little effect below 10 cm. Tillage with a moldboard plow showed inversion of the soil, but burial of seeds was greater than movement of buried seeds towards the surface. In no-tillage and moldboard plow treatments, an upward movement of seeds by natural processes was observed below 14 cm.

Crop rotations and management systems can also influence seedbank composition and density, but this influence has been found to be less intense than tillage effects in conventionally managed systems (Cardina, 2002). Organic and conventional systems with different tillage, nitrogen inputs, and herbicide applications, but the same crop sequences, have been found to differ in seedbank abundance and composition in the Midwest USA (Menalled et al., 2001). After six years, weed seedbank densities decreased in the systems with lower herbicide inputs and high tillage intensity. Species composition also varied among management systems, with annual grasses being more common in the high chemical input systems and annual dicots dominating in the lower input and organic systems. Davis et al. (2005) conducted a study at the same site in Michigan as Menalled et al. (2001), but over twelve years. They also saw a divergence in the weed seedbank communities between the higher input systems and the low and no input systems. The seedbank had a positive correlation with the aboveground weed community in the organic and low-input systems, but very little predictive value in the conventional and no-tillage systems.

Within organic systems, crop rotation can have a more noticeable effect in some rotations than in others (Teasdale et al., 2004). Overall, longer rotations with more phenological variation in crops used, had the largest effect on reducing the density of the weed seedbank. Teasdale et al. (2004) also observed that the initial crop in the rotation affected the density and composition of the seedbank later in the study, located in Maryland.

Seedbank Dynamics

Assessment Methods. Artificially established seedbanks can often be used to quantify emergence times, dormancy levels, seedbank persistence, and other factors affecting weed seedbank dynamics. However, there are a number of potential problems with some methods commonly used to establish these seedbanks. Leon and Owen (2004) compared artificial seedbanks contained within PVC rings of 20 cm in diameter with those that were placed in the soil without containing rings. The contained seedbanks differed in emergence times and temperature fluctuation from those that were not surrounded by PVC pipes. This difference in seedbank behavior was greater in species that had a higher rate of environmentally enforced rather than morphological dormancy. In light of these findings, the design of seedbank studies and the interpretation of their results should be done with caution.

Environmental and Management Factors

Affecting Seedbank Dynamics. A number of studies conducted in the Midwest USA assessed the emergence patterns and dynamics of weed seedbanks (Forcella et al., 1992; Forcella et al., 1993; Anderson and Nielsen, 1996; Buhler et al., 2001; Menalled et al., 2004). These studies found that seedbank dynamics were influenced through a complex combination of factors, including soil water content, crop rotation, compost amendments, and tillage regime. Despite the importance of understanding how management systems impact seedbanks, very little is known of the factors affecting the composition and dynamics of seedbanks in the Northern Great Plains of North America. One study conducted in Colorado on feral rye (*Secale cereale* L.) found that most seeds germinated in the first year, but a small percentage remained dormant for four years (Stump and Westra, 2000). These results indicated that feral rye seedling emergence could be controlled by tillage and herbicide treatments during the fallow period. However, a year of increased rain or other favorable climate conditions, together with a weed control failure, could recharge the seedbank.

The position of a seed within the soil profile and in relation to other seeds in the seedbank could affect its ability to germinate and emerge. Benvenuti et al. (2001) found that seeds had much lower emergence from greater depths (3.6 to 7 cm) over a range of 20 species with the greatest effect on seeds of smaller weight. Boyd and Van Acker (2003) compared 14 species and found that all but three species (barnyardgrass *Echinochloa crus-galli (L.) Beauv.,* wild mallow *Malva pusilla* Sm., and common milkweed *Asclepias syriaca L.*) had higher emergence when planted near the soil surface (1-4 cm). Mohler and Galford (1997) found that for *Chenopodium album* (L.), *Amaranthus retroflexus* (L.), and *Abutilon theophrasti* (L.), seedling emergence decreased exponentially with increasing burial depth, although emergence increased with slight burial. In a five-year study, Roberts and Feast (1972) determined that most seeds germinated in the first growing season after planting. Egley and Williams (1991) also found that the greatest percentage of seedling emergence occurs in the first year after seed is introduced into the soil. When Roberts and Feast (1972) compared emergence rates of seeds buried at 2.5, 7.5, and 15 cm, they determined that seeds buried deeper had lower emergence rates and that increasing cultivation decreased the number of viable seeds. Froud-Williams et al. (1984) also found that seed burial decreased the emergence of small seeded weed species but germination and emergence of larger-seeded weed species was increased by burial. Grundy et al. (2003) found that larger and heavier seeds were able to overcome the effect of depth to some degree, being able to emerge from greater depths. Also, several species showed lower rates of emergence at higher seeding density, possibly an evolved response to decrease sibling competition.

Chauhan et al. (2006) studied the effects of tillage systems on the vertical distribution of rigid ryegrass (*Lolium rigidum* Gaudin) as well as the seedling recruitment and persistence of seeds in the seedbank. As expected, seedling recruitment was lower in the low disturbance systems, with recruitment two to four times higher in minimum tillage as compared to no-tillage systems. The number of residual viable seeds remaining in the seedbank from year to year was similar between systems, but the seed decay was much greater in no-tillage than under minimum tillage. While this study only observed one species, it shows the great impact that tillage can have on seedbank dynamics.

Position of the seed in the soil profile is only one of the factors that affect seed germination. The combination of other factors such as water, light conditions reaching the ground, percentage of bare ground, and disturbance regime also have an effect on whether a seed is able to germinate and establish (Burke and Grime, 1996; Booth et al., 2003). A favorable combination of these factors is referred to as a "safe site" for germination (Fowler, 1988). Boyd and Van Acker (2004) compared the relative importance of seed availability and safe site limitations in determining the emergence and establishment of new weed populations. They found that both factors had an effect on weed presence and recommend managing for both seedbank and site conditions to control weed emergence and establishment.

Predation Effects on Weed Seedbank Dynamics. Seed predation has been shown to be an important source of weed seed loss in the field, reducing the input into the seedbank for future years (Mittelbach and Gross, 1984; Cromar et al., 1999; Davis and Liebman, 2003; Westerman et al., 2003a; Holmes and Froud-Williams, 2005; Marino et al., 2005; Westerman et al., 2005; Heggenstaller et al., 2006; Jacob et al., 2006). Indeed, in a modeling exercise, Jordan et al. (1995) determined that weed seed survival was the most sensitive factor determining the abundance of weed seeds in a system. As with any biological process, the amount of seed predation can vary greatly dependent upon environmental factors such as canopy cover (Heggenstaller et al., 2006), tillage and crop residue (Cromar et al., 1999), presence of a cover crop (Davis and Liebman, 2003), and position in the field (Hulme, 1994; Jacob et al., 2006). Despite this dependence, weed demography studies determined that seed predation represents an important mortality factor on the abundance of weed in crop fields (Davis and Liebman, 2003; Westerman et al., 2005; Westerman et al., 2006).

Several studies have found density dependence in seed removal (Cromar et al., 1999; Marino et al., 2005). In a study conducted in southern Ontario, Cromar et al. (1999) found an increased amount of weed seed loss with seed density when the response analyzed was the weight of seed consumed. Marino et al. (2005) measured seed loss from cereal fields in the Netherlands as a percentage of initial seeds and although they were not able to find a clear density dependent relationship; they found a positive relationship between percent seed loss and the aggregation of seed in the field. When the effects of varying density and spatial arrangement of weed seeds on predation rates were compared, seed predators, mainly rodents, responded strongly to aggregated seeds, but there was no consistent response to seed density. The amount of predation was also temporally variable. This caused Marino et al. (2005) to conclude that density response may vary between types of seed predators.

Distance from field edge has not been shown to have consistent effect on weed seed removal (Marino et al., 1997; Westerman et al., 2003b). However, Hulme (1994) found that vertebrate predators lack the cover needed in the center of fields, decreasing seed predation and Jacob et al. (2006) found higher predation along field edges near bordering vegetation.

In another study, Holmes and Froud-Williams (2005) determined that different species of seed predators cause differing levels of seed loss. Heggenstaller et al. (2006) found that seed predation rates were crop-specific, were positively correlated with canopy cover, and varied throughout the season. The authors concluded that seed predation could be kept at a high level throughout the season by including crops with different phenology in the farming system.

Management practices could impact the abundance and effectiveness of weed seed predators. Cromar et al. (1999) compared weed seed predation rates among different tillage regimes in southern Ontario. They observed that seed removal was highest in no-till fields and moldboard plowed fields and lowest in chisel-plowed fields. Seed predation showed a non-linear response to disturbance suggesting there were other factors, such as crop residue characteristics, affecting predation rates in no-till fields. Several studies suggest that seed predation may be higher in vegetated habitats than highly disturbed areas (Mittelbach and Gross, 1984; Hulme, 1994; Holmes and Froud-Williams, 2005; Heggenstaller et al., 2006).

Gallant (2005) found that the substrate used in seed predation studies has an effect on the rates of seed predation observed. Six different substrates, such as sandpaper and cleaning pads, were tested with six species of weed seeds. Four of these species showed different levels of predation on different substrates. While this should not affect a study where treatments are being compared, it makes comparisons between different studies more difficult. This substrate effect also needs to be taken into account when making estimates of the absolute predation rate based on experimental data.

As seed predation occurs mainly on the soil surface (Hulme, 1994), the vulnerability of seeds to predation is based on the time span between seed rain and seed burial. This is emphasized in a conceptual model that combines seed dispersal, burial, and demand to estimate weed seed losses to predation (Westerman et al., 2006). This conceptual model found that factors relating to seed availability were more important to seed loss than factors relating to demand. The longer seeds are exposed on the soil surface, the more likely they are to be eaten by predators. Using this information, a producer could maximize the seed loss to predation by using practices that postpone seed burial. Westerman et al. (2006) recommend delaying the harvest date to increase availability of seeds to predators and destroying any unshed weed seeds during harvesting to avoid inputs into the seedbank.

Seed Decay Effects on Weed Seedbank Dynamics. After a seed has been incorporated into the seedbank, there is no guarantee it will germinate and produce an adult plant as it may be eaten or removed from the field by predators or die through decay caused by fungi and pathogens. Several studies evaluated the magnitude and impact of weed seed decay in agricultural systems (Pitty et al., 1987; Kremer, 1993; Kremer and Souissi, 2001; Gallant et al., 2004).

Pitty et al. (1987) evaluated the impact of crop residues in Iowa on the colonization of caryopses of *Setaria* species by fungi that negatively affect seed germination and observed that in conservation-tilled fields, seedbank decay was directly related to the amounts of crop residues in the top 7.5 cm. However, in tilled fields, higher fungal colonization and seedbank decay occurred between 7.5 and 15 cm within the soil. In contrast, Gallandt et al. (2004) found that in both no-tillage and conservation-tillage systems in eastern Washington state, seed decay had little effect on the seedbank of wild oats, with over half of the losses from the seedbank due to germination. Chauhan et al.

(2006) found that seed decay in no-tillage systems (48 to 60%) was much higher than under minimum tillage (12 to 39%).

Although microorganisms have the potential to be important components of integrated weed management programs, there are relatively few studies assessing their impact on weed seed decay (Kremer, 1993). Kremer and Spencer (1989) tested the effectiveness of several fungi to control velvetleaf (*Abutilon theophrasti* Medik.) in soybean fields. The fungi, in combination with seed predation, reduced the viability of velvetleaf seeds by as much as 80% in comparison to sites with no insects and fungi. Combining insects and microorganisms in the form of biocontrol could be very useful in weed management (Kremer, 2000).

Fatal Germination Effects on Weed Seedbank Dynamics. Fatal germination has been defined as a plant dying after the radical has emerged, but before a self-sufficient seedling has established (Fenner and Thompson, 2005). This is often caused by seeds germinating too deep in the soil for the seedling to emerge. It is also possible for fungal pathogens to cause fatal germination. Davis and Renner (2007) found that fatal germination was uncommon, but increased with depth. In addition, soil pathogens can increase the occurrence of fatal germination.

Dormancy Effects on Weed Seedbank Dynamics. Not all seeds in the seedbank germinate in each growing season. A number of seeds will not be exposed to the correct combination of factors such as temperature, light, water, and oxygen to cause germination. Seeds which are alive, but unable to germinate are considered dormant. Although seed dormancy classification is complicated, it is based on three types of dormancy: morphological, physical, and physiological (Baskin and Baskin, 2004; Fenner and Thompson, 2005). Morphological dormancy occurs in seeds that are not fully developed when released from the parent plant and must mature in the seedbank before they can germinate. Physically dormant seeds have impermeable seed coats that must be broken or imbibed before germination, generally by animals or natural disturbances. Lastly, seeds with physiological dormancy require a chemical change in the seed itself before germination can occur.

Knowing how dormancy induction can be affected by environmental factors can help in the management of seedbanks. Dormancy is often caused by a low red:far-red ratio of phytochrome in the seed and is influenced by other environmental variables such as temperature. Dormancy of this type is induced by darkness and keeps seeds from germinating in the fall immediately after dispersal (Pons, 1991). The induction of dark dormancy is faster at higher temperatures, but varies between species (Pons, 1991).

Leon and Owen (2003) studied the effects of temperature and light interactions on the dormancy of velvetleaf, common waterhemp, and giant foxtail seeds. The three species had differing effects to cold treatment and exposure to light. Common waterhemp showed a response to light, with increased germination at higher light levels, giant foxtail was partially regulated by light, and velvetleaf had no reaction to light treatments. This study shows that a seedbank varied in composition may have unpredictable responses to light and temperature, increasing the difficulty of management.

Weed seedbanks serve as a physical history of the management successes and failures of a cropping system. They are also the main source of annual weeds in following years, making them an important management objective. Seedbank studies help to increase the efficiency and efficacy of management decisions. However, there are areas that have not been well studied. Studies of the relationship between the soil seedbank and the aboveground weed community have not found a conclusive result. Although seedbanks have been studied extensively in other parts of the U.S., relatively few seedbank studies have been conducted in the northern Great Plains region. This work will add to knowledge about weed seedbank dynamics in the NGP region as well as shedding light on the relationship between seedbanks and the aboveground weed community in different cropping systems.

Project Justification and Objectives

In order to improve current weed management and increase the sustainability of agriculture, it is necessary to take a whole systems approach to management. Integrated weed management will be a part of this change in approach. By focusing on the ecology of crops and pests, more effective and efficient management plans can be developed and the environmental problems such as erosion, fertilizer run-off, and human health concerns often associated with agriculture can be minimized. This transition to more sustainable and whole systems management is only beginning. To increase its effectiveness, there must be scientific research to support producer decisions. As weed seedbanks are the source for the majority of annual weeds found in cropping systems, adding information about their composition and biology will increase the efficiency and efficacy of management decisions.

There are four main objectives to this study:

Objective 1: Quantify the effect of species identity, burial depth, seed density, and crop sequence on weed seedling emergence.

Objective 2: Quantify the importance of speices identity, burial depth, crop sequence, and seed density on weed seed decay.

Objective 3: Quantify post-dispersal weed seed predation rates in wheat and tilled fallow fields for four weed species at two density levels.

Objective 4: Compare weed seedbank abundance and composition between conventional and organic spring wheat fields and relate the diversity, density, and richness of those seedbanks to the aboveground weed community.

By necessity, this study was focused on a fairly small scale and a small range of factors. However, it was hoped that knowledge gained about seedbanks will be used to fill the gaps in weed seedbank information and increase the efficiency of weed management. At a smaller scale, it was hoped that information on weed seedbank dynamics, seed predation, and the relationships between the seedbank and aboveground weed community can be used by producers in the area to tailor management to appropriate systems.

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CHAPTER 2

EFFECT OF WEED SEED DENSITY AND BURIAL DEPTH ON SEEDLING EMERGENCE IN A NO-TILLAGE SPRING WHEAT-FALLOW SYSTEM

Introduction

In recent years there has been growing concern about the environmental and human health impacts of current food and fiber production systems highly dependent upon off-farm chemical inputs (NRC, 2003). As herbicides represent up to 80% of all pesticide inputs in United States agriculture (NRC, 1989), it is necessary to rethink the usual approach to weed management. Consequently, there has been a growing interest among weed scientists, agricultural professionals, and producers in developing integrated weed management practices. This approach to weed management combines two main ideas: the use of mechanical, cultural, biological, and chemical management tactics to reduce abundance and spread of weeds, and the incorporation of an understanding of pest biology into management planning (Buhler et al., 2000).

Increasing the understanding of the many factors affecting the weed seedling emergence will help in the design and implementation of integrated weed management programs. For example, the many species of weeds whose seeds make up the seedbank vary greatly in over-winter survival, persistence, and emergence times (Buhler and Hartzler, 2001). Moreover, these variables can be affected by both the crop rotation (Bellinder et al., 2004) and weed management practices (Cardina et al., 2002). Also, late emerging weeds often do not significantly affect crop yield, weed management strategies should be concentrated during a short period of time, referred to as the “critical weed-free period” (CWFP) (Zimdahl, 2004). Thus, knowledge on the environmental, biological, and management practices that modify weed seedling emergence patterns will allow producers to apply management practices when the most possible damage will be done to weeds and the least possible damage will be done to the crop (Hilgenfeld et al., 2004).

O'Donovan et al. (1985) studied the influence of relative emergence time of wild oats (*Avena fatua*) on yield loss in both barley (*Hordeum vulgare*) and spring wheat (*Triticum Aestivum*) in Alberta, Canada. They found that the highest yield loss occurred when the wild oats had emerged much earlier than wheat. However, at high wild oat densities, there was still a significant yield loss regardless of timing of emergence. Another study conducted in organic winter wheat in the United Kingdom found that the CWFP for a 5% yield loss began at 506 GDD, after planting in November, and ended at 1023 GDD, after planting in February (Welsh et al., 1999). In the U.S., two studies have been conducted on the CWFP for barley (*Hordeum vulgare*) in competition with wild oat (Peters, 1984; Morishita and Thill, 1988). Peters (1984) found that barley yield loss in the UK occurred if wild oats were left with the crop after the four-leaf stage of barley. Morishita and Thill (1988) found that interference occurred between the two-node and heading stage of wild oat. From these studies, it is observed that the timing of competition as well as the duration has an important impact on the yield of the crop. Therefore, it is important to understand when weeds and crops emerge and to use that information to minimize competitive interactions.

A combination of factors including soil moisture, light conditions reaching the ground, percentage of bare ground, and disturbance regime have an effect on whether a seed is able to germinate and emerge (Burke and Grime, 1996; Booth et al., 2003). A favorable combination of these factors is referred to as a "safe site" for germination (Fowler, 1988). Boyd and Van Acker (2004a) compared the relative importance of seed availability and safe sites limitations in determining the emergence and establishment of new weed populations. They found that both factors had an effect on weed presence and recommend managing for both seedbank and site conditions to control weed emergence and establishment.

The position of a seed within the soil profile and in relation to other seeds within the seedbank affects its ability to germinate and emerge. When studying a range of 20 species, Benvenuti et al. (2001) found that seeds had lower emergence from greater depths with the greatest effect on seeds of smaller weight. Boyd and Van Acker (2003) compared 14 species and found that all but three species [barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), wild mallow (*Malva pusilla* Sm.), and common milkweed (*Asclepias syriaca L.*)] had higher emergence when planted near the soil surface. In a five-year study, Roberts and Feast (1972) determined that most seeds germinated in the first growing season after planting. When comparing emergence rates of seeds buried at 2.5, 7.5, and 15 cm, they determined that seeds buried deeper had lower emergence rates, and that increasing cultivation decreased the number of viable seeds. Grundy et al. (2003a) found that larger and heavier seeds were able to overcome the effect of depth to some degree, being able to emerge from greater depths. Additionally, several species showed lower rates of emergence at higher seeding density, possibly an evolved response to decrease sibling competition. This response may be due to chemicals given off by the seeds to decrease the number of seeds which can germinate and therefore increasing the chances of success for those who do germinate and emerge.

While weed seedbanks have been extensively studied in the Midwest USA region (Forcella et al., 1992; Forcella et al., 1993; Anderson and Nielsen, 1996; Buhler et al., 2001; Menalled et al., 2001; Cardina et al., 2002; Bellinder et al., 2004; Teasdale et al., 2004), very few studies have been performed in the Northern Great Plains (NGP) region of North America (O'Donovan et al., 1985; Derksen and Watson, 1998; Mickelson and Stougaard, 2003). Nevertheless, understanding weed seedbank characteristics and dynamics has been identified as a research priority for increasing cropping systems' efficiency in the NGP region (Hirnyck, 2004). To counter this lack of knowledge, this project quantifies weed seedling emergence patterns over two years in a spring wheat-fallow system with varying density and seed burial depth distributions.

Materials and Methods

This study was conducted between October 2004 and October 2006 at the Post Research Farm, Montana State University, near Bozeman MT. This site is located in the convoluted Agroecoregion 9, which consists of loamy glacial till and clayey lacustrine deposits underlain by sandstone and shale (Padbury et al., 2002). The field site had been in tilled fallow for two years previous to this study and during this time, no herbicide applications had been made.

Seeds of green foxtail ([(*Setaria viridis* L.) (Beauv.)], wild oat, field pennycress (*Thlaspi arvense* L.) and kochia [(*Kochia scoparia* L.) (Schrad.)]) were collected during the summer and fall of 2004 from local populations distributed within 8 km of Bozeman, Montana. These four species were chosen because of their importance as agricultural weeds in the northern Great Plains and because they have a variety of seed morphologies and emergence times (Delorit, 1970; Anderson and Nielsen, 1996; Nord et al., 1999; Warwick et al., 2002; Dekker, 2003; Boyd and Van Acker, 2004b). Seeds were stored at 7.2°C +/- 3°C for 6-8 wk until planting. Viability and germinability of the seeds were tested before planting (Table 1).

A total of sixty-four 0.56 m by 4 m plots were set up in four replications following a split-split plot design. The first split took place between the wheat and fallow treatment and the second split took place between the surface and buried planting treatments. Each replication included sub-plots for each of five densities of seed additions (0, 800, 1600, 3200, and 6400 seeds m^{-2}), two burial depths (raked into the surface of the soil or mixed into the top 10 cm of soil), and a wheat (*Triticum aestivum* L.) or fallow treatment (Fig. 2.1). All treatments were sown as a mixture of the four studied species on October 25-27, 2004.

Table 2.1: Percentage of seeds in each of four states before planting in fall 2004 and average seed weight

Species	Germinable	Dormant	Dead	Weight (mg)
Wild Oat	3.5	96.5	0	23.0
Kochia	71	27.5	1.5	0.7
Green Foxtail	6.2	58.5	35.3	0.7
Field pennycress	9	89.4	1.6	1.4

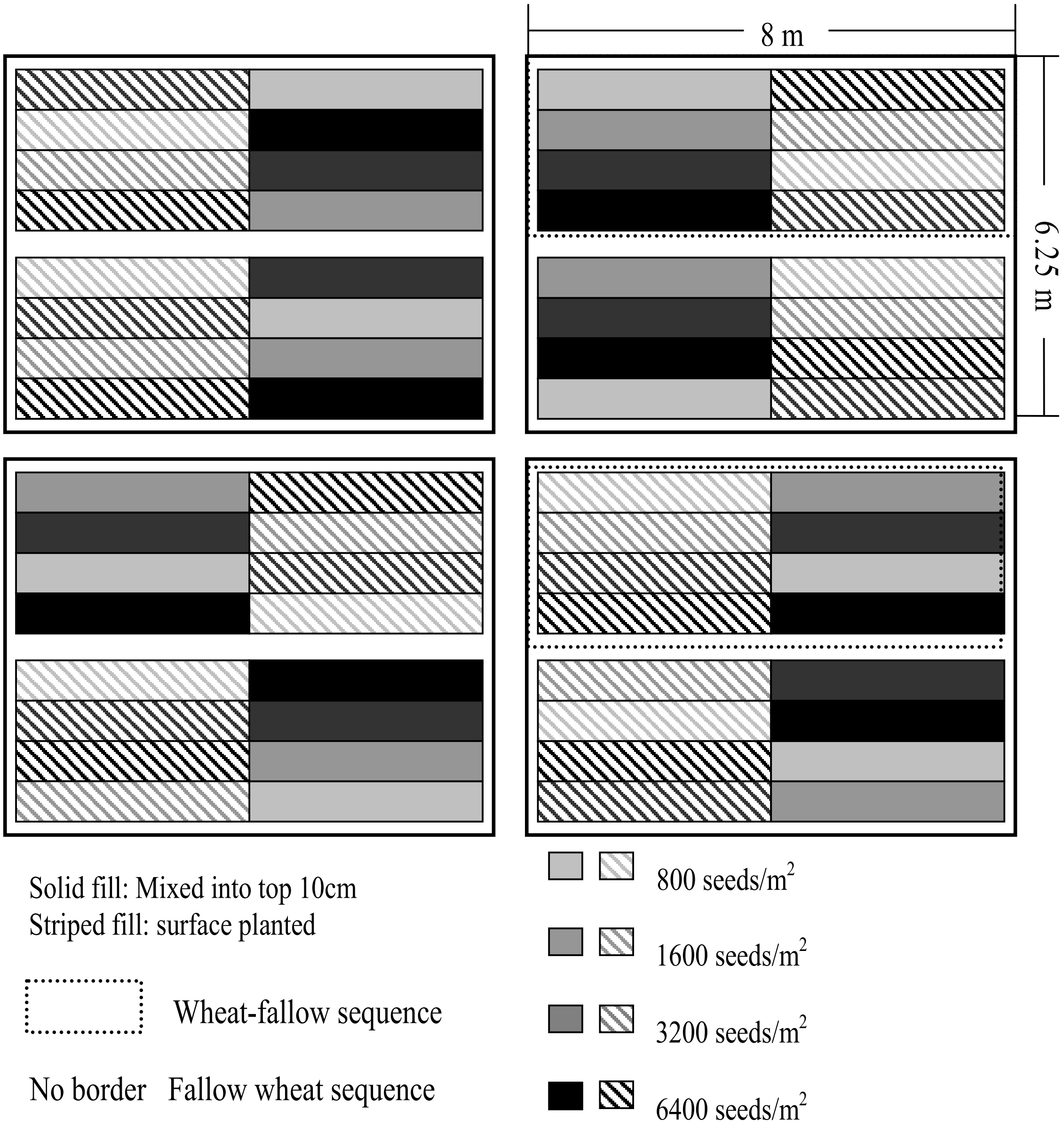

Figure 2.1. Experimental design used to study weed seedling emergence patterns in response to seeding density, burial depth, and crop sequence.

Fifteen soil samples of 1.6 cm in diameter per block were obtained within 1 m of the plots to a depth of 10 cm in November 2004 to determine the composition and density of the background seedbank. Samples were spread over a base of sand in a greenhouse and watered daily for six weeks. The soil was then mixed and watering continued for another month. No weed seedlings were observed in any of the samples. Samples were then sieved through a set of standard sieves of size 2 mm, 1 mm, and 420 microns for recovery of any dormant or non-viable seeds. Seeds of three weed species were found [redroot pigweed (*Amaranthus retroflexus* L.), mean (S.E) = 13.5 (4.97) seeds/m^2; dandelion (*Taraxacum officinale* G.H.), mean (S.E) = 0.25 (0.25) seeds/m^2; and wild buckwheat (*Polygonum convovulus* L.), mean (S.E) = mean 0.25 (0.25) seeds/m^2], but none of the seeds were viable.

On May 16, 2005, half of the plots were planted with a no-tillage drill with McNeal spring wheat at 25 cm row spacing and a seeding rate of 68 kg ha^{-1} with added pelleted nitrogen at a rate of 34 kg ha^{-1}. The other half of the plots were left fallow for one year. On May 15, 2006, all plots previously planted with spring wheat were left fallow and previously fallow plots were planted with spring wheat. As wheat germinated during the 2005 and 2006 growing season, canopy development was assessed with the LAI 2000 (LI-COR, 1999). Every week following wheat planting, LAI measurements were taken in each plot. One measurement was taken above the canopy and three measurements were taken below the canopy in a diagonal pattern to capture the full range of canopy between wheat rows.

Weekly emergence counts were taken in each subplot, starting with the first seedling emergence and ending in mid to late August. Seedlings were hand removed when they were approximately 1 cm above the soil surface to reduce soil disturbance from removal that would occur if seedlings were pulled at an earlier stage. Wild oat seedlings were removed at the two-leaf stage to avoid resprouting. Any weeds growing outside the plots were periodically removed by hand or with a hoe. Occasional unwanted Canada thistle (*Cirsium arvense* L.) plants were spot-sprayed with glyphosate at a rate of 0.529 g/L for control.

Seedbank samples were taken in the subplots for an accompanying study assessing seedbank dynamics. Results from this study indicated that numbers of field pennycress seeds were higher than the number put into the seedbank. Because no field pennycress seeds were observed in the background seedbank samples and none were seen emerging outside plot areas, we suspect that an error was made in the number of pennycress seeds placed in the original seedbanks. As seeds were counted by weight, the weighing was redone after this inconsistency was found and a weight of 24% less was found from original numbers. This inconsistency caused field pennycress to be removed from data collection and analysis.

Data Analysis

Mean time of emergence (MTE) was estimated as:

$$MTE=\Sigma n_i d_i/\Sigma n_i \qquad \text{Eq. 2.1}$$

where n_i is the number of seedlings at growing degree day $(GDD)_i$ and d_i is GDD from the beginning of the experiment (Mohler and Teasdale, 1993; Mulugeta and Stoltenberg, 1998; Menalled et al., 2005). Mean time of emergence gives a picture of emergence patterns taking into account the length of time during which emergence occurs and the period of highest emergence. GDD was calculated as:

$$\text{GDD} = (\text{Maximum Air Temperature} + \text{Minimum Air Temperature}) / 2 - \text{Base Temperature (5 C)} \qquad \text{Eq. 2.2}$$

Daily air temperatures were obtained from the AgriMet weather station located within 0.5 km of research site.

Mean time of emergence (MTE) was compared for the 2005 growing season and the total experiment length with a full split-split ANOVA model including seed density, seeding depth, and presence of crop as prediction factors. The full model was reduced when factors were not significant. The ANOVA was carried out both among species and within species. The number of GDD needed to reach 50% and 75% emergence over the complete experiment was compared across treatments using ANOVA. When actual sampling times did not coincide with 50% or 75% emergence, the values were calculated using a linear interpolation between the values before and after the desired percent emergence. Linear interpolation was used as this point was reached fairly early in the growing season when rates of increase were very nearly linear.

For the 2005 growing season, cumulative percentage emergence was compared across treatments using a repeated measures ANOVA model. Cumulative percentage emergence was arcsine transformed to improve normality. As the 2006 growing season was not a separate study, but a continuation of the one conducted during the 2005 growing season, separate analyses were not performed on cumulative percentage emergence, GDD to 50 and 75%, and MTE in the 2006 growing season. All ANOVA analyses were performed as a split-split plot design.

The critical weed free period was based on work done by (O'Donovan et al., 1985) on the yield loss in relation to the relative emergence time of wild oat. The equation:

$$\text{Yield loss} = 8.42 - 2.61X_1 + 3.41\sqrt{X_2} \qquad \text{Eq. 2.3}$$

was used to calculate expected yield loss where X_1 was the relative emergence time (days) of the weed seedlings in relation to wheat emergence and X_2 was the density of weed seedlings/m^2 at time of wheat emergence. The density of weed seedlings was estimated by the number of wild oat seedling which had emerged before first wheat leaf emergence. While all three weed species were present in combination, the seedling numbers were not combined as this inflated the estimated yield loss beyond a reasonable level. As weed seedlings were removed each week at counting, it is reasonable to assume that cumulative emergence numbers would have been lower in a system where previously emerged seedlings compete for resources with later emerging seedlings. Percentage emergence in the 2005 and 2006 growing season was correlated with LAI and cumulative rainfall using Pearson's correlation coefficient. These correlations were conducted separately by species and crop presence.

Results

Mean Time of Emergence

The mean time of emergence was significantly affected by weed species identity, burial treatment, and crop presence or absence during the 2005 growing season (Table 2.2). Mean time of emergence was slightly higher in plots with wheat present and wild oat showed an increase of MTE in surface planted treatments (Fig. 2.2). There were several significant interactions among the predictor variables (Table 2.2). Over the full course of the experiment, MTE was significantly affected by weed species identity, burial treatment, density, crop sequence and a number of interactions (Table 2.3).

Table 2.2. Analysis of variance table with mean time of emergence for the 2005 growing season as the response variable

	Df	F-value	Pr (> F)
Species	2	520.87	<0.001
Burial treatment	1	90.42	<0.001
Density	1	0.008	0.93
Crop	1	63.15	<0.001
Species*burial	2	150.85	<0.001
Species*density	2	0.24	0.79
Species*crop	2	96.67	<0.001
Burial*density	1	0.062	0.82
Burial*crop	1	70.79	<0.001
Density*crop	1	4.35	0.039
Species*burial*density	2	0.22	0.80
Species*burial*crop	2	71.99	<0.001
Species*density*crop	2	1.41	0.25
Burial*density*crop	1	1.09	0.30
Species*burial*density*crop	2	2.30	0.10

Table 2.3. Analysis of variance table with mean time of emergence for the complete experiment as the response variable

	Df	F-value	Pr (>F)
Species	2	60.59	<0.001
Burial treatment	1	15.41	<0.001
Density	1	70.15	<0.001
Crop sequence	1	4.3	0.040
Species*burial	2	53.61	<0.001
Species*density	2	4.15	0.017
Species*crop sequence	2	5.87	0.003
Burial*density	1	0.089	0.76
Burial*crop sequence	1	0.49	0.48
Density*crop sequence	1	0.94	0.33
Species*burial*density	2	1.26	0.29
Species*burial*crop sequence	2	5.78	0.004
Species*density*crop sequence	2	1.12	0.33
Burial*density*crop sequence	1	0.30	0.58
Species*burial*density*crop sequence	2	0.66	0.52

When the MTE of each weed species was analyzed separately, MTE for kochia was affected by seeding depth ($P < 0.001$) in the 2005 growing season with a lower MTE for kochia mixed into the soil and crop presence (P=0.04). Kochia also exhibited a significant interaction between density and crop (P = 0.04), and crop and depth (P = 0.04) in 2005. Wild oat MTE for the 2005 growing season was significantly affected by depth and presence of crop (P<0.001 for both) with a significant depth by crop interaction (P<0.001). Wild oat MTE increased with surface planting and in fallow plots. There were no significant treatment effects on green foxtail MTE for the 2005 growing season.

When mean time of emergence over the full experiment was analyzed separately by species, MTE of kochia was significantly affected by depth (P=0.002), seeding density (P=0.001), and crop sequence (P<0.001) with a significant interaction between density and crop sequence (*P*=0.03). Over the complete experiment, wild oat MTE was affected by depth (*P*<0.001) and density (*P*<0.001) with no interaction effects. Mean time of emergence was significantly greater in surface planted treatments and decreased as seeding density increased (Fig. 2.3). The MTE of green foxtail over the course of the experiment was significantly affected by seeding density (*P*<0.001) with a decrease in MTE with increased seed density (Fig. 2.4) as well as a depth-by-crop sequence interaction (*P*=0.004).

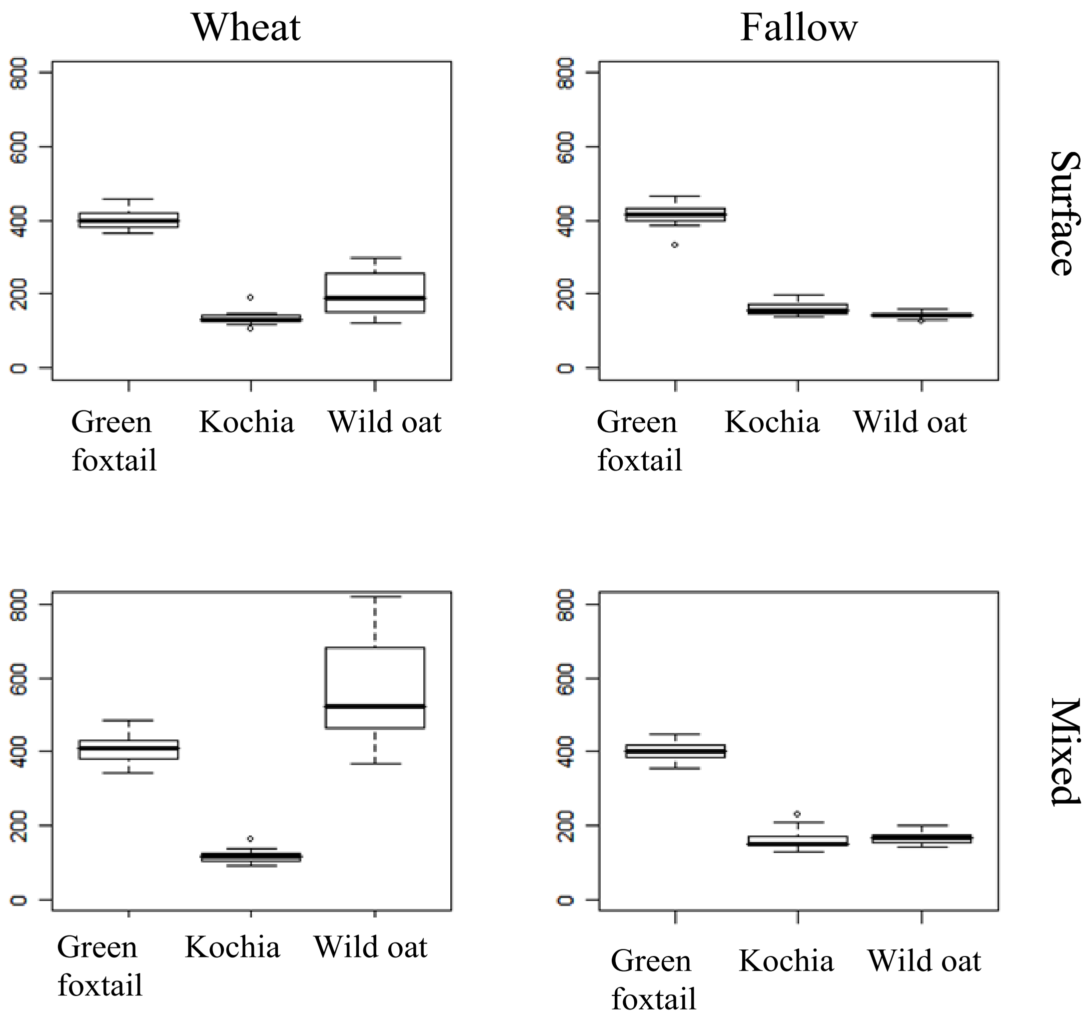

Figure 2.2. Mean time of emergence by species for the 2005 growing season at all crop and burial depth treatments.

Cumulative Percentage Emergence

When all species were analyzed together, cumulative percentage emergence in the 2005 growing season was affected by seeding depth ($P<0.001$) and seed density ($P<0.001$). There were also significant interactions between species identity and seeding depth as well as species identity, seeding depth, and crop presence. Over the entire experiment, cumulative percentage emergence was affected by species identity ($P=0.002$), depth ($P<0.001$), and seeding density ($P<0.001$). There were significant interactions between species identity and seeding depth ($P<0.001$) and species identity, crop sequence, and depth ($P=0.003$).

When species were analyzed separately, cumulative kochia percentage emergence in the 2005 growing season was affected by density ($P=0.003$) with decreased emergence as seedling density increased. Kochia cumulative percentage emergence was additionally affected by burial depth ($P<0.001$), with decreased emergence in the mixed treatment (Table 2.4). Kochia cumulative percent emergence at the end of two years was significantly affected by density ($P<0.001$) and depth ($P=0.02$) with decreasing percentage emergence with increased density, and higher percentage emergence in surface planted treatments (Figure 2.4).

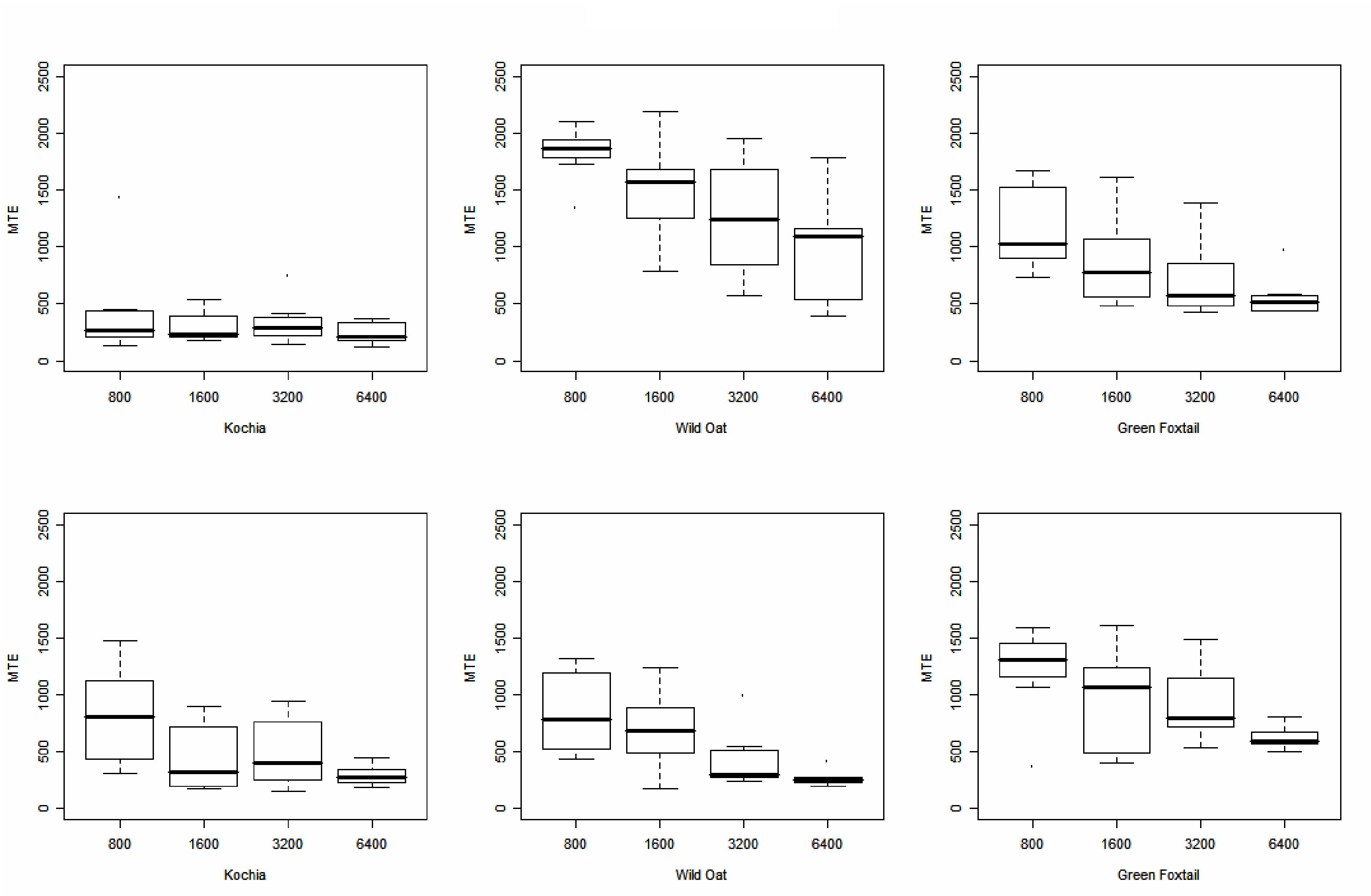

Figure 2.3. Mean time of emergence (MTE) for all studied species over the course of the experiment at both burial depths. The top row represents surface burial while the second row is mixed burial

Wild oat percentage emergence in the 2005 growing season was significantly affected by seed density (*P*=0.03), with decreased percentage emergence with increased seeding density. Wild oat percentage emergence was also significantly affected by burial depth (*P*<0.001), with increased emergence in the mixed treatments (Table 2.4). Wild oat also exhibited a significant interaction between seeding depth and crop presence (*P*=0.005). Over the complete course of the experiment wild oat percent emergence was affected by seeding depth (*P*<0.001) and seeding density (*P*=0.03). Wild oat also showed a significant interaction between seeding depth and crop sequence (*P*=0.01).

During the 2005 growing season, green foxtail exhibited the same decrease in percentage emergence with increased seed density as kochia (*P*<0.001), a decrease in emergence in the cropped treatments (*P*=0.02), and an interaction between seeding depth and crop presence (*P*=0.004). Over the course of the experiment, green foxtail percentage emergence was significantly affected by seeding depth (*P*<0.001) and seeding density (*P*=0.003). Green foxtail had higher percentage emergence in surface planted treatments and decreased percentage emergence with increased seeding density (Fig 2.5).

Table 2.4: Mean cumulative percentage emergence values at the end of the 2005 growing season for all species and treatments. Values in parentheses represent standard error.

Density	Depth	Kochia wheat	Kochia fallow	Wild oat wheat	Wild oat fallow	Foxtail wheat	Foxtail fallow
800	Surface	25.36 (5.2)	26.29 (5.7)	6.01 (1.1)	2.80 (1.7)	15.28 (2.2)	21.00 (4.1)
1600	Surface	26.72 (3.9)	24.71 (4.1)	6.46 (0.6)	1.16 (0.70)	16.22 (2.3)	19.07 (4.1)
3200	Surface	13.16 (3.9)	17.16 (2.2)	5.43 (1.6)	1.06 (0.83)	12.24 (2.3)	19.76 (1.2)
6400	Surface	17.08 (2.5)	17.73 (2.9)	3.31 (0.55)	3.96 (3.8)	10.25 (1.3)	18.91 (1.8)
800	Mixed	10.22 (1.3)	17.26 (2.6)	38.89 (9.9)	42.16 (21.8)	15.63 (2.1)	18.51 (2.2)
1600	Mixed	14.54 (1.9)	13.26 (0.8)	35.36 (1.8)	38.89 (16.5)	19.06 (2.7)	18.89 (3.4)
3200	Mixed	10.36 (1.7)	11.41 (2.1)	27.46 (4.6)	35.02 (10.5)	12.10 (0.9)	9.27 (0.9)
6400	Mixed	12.08 (1.5)	9.12 (1.1)	25.39 (2.5)	30.91 (9.4)	12.46 (1.8)	10.79 (1.9)

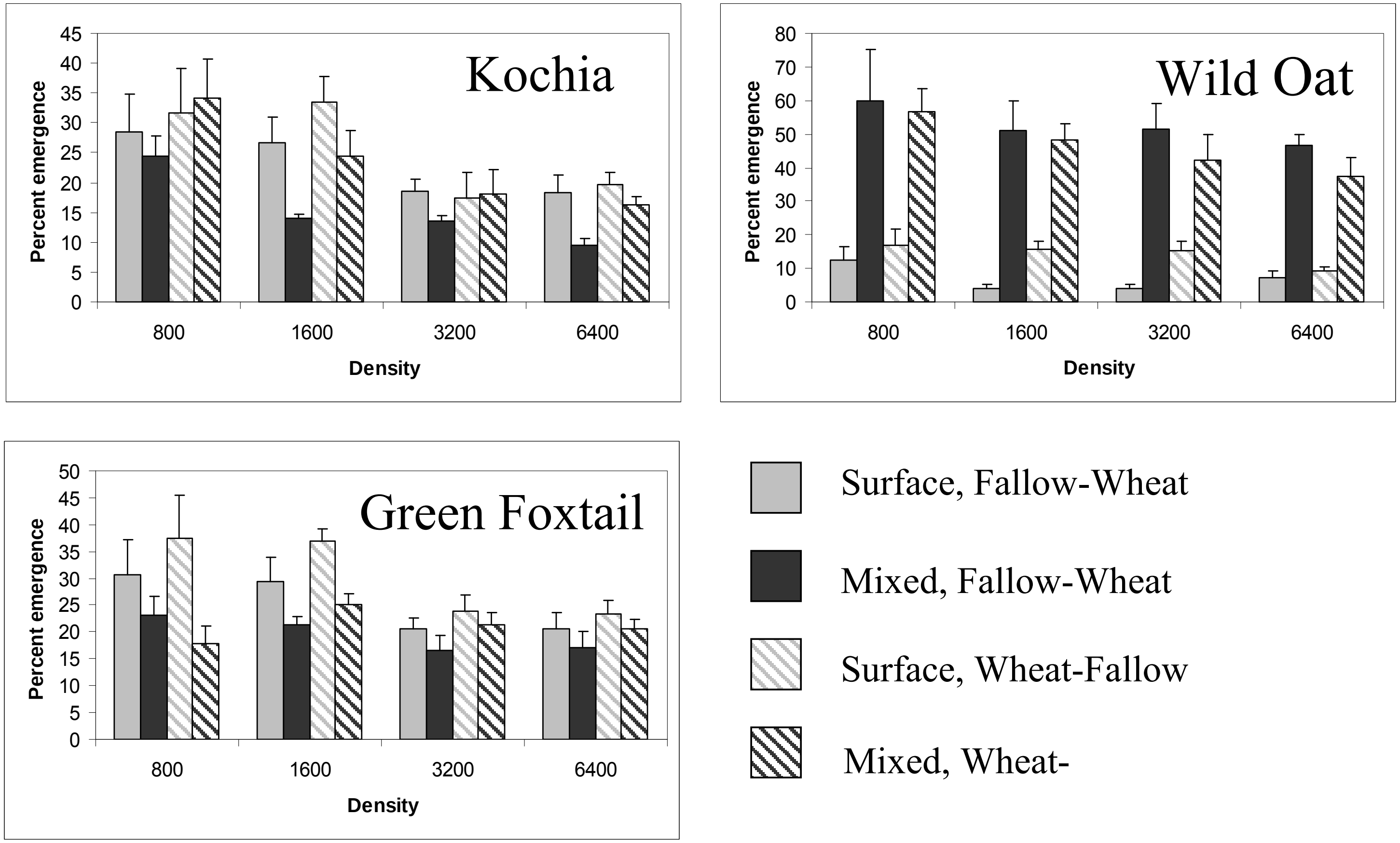

Figure 2.4. Cumulative percentage emergence after two years for all densities, burial depths, and crop treatments.

Growing Degree Days to 50 and 75% Emergence

When species were analyzed together, the number of growing degree days needed to reach 50% of total emergence was affected by species identity (*P*<0.001), seeding depth (*P*<0.001), and crop presence (*P*=0.002). There were also several significant interaction terms (Table 2.5). GDD needed to reach 75% emergence was also affected by species identity (*P*<0.001), seeding depth (*P*<0.001), and crop presence (*P*<0.001) with several interaction terms (Table 2.5).

When species were analyzed separately, GDDs to 50% and 75% emergence in kochia were affected by seeding depth, density, and crop (*P*<0.01 for all), although all these predictors also exhibited significant high order interactions (*P*<0.05 level). The GDDs to 50% and 75% emergence for wild oat were affected by depth (*P*<0.001 for both) and a three-way interaction between depth, density, and crop presence (*P*=0.001 for both). The time to 50% and 75% emergence for wild oat increased in surface planted treatments (Table 2.6 and 2.7). The GDD to 50% emergence in green foxtail was affected by crop presence (*P*=0.02), with increased time to 50% emergence in fallow treatments (Table 2.6 and 2.7). GDD to 75% showed no main effects, although GDD to both 50% and 75% for green foxtail were affected by a number of interactions (Table 2.8).

Table 2.5. Interaction effects on growing degree days to 50% and 75% emergence

Term	P-value GDD to 50%	 GDD to 75%
Species*depth	<0.01	<0.01
Species*density	0.04	0.11
Species*crop	<0.01	0.01
Density*crop	0.02	0.04
Species*depth*density	<0.01	<0.01
Species*depth*crop	<0.01	<0.01
Species*density*crop	<0.01	<0.01
Depth*density*crop	<0.01	<0.01
Depth*density*crop*species	0.01	0.05

Table 2.6. Growing degree days to 50% emergence for all treatment combinations. Numbers in parentheses represent standard error.

Density	Depth	Kochia wheat	Kochia fallow	Wild oat wheat	Wild oat fallow	Foxtail wheat	Foxtail fallow
800	Surface	96 (2.7)	85 (6.2)	2051 (81.8)	1178 (493.7)	372 (11.8)	1189 (366.0)
1600	Surface	99 (2.9)	93 (7.0)	2311 (59.2)	1780 (250.7)	375 (9.5)	891 (410.0)
3200	Surface	102 (1.7)	101 (7.3)	2191 ((97.5)	1717 (304.8)	375 (8.6)	975 (391.2)
6400	Surface	105 (3.7)	49 (48.3)	1316 (558.1)	2079 (6.8)	369 (8.8)	433 (24.0)
800	Mixed	131 (28.9)	1811 (161.8)	131 (7.6)	271 (117.6)	383 (17.6)	449 (55.1)
1600	Mixed	117 (9.3)	1195 (377.7)	133 (10.8)	156 (22.2)	445 (34.6)	827 (446.8)
3200	Mixed	113 (9.8)	475 (353.3)	137 (11.6)	143 (8.9)	489 (67.1)	1250 (490.0)
6400	Mixed	117 (8.8)	110 (4.1)	581 (442.0)	148 (7.9)	1307 (515.0)	463 (72.2)

Table 2.7. Growing degree days to 75% emergence for all treatment combinations. Numbers in parentheses represent standard error.

Density	Depth	Kochia wheat	Kochia fallow	Wild oat wheat	Wild oat fallow	Foxtail wheat	Foxtail fallow
800	Surface	115 (2.1)	117 (5.8)	2090 (83.9)	1258 (484.1)	416 (16.9)	2736 (929.7)
1600	Surface	119 (1.9)	124 (6.2)	2411 (60.4)	2303 (145.3)	432 (6.3)	1121 (388.4)
3200	Surface	123 (3.8)	122 (7.6)	2256 (100.0)	1937 (169.4)	424 (8.5)	2666 (1497.1)
6400	Surface	121 (5.2)	97 (24.5)	1419 (562.2)	2761 (602.1)	418 (5.0)	624 (101.2)
800	Mixed	165 (34.5)	2604 (342.3)	253 (75.5)	528 (309.3)	468 (29.8)	827 (345.1)
1600	Mixed	143 (12.3)	1574 (492.2)	210 (48.3)	253 (90.5)	580 (55.0)	915 (440.1)
3200	Mixed	137(12.1)	685 (493.1)	231 (37.1)	251 (62.9)	893 (243.2)	1363 (491.1)
6400	Mixed	142 (14.0)	131 (4.1)	643 (431.8)	224 (17.3)	1473 (572.6)	828 (367.4)

Table 2.8. Interaction effects on growing degree days to 50% and 75% foxtail emergence

Term	P value	
	GDD to 50%	GDD to 75%
Depth*density	0.04	0.07
Density*crop	0.02	0.07
Depth*crop	0.13	0.02

Critical Weed Free Period

The number of wild oat seedlings emerging during the CWFP varied between years (Figure 2.5). More wild oat seedlings emerged in the 2005 growing season and a increase in yield loss was seen in the 2005 growing season. In buried treatment plots, a strong trend for increased yield loss with increased seed density was observed. This trend was not as apparent in the surface treatment plots. In the 2005 growing season, estimated yield loss ranged from 27 to 95% among densities. In 2006, the estimated yield loss ranged from 27 to 60% among density levels (Figure 2.5).

Correlation of Seedling Emergence with LAI and rainfall

Leaf area index values for wheat plots were similar during the 2005 and 2006 growing seasons (Figure 2.6). Leaf area index in fallow plots followed a similar pattern in both growing seasons, but began slightly higher in 2006 as a product of the stubble left from the previous year’s wheat crop. Rainfall was higher overall in the 2006 growing season (Figure 2.6).

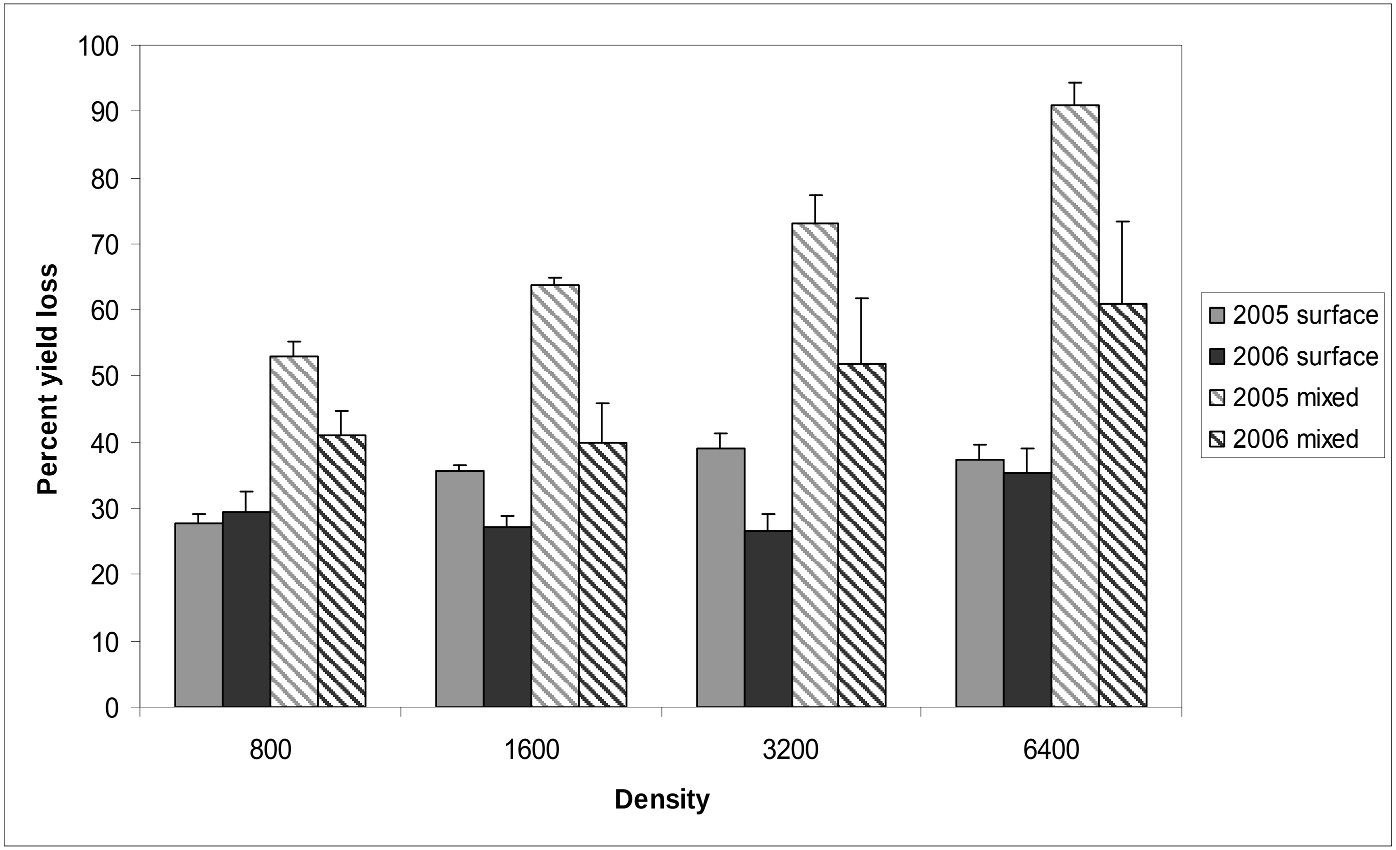

Figure 2.5. Percent yield loss caused by wild oat as estimated by Eq. 2.3 for all years and burial treatment. Bars represent standard error.

Correlations between weed cumulative emergence and LAI were significant for all species in both years and cropping treatments. In the 2005 growing season, all correlations were positive. However, in the 2006 growing season, correlation coefficients for all species were negative in the fallow treatment where LAI was caused solely by stubble from the previous year (Table 2.9). While all correlations were significant, the strength of these correlations varied with the fallow treatment showing weaker correlations, and the 2006 fallow treatment being the weakest. Correlations between cumulative weed emergence and cumulative rainfall were significant and strong for all species in both years and cropping treatments (Table 10).

Table 2.9. Correlations and p-values between weed cumulative emergence and leaf area index

	2005				2006			
	Wheat		Fallow		Wheat		Fallow	
	Corr	P	Corr	P	Corr	P	Corr	P
Kochia	0.65	<0.01	0.27	<0.01	0.51	<0.01	-0.14	<0.01
Wild oat	0.64	<0.01	0.30	<0.01	0.70	<0.01	-0.10	0.018
Green foxtail	0.87	<0.01	0.23	<0.01	0.86	<0.01	-0.10	0.025

Table 2.10. Correlations and p-values between weed cumulative emergence and cumulative rainfall

	2005				2006			
	Wheat		Fallow		Wheat		Fallow	
	Corr	P	Corr	P	Corr	P	Corr	P
Kochia	0.71	<0.01	0.63	<0.01	0.54	<0.01	0.68	<0.01
Wild oat	0.69	<0.01	0.65	<0.01	0.80	<0.01	0.93	<0.01
Green foxtail	0.89	<0.01	0.89	<0.01	0.92	<0.01	0.97	<0.01

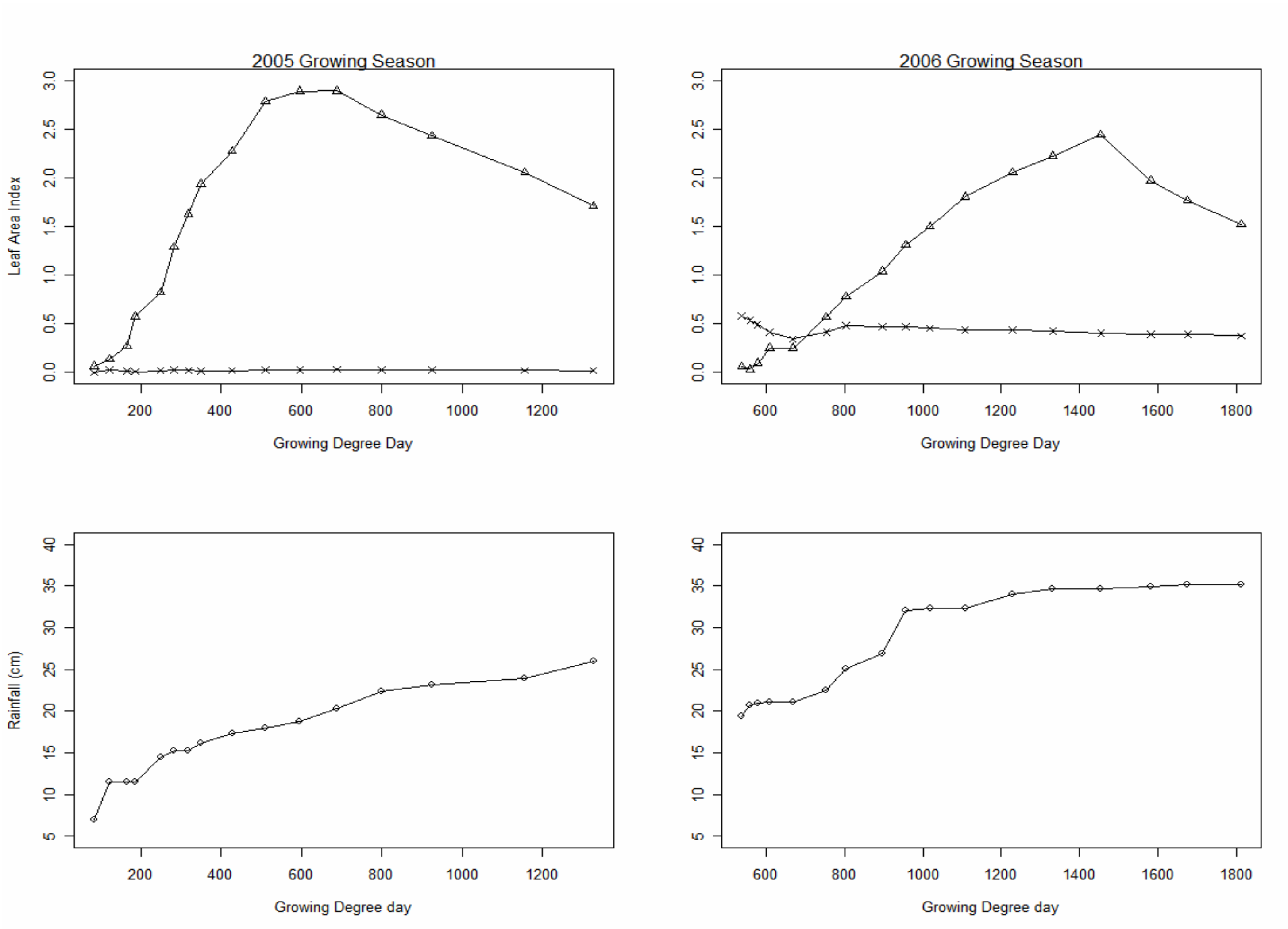

Figure 2.7. LAI (top) and cumulative rainfall (bottom) values measured during the 2005 and 2006 growing season. For LAI graphs, triangles represent wheat plots and crosses represent fallow plots

Discussion

Mean Time of Emergence

The mean time of emergence during both the 2005 growing season and the overall course of the experiment varied among species. These differences were to be expected as the weed species chosen for this study were known to have different seedbank dynamics (Banting et al., 1973; Sharma and Vandenborn, 1978; Anderson and Nielsen, 1996; Dekker, 2003; Boyd and Van Acker, 2004c). Seed burial also affected MTE in the 2005 growing season. In accordance, Roberts and Feast (1972) have shown that seeds do not emerge as well or early from greater depths. In 2005, crop presence or absence was also a significant factor in MTE. A number of seeds have moisture, light, or oxygen cues for germination (Leon and Owen, 2003; Boyd and Van Acker, 2004b; Boyd and Van Acker, 2004c) and the presence or absence of a crop will affect all of these factors. Having information on the emergence times of weeds in responses to time will aid producers in choosing when to manage these weeds to increase control while decreasing damage to the crop.

Several studies have found decreased emergence in buried plantings of small seeds (Benvenuti et al., 2001; Boyd and Van Acker, 2003; Grundy et al., 2003a). In accordance, MTE for kochia in the first year was later in buried seeding treatments, probably because small seeds such as kochia do not have the energy reserves to emerge from greater depths, although this affect was not seen when the course of the experiment was analyzed as a whole. Knowing that the first year after dispersal, kochia takes longer to emerge and that total emergence is reduced when seeds are buried, affects management decisions in different tillage systems, specifically the timing of management. In accordance with other studies, crop rotation affected kochia emergence dynamics (Blackshaw et al., 2001; Cardina et al., 2002; Benoit et al., 2003; Bellinder et al., 2004; Teasdale et al., 2004).

Over the complete length of the experiment, mean time of emergence of wild oat was affected by density with MTE shortening as a function of increased seeding density. The higher density of seeds may maximize the possibility of a seed being placed in a safe site for germination leading to increased germination and emergence. Seedling emergence has been shown to be affected by both seed availability and number of safe sites (Fowler, 1988; Eriksson and Ehrlen, 1992). This shortening in MTE at higher seed densities could be a factor of a limited number of weed seeds encountering safe sites for germination at low densities.

Like kochia, the other small-seeded species in this study, green foxtail MTE was affected by seeding depth and seeding density over the course of the experiment. Mean time of emergence decreased with increased seeding density. The increased number of seeds increases the chance that seeds will find a safe site for germination, which could also cause the decreased MTE observed at higher seeding densities.

Cumulative Percent Emergence

In accordance with previous studies (Roberts and Feast, 1972; Mohler and Galford, 1997; Benvenuti et al., 2001; Grundy et al., 2003a), I observed a decrease in emergence with seed burial has been seen in other studies. As two of the species studied had small seed size, they were more likely to have difficulties in emerging from greater depths, explaining the general decrease in emergence in mixed plantings. Light, temperature, and oxygen levels are lower at greater burial depths, decreasing weed seed emergence. Fatal germination is also more common at greater soil depths (Davis and Renner, 2005), decreasing the number of emerged seedlings.

In general, percentage emergence decreased as seed density increased. This effect has been observed in other studies (Grundy et al., 2003b; Boyd and Van Acker, 2004a) although it is difficult to explain. Some seeds have been shown to exude possible allelopathic compounds (Fenner and Thompson, 2005) and at high enough seed densities, these compounds could affect germination of adjacent seeds in the seedbank. Higher densities of weed seeds may also be more likely to attract weed seed predators, causing increased loss to predation (Cromar et al. 1999; Marino et al. 2005).

Kochia percentage emergence decreased as seeding density increased. This effect was seen in green foxtail and wild oat as well and observed in a previous study (Grundy et al., 2003). This decrease in percentage emergence could be caused by several factors. At higher densities and with greater aggregation, seeds are more prone to seed predation (Cromar et al., 1999; Marino et al., 2005). Higher densities of seeds may also be more prone to attack by pathogens, leaving fewer viable seeds to germinate. The effects of seed density on both predation rates and seed decay were tested in separate studies for this project (Chapters 3 and 4).

Wild oat’s increased emergence when mixed into the soil differs from that found by Gallant et al. (2004). This difference may be explained by their use of a highly dormant biotype of wild oat. However, the observation in the current study does agree with results found by Cumming and Hay (1958) who found that light could inhibit germination in dormant wild oat seeds. The increase in wild oat germination when mixed into the soil has definite implications for weed management. If conservation tillage increases wild oat emergence, it should be reevaluated as part of a management plan. Tillage could be useful as a means of depleting a wild oat seedbank with an application of management as wild oat seedlings emerge. This possibility must also be tempered with an understanding of how repeated tillage can have adverse effects on soil characteristics.

Crop presence or absence affected green foxtail percent emergence in 2005. Green foxtail emerged much later than the other studied species and after crop emergence. This would have caused a large difference in soil and light conditions that could explain the differences in emergence. However, green foxtail has been observed to have low response to changing light environments (Boyd and Van Acker, 2004c), suggesting that other factors affected green foxtail response to cropping type. Over the complete experiment, green foxtail emergence was affected by burial treatment. As green foxtail seeds are relatively small, they would be more susceptible to failure when emerging from greater depths (Benvenuti et al., 2001; Grundy et al., 2003a).

Growing Degree Days to 50 and 75% Emergence

As two of the species studied have small seeds, the effect of depth on the time to 50 and 75% emergence is not surprising. A number of studies have shown that depth in the soil profile affects the percentage of weed seeds that emerge successfully (Roberts and Feast, 1972; Froud-Williams et al., 1984; Mohler and Galford, 1997; Grundy et al., 2003a; Taylor et al., 2005) and this effect is more important in smaller seeds with less energy to emerge from greater depths. While the buried treatment in this study did not place seeds at discrete depths, seeds were more likely to have to emerge from greater depths.

The presence or absence of a crop has a great effect on the light, temperature, and moisture of the soil surrounding a seed. These factors affect the germination and emergence of weeds. Other studies have also shown an effect of crop sequence and crop identity on the emerged weed populations (Blackshaw et al., 2001; Benoit et al., 2003; Smith and Gross, 2006).

Boyd and Van Acker (2004a) have shown there is an interacting combination of factors affecting seedling emergence. With this in mind, the numbers of significant interactions affecting GDD to 50% and 75% kochia emergence are not unusual. Seed effects on the possibility of seed predation (Cromar et al., 1999), fungal attack, and fatal germination (Davis and Renner, 2007). Crop presence or absence will affect the light and moisture environment of the seed, again affecting germination. These factors are not separated easily in a cropland setting, making interactions likely and understandable.

The GDD to 50% and 75% emergence were affected by seeding depth, with more GDD needed for surface-planted wild oat to reach these levels of emergence. Management of wild oats can be optimized for most weed and least crop damage by refining the timing of management. GDD to 50% and 75% emergence were also affected by several interactions. This again can be related to the number of factors that have an effect on seedling emergence (Boyd and Van Acker, 2004a). Crop sequence affected both GDD to 50% and 75%. This was most likely a factor of foxtail's later emergence time and the crop stage at that point.

Correlation of Seedling Emergence with LAI and Rainfall

The correlation between weed seedling emergence and cumulative rainfall was significant for all species, crops, and years. This is not a surprising result as other studies have shown the importance of soil moisture to seed germination and emergence (Sharma and Vandenborn, 1978; Burke and Grime, 1996; Booth et al., 2003; Boyd and Van Acker, 2003). A number of weed species need increased soil moisture as a trigger for breaking dormancy (McIntyre and Hsiao, 1985; Baskin and Baskin, 2004) and increased soil moisture through rainfall could provide this trigger. It is important to consider that while canopy cover and cumulative rainfall may have significant effects on cumulative weed seedling emergence, they are part of a larger factor. As the crop canopy cover increases, this means that conditions are good, and will be good for a weed seedling as well.

Critical Weed Free Period

Zimdahl (2004) and others have emphasized the importance of the critical weed free period (CWFP) to minimize crop yield loss when in competition with weeds. This was underlined by the extremely high possible yield losses calculated from wild oat seedling numbers observed in this study. However, it is interesting to note that the level of possible yield loss was not always directly related to the seedbank density. This can be explained by the often poor relationship observed between weed seedbanks and the resulting weed flora (Ball and Miller, 1989; Cardina and Sparrow, 1996), but is more likely due to the low rates of wild oat seedling emergence seen in surface planted treatments.

As useful as information on the CWFP can be, too few studies have been conducted on the critical weed free period in the NGP region. While the O'Donovan et al. (1985) study is useful; it focuses on one weed species and a few weed density levels. Weed species have different growth habits and different levels of competitiveness with crops (Wilson and Wright, 1990). Also, weed species in combination may have different effects than one species alone. While the yield losses calculated in this study have found that low weed densities can cause significant crop yield loss; the precision of this estimation could be improved greatly.

Conclusions

The information gained in this study is an important addition to knowledge on weed seedbanks in the NGP region. The relationship between weed seed depth and seedling emergence has been studied before in other areas (Roberts and Feast, 1972; Grundy et al., 2003), but this is the first study done in Montana. The lack of knowledge on the critical weed free period for wheat in the NGP region is an important problem that limits the adoption of integrated weed management practices.

Overall, this study adds important information to what is known about weed seedbanks and shows important implications for management. The effect of depth can be most easily applied to tailored weed management through control of tillage systems. In addition, the effect of seed density indicates a need to better understand the mechanics of weed seedbank. The differing emergence patterns of the studied species also add useful information for management timing by giving managers information on weed emergence that can be used to best plan management for increase efficacy with the least damage to the crop.

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CHAPTER 3

INFLUENCE OF SEED DENSITY, CROP SEQUENCE, AND BURIAL DEPTH ON WEED SEED DORMANCY AND DECAY IN A NORTHERN GREAT PLAINS WHEAT-FALLOW SYSTEM

Introduction

Weed seeds in the seedbank can experience several fates. They can germinate and leave the seedbank, leave through emigration, they can persist, or die (Chambers and MacMahon, 1994; Forcella, 2003). Those weed seeds that do persist may remain viable in the seedbank for many years and have long-lasting effects on crop yields (Cavers and Benoit, 1989). The residence time of viable seeds in the seedbank can be modified either by the management system (Ball, 1992; Cardina et al., 2002; Chauhan et al., 2006; Davis et al., 2006) or environmental effects (Cumming and Hay, 1958; Murdoch and Ellis, 2000; Leon and Owen, 2003).

Weed seed residence time in the soil can also be increased by dormancy, and both environmental and management factors can affect a species level of dormancy in a seedbank. Some species show darkness-induced dormancy (Pons, 1991) and others show a decrease of germination when exposed to light (Cumming and Hay, 1958; Murdoch and Ellis, 2000), although the relationship between light and germination is variable between species (Leon and Owen, 2003).

To gain a better understanding of seedbank dynamics and the many processes which affect them, artificially established seedbanks are often used. However, there are a number of potential problems with some methods commonly used to establish these seedbanks. Leon and Owen (2004) compared seedbanks contained in PVC rings of 20 cm in diameter with those placed in the soil without containing rings. The contained seedbanks differed in emergence times and temperature fluctuations from those that were not contained. This difference in seedbank behavior was unsurprisingly greater in species that had dormancy more dependent upon environmental factors. In light of these findings, the design of seedbank studies and the interpretation of their results should be performed with caution and an understanding of how seedbank setup may affect the environment of the seeds themselves.

While weed seedbanks have been extensively studied in the Midwest USA region (Forcella et al., 1992; Forcella et al., 1993; Anderson and Nielsen, 1996; Buhler et al., 2001; Menalled et al., 2001; Cardina et al., 2002; Bellinder et al., 2004; Teasdale et al., 2004), few studies have been done in the northern Great Plains region of North America. Despite this lack of knowledge, weed seedbank characteristics and dynamics have been identified as a research priority for increasing cropping systems' efficiency in the Northern Great Plains region (Hirnyck, 2004). This study aims to fill some of those knowledge gaps by assessing the impact of management factors on seed dormancy and seed decay of common agricultural weeds of the northern Great Plains region.

Materials and Methods

This study was conducted between October 2004 and October 2006 at the Arthur H. Post Research farm located at 45° 40' 29" N 111° 09' 14" W, 1432 m elevation. This site is located in the convoluted Agroecoregion 9, which consists of loamy glacial till and clayey lacustrine deposits underlain by sandstone and shale (Padbury et al., 2002). The field site had been in tilled fallow for two years previous to this study and no herbicide applications were made prior to the study beginning.

Seeds of green foxtail [(*Setaria viridis* L.) (Beauv.)], wild oat (*Avena fatua* L.), field pennycress (*Thlaspi arvense* L.), and kochia [(*Kochia scoparia* L.) (Schrad.)] were collected during the summer and fall of 2004 from local populations distributed within 8 km of the study site. These four species were chosen because of their importance as agricultural weeds in the Northern Great Plains and because they have a variety of seed morphologies and emergence times (Delorit, 1970; Sharma and Vandenborn, 1978; Douglas et al., 1985; Anderson and Nielsen, 1996; Nord et al., 1999; Warwick et al., 2002; Dekker, 2003; Boyd and Van Acker, 2004). The seeds were stored at 7.2°C +/- 3°C for 6-8 wk until planting. Initial viability and average weight of all seeds was tested before seedbanks were established (Table 3.1). Germinable seeds were determined through germination tests in a growth chamber for 7-10 d at 20° C with 8 hr light and 16 hr of darkness. Viability was determined using a tetrazolium test (Sawma and Mohler, 2002).

Table 3.1: Percentage of germinable, dormant, and dead seeds before planting in fall 2004 and average seed weight.

Species	Germinable	Dormant	Dead	Weight (mg)
Wild Oat	3.5	96.5	0	23.01
Kochia	71	27.5	1.5	0.72
Green Foxtail	6.2	58.5	35.3	0.74
Field pennycress	9	89.4	1.6	1.35

A total of sixty-four 0.56 m by 4 m plots were set up in four replications following a split-split plot design. The first split took place between the wheat and fallow treatment and the second split took place between the surface and buried planting treatments. Each replication included sub-plots for each of five densities of seed additions (0, 800, 1600, 3200, and 6400 seeds m^{-2}), two burial depths (raked into the surface of the soil or mixed into the top 10 cm of soil), and a wheat (*Triticum aestivum* L.) or fallow treatment (Fig. 3.1). All treatments were sown as a mixture of the four studied species on October 25-27, 2004.

During Novermber 2004 fifteen soil samples with a diameter of 1.6 cm were obtained in each block near the plots to a depth of 10 cm. These samples were utilized to determine the composition and density of the background seedbank. Samples were spread over a base of sand in a greenhouse and watered daily for six weeks. The soil was then mixed and watering continued for another month. No weed seedlings were observed in any of the samples. Samples were then sieved through a set of standard sieves of size 2 mm, 1 mm, and 420 microns for recovery of any dormant or non-viable seeds. Three weed species were found [redroot pigweed (*Amaranthus retroflexus* L.) mean (SE) = 13.5 (5) seeds/m^2, dandelion (*Taraxacum officinale* G.H.) mean (SE) = 0.3 (0.3) seeds/m^2; and wild buckwheat (*Poligonum convovulus* L.) mean (SE) = mean 0.3 (0.3) seeds/m^2], but none of the seeds were viable when tested using a tetrazolium solution. Any weeds growing outside the plots during the course of the study were periodically removed by hand, with a hoe, or by spot glyphosate application at a rate of 0.529 g/L before setting seed.

On May 16, 2005, half of the plots were planted with McNeal spring wheat at 25 cm row spacing and a seeding rate of 68 kg ha^{-1} with added pelleted nitrogen at a rate of 34 kg ha^{-1}. The plots were planted with a no-till drill to minimize seedbank movement. The other half of the plots were left fallow for one year. On May 15, 2006, all plots previously planted with spring wheat were left fallow and previously fallow plots were planted with spring wheat. As wheat germinated during the 2005 and 2006 growing season, canopy development was assessed with a LAI 2000 (LI-COR, 1999). Every week following wheat planting, LAI measurements were taken in each plot. One measurement was taken above the canopy and three measurements were taken below the canopy in a diagonal pattern to capture the full range of canopy between wheat rows.

Before seedling emergence in the spring of 2005 and 2006, and after emergence in the fall of 2005 and 2006, seedbank samples were taken in all subplots. These samples were taken in randomly selected locations in each subplot. Samples were 24 cm by 40 cm by 10 cm deep. Weed seeds were extracted from soil samples at the USDA Northern Plains Agricultural Research Laboratory in Sidney, Montana using an elutriator and a dissecting scope. An elutriator separates seeds from smaller soil particles using water and has a minimum effect on the viability levels of the seeds (Gross and Renner, 1989). Recovered seeds were placed in a growth chamber at 20° C with constant light for 7-10 d to test for germination. Germinated seeds were counted and removed. Remaining seeds were tested for viability using a 1% tetrazolium solution (Sawma and Mohler, 2002).

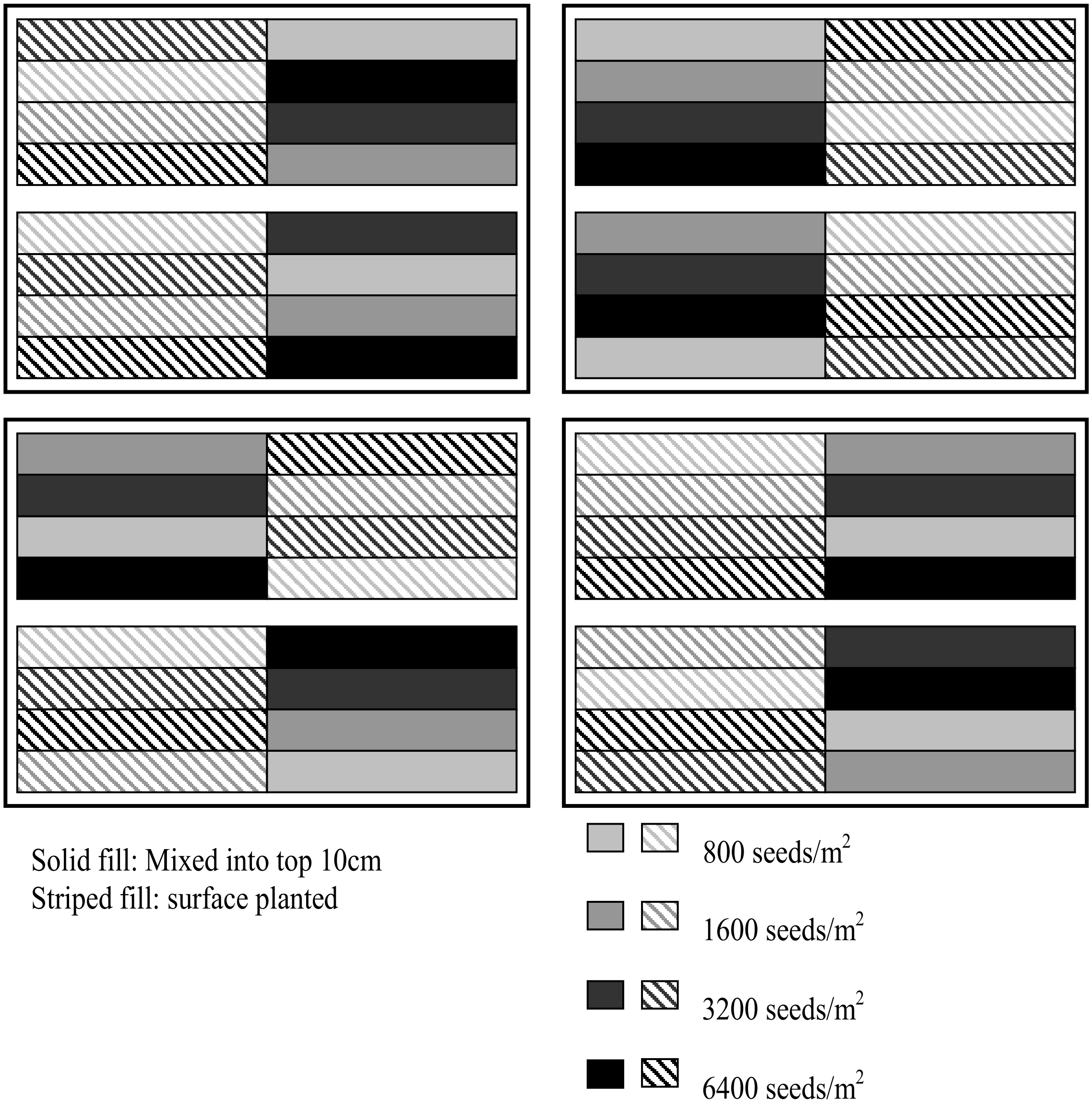

Figure 3.1. Experimental design used to study weed seedling emergence patterns in response to seeding density, burial depth, and crop sequence.

Concurrent with the first removal of seedbank samples, the efficacy of the seed recovery method was tested for the species of interest. Clean soil samples had 100 seeds of wild oat, kochia, field pennycress, or green foxtail added and run through the elutriation and separation process. The number of seeds remaining after separation was counted and recorded (Table 3.2). As kochia had a very low recovery rate after elutriation, this species was removed from data collection and analysis.

Table 3.2: Effectiveness of elutriator and dissecting microscope method for recovering seed (n =100). Numbers in parentheses represent standard error.

Species	% Recovered
Wild oat	96 (4)
Kochia	23 (17)
Green foxtail	47 (5)
Field pennycress	34 (5)

In the sample taken in the spring of 2005, numbers of field pennycress seeds were significantly greater than the number put into the seedbank. However, as no field pennycress seeds were observed in the background seedbank samples or emerged outside plot areas, we suspect that an error was made in the number of pennycress seeds placed in the original seedbanks. As seeds were counted by weight, the weighing was redone after this inconsistency was found and a difference of ??% was found from original numbers. This inconsistency caused field pennycress to be removed from data collection and analysis.

Data Analysis

Seed was collected and split into germinable, dormant, and dead fractions. Germinable and dormant fractions were counted and combined into the viable seed fraction. Percentage of germinable, dormant, and viable seeds was arcsine transformed to improve normality and homogeneity of variance. Data was analyzed as a split-split plot design using a full ANOVA with seed density, species, burial depth, and crop sequence as predictors. Each sample period was analyzed separately. All analyses were conducted using the R program (R Development Core Team, 2006).

Results

The total number of recovered seeds declined over the course of the experiment for both green foxtail and wild oat. By end of the experiment, between 5 and 29% of the original wild oat seedbank remained viable in the soil (Fig 3.2). The final seedbank contained many fewer green foxtail seeds, between zero and nine percent of the initial seedbank remaining viable in the soil (Fig 3.3).

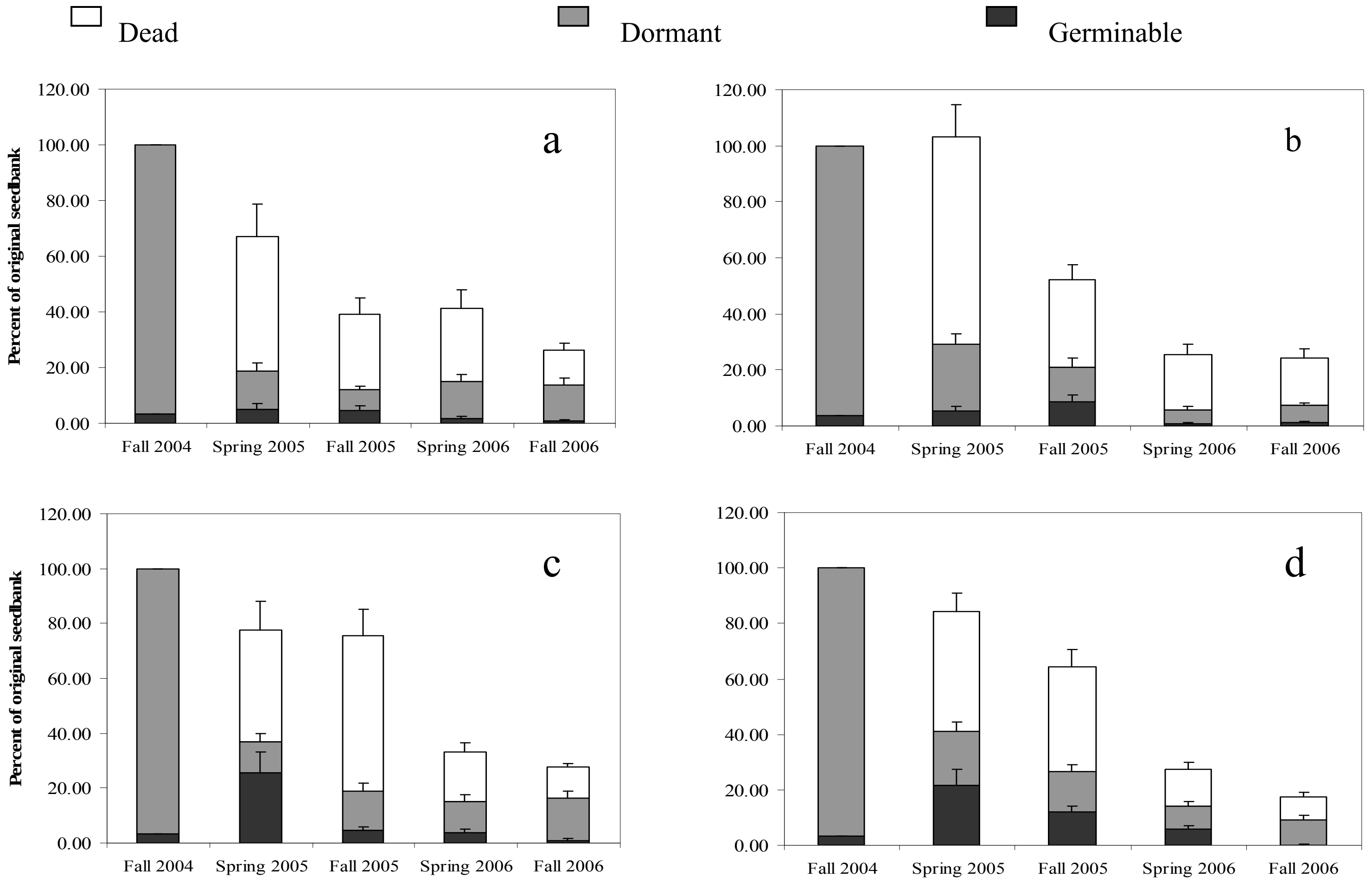

Figure 3.2. Wild oat seeds recovered from the seedbank. a) Surface planted, wheat-fallow crop sequence. b) Surface planted, fallow-wheat crop sequence. c) Mixed planting, wheat-fallow crop sequence. d) Mixed planting, fallow-wheat crop sequence. Bars represent standard error.

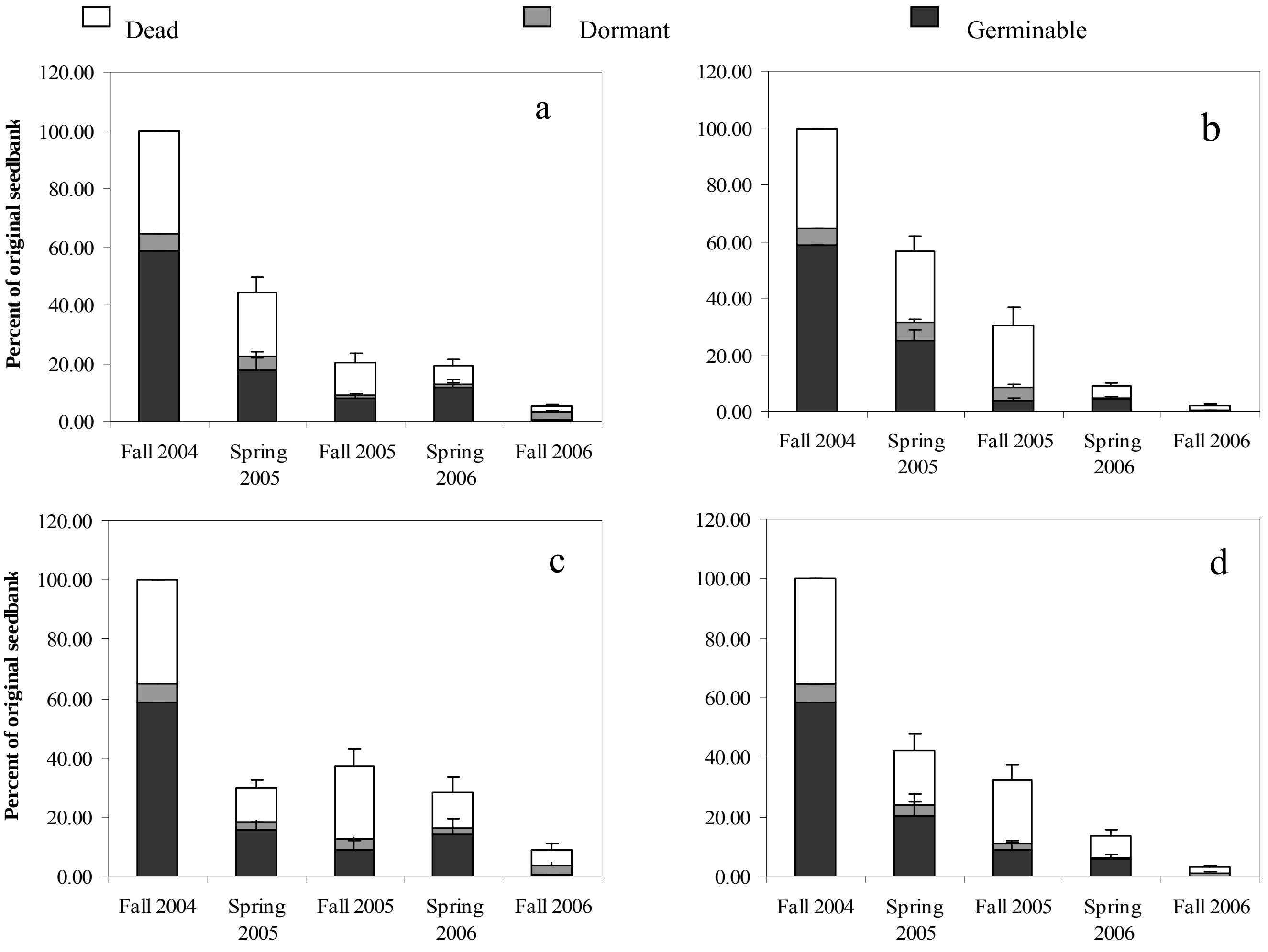

Figure 3.3. Green foxtail seeds recovered from the seedbank. A) Surface planted, wheat-fallow crop sequence. B) Surface planted, fallow-wheat crop sequence. C) Mixed planting, wheat-fallow crop sequence. D) Mixed planting, fallow-wheat crop sequence. Bars represent standard error.

Spring 2005

When the first sampling period was analyzed, the viable fraction showed no main effects, but did show an interaction between burial depth and species identity(*P*=0.03). The dormant fraction was significantly affected by burial depth (*P*=0.01), species and crop presence or absence (*P*<0.01 for both). The germinable fraction was affected by species identity (*P*<0.001) and a burial depth by species interaction (*P*<0.001).

When species were analyzed separately, both the viable and dormant fractions of wild oat were affected by crop presence or absence (*P*=0.048 and *P*<0.01 respectively). The germinable fraction of wild oat was affected by burial depth (*P*<0.01) with greater levels of germinable seeds in buried treatments. The viable fraction of the green foxtail seedbank had no significant predictors, although the dormant fraction was affected by burial depth (*P*=0.04) with higher numbers of dormant seeds in surface plantings. The number germinable green foxtail seeds showed no significant predictors.

Fall 2005

The viable fraction of the seedbank in the fall 2005 sample was affected by burial depth (*P*=0.04) and species identity (*P*<0.001) with interaction effects between burial depth and seeding density (*P*=0.01) and species identity and crop (*P*=0.02). The dormant fraction was significantly affected by species identity (*P*<0.001) with an interaction between burial depth and crop (*P*=0.03). The germinable fraction showed no main effects, but showed interactions between depth and density (*P*<0.01) and species and crop (*P*<0.01).

When species were analyzed separately, the viable fraction of wild oat was affected by burial depth (*P*=0.049) and crop (*P*<0.01), with an interaction between burial depth and seeding density (*P*=0.04). The dormant fraction showed no effects, but the germinable fraction of the wild oat seedbank was affected by crop (*P*<0.001) and an interaction between burial depth and seeding density (*P*<0.001). The viable and germinable fractions of the green foxtail seedbank showed no effects and the dormant fraction showed only an interaction between burial depth and crop (*P*=0.02).

Spring 2006

The viable fraction of the seedbank in the second spring was affected by crop sequence (*P*<0.001). The dormant fraction was affected by species identity (*P*<0.001) and crop sequence (*P*<0.001). The germinable fraction was affected by species identity (*P*<0.001) and crop sequence (*P*<0.01) with interactions between seeding density and species identity (*P*=0.01) and species identity and crop sequence (*P*<0.01).

When species were analyzed separately, the viable fraction of the wild oat seedbank was affected by crop sequence (*P*=0.04) and an interaction between burial depth and crop sequence (*P*=0.04). The dormant fraction was affected by crop sequence (*P*<0.01), with higher numbers of dormant seeds in the wheat-fallow treatment. The germinable fraction was affected by seeding depth (*P*=0.02), with higher numbers of germinable seeds in the mixed burial treatment. The viable fraction of the green foxtail seedbank was affected by crop sequence (*P*<0.001), with higher numbers in the wheat-fallow treatment. The dormant and germinable fractions of the seedbank were also affected by crop sequence (*P*=0.02 and *P*<0.001 respectively

Fall 2006

At the end of two growing seasons, the viable fraction of the seedbank was affected by species identity (*P*<0.001) and crop sequence (*P*<0.01) with higher numbers remaining of wild oat seeds and in the wheat-fallow treatment. The dormant fraction was also affected by species identity (*P*<0.001) and crop sequence (*P*<0.001), while the germinable fraction was only affected by species identity (*P*<0.01).

When species were analyzed separately, the viable and dormant fractions of the wild oat seedbank was affected by crop sequence (*P*<0.01 for both), with higher numbers of viable seeds remaining in the wheat-fallow treatment. The germinable fraction of the seedbank showed no significant effects. The viable and germinable fractions of the green foxtail seedbank showed no effects. The dormant fraction was affected by crop sequence (*P*<0.001), with higher numbers of dormant seeds remaining in the wheat-fallow treatment.

Discussion

While the abundance of viable wild oat and green foxtail seeds in the seedbank declined greatly over the course of the experiment to between zero and 29% of the original seedbank, the species differed slightly in the rate of decline. This result agrees with previous studies that have found differing rates of decline of seedbank abundance among species (Barralis et al., 1988; Lutman et al., 2002; Peltzer and Matson, 2002; Lutman et al., 2003). In this case, the wild oat seedbank contained more dormant seeds throughout the experiment length and declined more slowly than green foxtail. A study performed in

Dijon, France by Barralis et al. (1988) found that wild oat had a high annual rate of decrease (about 80% per year), a rate similar to that found in the first year of this study (approximately 80%), although the rate of decline for the second year of this study was very low (approximately 5-10%). Peltzer et al. (2002) found, in Western Australia, a wild oat seedbank decline of 80% in the first year, although the rate decreased to 50% in the second year. Lutman et al. (2003) found that wild oat seeds in two arable fields in the UK remained viable in the seedbank for 2-4 years with a decline rate of 34-60% each year in winter wheat, again a rate much lower than observed in the first year of this study. However, the cropping system used for this study differed from Lutman et al. (2003) and a separate study by Lutman et al. (2002) observed a lower rate of seedbank decline under winter wheat as compared to spring wheat. As this study was in a spring wheat-fallow system, a differing rate of decline would be expected than rates seen in winter wheat or other crops.

A study conducted in central Iowa by Buhler and Hartzler (2001) observed that giant foxtail (*Setaria faberi*), a species related to green foxtail, showed a much higher initial viability than the green foxtail used for this study, but declined at a much higher rate. After two years of burial, no viable giant foxtail seeds were found. This result was similar to the observations of green foxtail in this study.

Despite the high rates of decline observed in both species, live seeds of each species remained in the soil after two years (between 5 and 29% of wild oat seedbank and between zero and 5% of foxtail seedbank), so both species can be considered to have persistent seedbanks (Walck et al., 2005). This persistence underlines the importance of acknowledging seedbanks in an integrated management plan. If the seedbank is ignored, persistent seeds have the potential to cause long term crop loss as a source of annual weeds (Cavers and Benoit, 1989). In spite of the problem inherent in persistent seedbanks, the low number of live seeds at the end of two years suggests that if inputs into the seedbank of wild oat or green foxtail are limited or eliminated, the seedbank should decline to low levels within two years in the northern Great Plains Region.

Both species showed responses to crop presence or absence in the first growing season and to crop sequence with higher numbers of seeds remaining in the wheat-fallow treatment. In the first year, the higher numbers of seeds present in wheat plots may be a factor of the differing light and competition environment, with fewer seeds being triggered to germinate and emerge. The increase in the number of seeds remaining in the wheat-fallow phase may simply be a continuation of the effect of wheat presence in the first growing season.

The two study species had different levels of initial dormancy and seed sizes. Several studies have shown that seed size and shape can increase the ability of a weed seed to emerge from the soil and also to persist in the soil (Thompson et al., 1993; Grundy et al., 2003). However, other work has found little statistical difference in seedling recruitment depth between wild oat and green foxtail (du Croix Sissons et al., 2000), showing that this relationship is not straightforward.

While the number of viable wild oat seeds in the seedbank declined over two growing seasons, it is important to note the increase in germinable wild oat seeds observed after the first winter in the mixed planting and later in the growing season.

Increased wild oat emergence with increased burial depth has been observed previously (Froud-Williams et al., 1984), but the evidence of an increase in germinability at the seedbank level is new and has management implications. If a producer uses tillage, an increase in wild oat germinability has the potential to become a major weed problem and recharge the seedbank if not managed. If this flush of germinable seeds is planned for and managed, the weed seedbank can be depleted more rapidly.

While there are a large number of environmental and physical factors that affect the longevity of weed seeds in the soil (Chambers and MacMahon, 1994), this study was able to find several significant factors in weed seedbank decline. The increase in the proportion of germinable seeds in buried treatments shows the importance of management decisions in affecting the seedbank. While producers cannot be in control of all the factors which affect weed seedbank decline, it is useful to know that weed seed depth can be effective in increasing the rate of seedbank decline with proper weed control, giving producers another tool for integrated management of weed seedbanks.

Conclusions

This study showed that, in the absence of weed seed input, seedbanks of wild oat and green foxtail will decline to very low levels in this region. Seedbank density and burial depth to 10 cm had no effect on green foxtail, indicating that this decline of the seedbank may occur under many management systems. However, the seeds of wild oat exhibited a spike in germinability after the first winter when mixed into the soil to a depth of 10 cm. This points to a serious concern for producers using tillage for management, as stated previously. Future studies should focus on additional species common to northern Great Plains cropping systems and the effects that management system have on the decay of these seeds in the weed seedbank.

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CHAPTER 4

INFLUENCE OF WEED SEED DENSITY AND CROP PRESENCE ON POSTDISPERSAL SEED PREDATION OF FOUR WEED SPECIES IN SPRING WHEAT AND FALLOW FIELDS

Introduction

With the increased interest in integrated weed management programs occurring in recent years, agricultural systems are now being evaluated as ecological settings. The acknowledgement of the complexity of agricultural fields is accompanied by the development and possible adoption of new management options. Liebman and Gallant (1997) introduced the concept of “many little hammers” to illustrate management systems that do not depend solely upon herbicides or tillage for weed control but on a whole array of practices that collectively help producers reduce the abundance and impact of weeds. A truly integrated management plan will include not only these multiple management tactics, but will also rely on an understanding of weed biology and ecology (Buhler et al., 2000).

The majority of weeds in row cropping systems are annual species whose largest source of propagules is from the weed seedbank of previous years (Cavers, 1983). Therefore, controlling weed seed abundance is an important component of an integrated management plan. Previous studies have shown that seed predation is a major cause of the decline in weed seed abundance in agricultural systems around the world. For example, Westerman et al. (2003a) observed up to 70% weed seed loss in organic cereal fields in the Netherlands. Honek et al. (2003) observed seed removal of up to 1000 seeds per m^2 per day by ground beetles in a variety of crop fields in the Czech Republic. The large seed removal rates observed in arable systems could serve as a tool for integrated weed management. Indeed, in a modeling exercise, Jordan et al. (1995) determined that weed seed survival was the most sensitive factor determining the abundance of weed seeds in a system.

An understanding of the factors affecting seed predation can increase the effectiveness of an integrated weed management plan. Seed predation in crop fields is affected by a number of factors such as canopy cover (Heggenstaller et al., 2006), tillage and crop residue (Cromar et al., 1999), crop species (Honek et al., 2003; O'Rourke et al., 2006), presence of a cover crop (Davis and Liebman, 2003), seed density dependence (Cromar et al., 1999), and spatial aggregation (Marino et al., 2005). The impact of within-field location on seed predation has been variable. While Jacob et al. (2006) found a trend for higher predation along field edges in Western Australia, several other studies failed to determine a consistent relationship between location and predation rate in several other countries (Hulme, 1994; Marino et al., 1997; Westerman et al., 2003b). Despite the knowledge gained in the last few years on the magnitude and importance of weed seed predation, several factors have not been analyzed in the northern Great Plains (NGP) region. Specifically, although summer fallow is a common practice in the NGP, to our knowledge no studies have examined the effect of crop presence or absence on weed seed removal. This study aims to fill that gap and to add to knowledge on the effects of weed seed density and weed species identity on the post dispersal weed seed removal rates in cereal fields of the NGP.

Materials and Methods

During the 2006 growing season, seed predation rates of kochia [(*Kochia scoparia* L.) (Schrad.)], field pennycress (*Thlaspi arvense* L.), green foxtail [(*Setaria viridis* L.) (Beauv.)], and wild oat (*Avena fatua* L.) were measured at the Arthur H. Post Agronomy Farm located at 45° 40’ 29” N 111° 09’ 14” W, 1432 m elevation. Seeds were collected locally in the fall of 2004 and stored at 7.2°C ±3°C until use. Four tilled fallow and four spring wheat (*Triticum aestivum* L.) fields ranging in size from 0.3 to 2.4 ha were chosen for the experiment. Spring wheat fields were conventionally managed with herbicide for weed control during the study. All fields followed a wheat-tilled fallow rotation with herbicide management during the wheat phase and tillage during the fallow phase.

Predation rates were estimated utilizing 9.3 cm by 11.4 cm seed cards following the procedures described in Westerman et al. (2003a). Seed cards were made from 80-grit sandpaper and sprayed with an adhesive (3M Spraymount 6065) with seeds applied at two densities: 15 or 40 seeds card^{-1}, or approximately 1400 and 3800 seeds m^{2}. Six cards of each species and seed density treatment combination were placed in each field along two linear transects at least 2 m from each other. In wheat fields, these transects were placed parallel to wheat rows. Two of these cards were placed within wire mesh bags (1 mm mesh size) and used as controls. Transects were located at least 15 m from all field edges, with species and treatments randomly located within transects and different randomizations used in each sampling period. The same transects were used throughout the study. Individual transect length varied from 14 to 46 m and the number of transects per field varied from one to three. Cards were placed in the field every two weeks between 20 June and 27 September except during harvest of wheat fields. All cards were left in the field for 48 h, removed, and the remaining seeds were counted.

During the 48-h period while seed cards were left in the field, leaf area index (LAI) measurements were taken in all wheat fields with an LAI-2000 (LI-COR, 1999). LAI was measured at several points on each transect and an average LAI was calculated for each field and measurement period.

Data Analysis

Data were recorded as the percent loss of seeds from cards. For each field, mean percent loss from control cards was subtracted from measured loss for all other cards. Data were compared across density level, species, and crop presence or absence using repeated measures ANOVA. Because of significant field and weed species interactions, it was necessary to analyze species separately. The relationship between seed loss and LAI was evaluated using Pearson's product moment correlation coefficient. All data analysis was performed using the R statistical program (R Development Core Team, 2006) and results were considered significant at the $P < 0.05$ level.

Results

Seed Loss From Control Cards

Ambient seed losses differed among species (Figure 4.1), but showed no differences between sampling periods (P=0.48). No differences were detected in ambient seed loss between wheat and fallow fields (*P*=0.51) or between high and low density cards (*P*=0.68). Averaged over all fields and all sampling periods, percent loss from control cards was 12.9±2.8 for green foxtail, 21.3±2.7 for kochia, 14.2±1.8 for field pennycress, and 1.7±0.4 for wild oat.

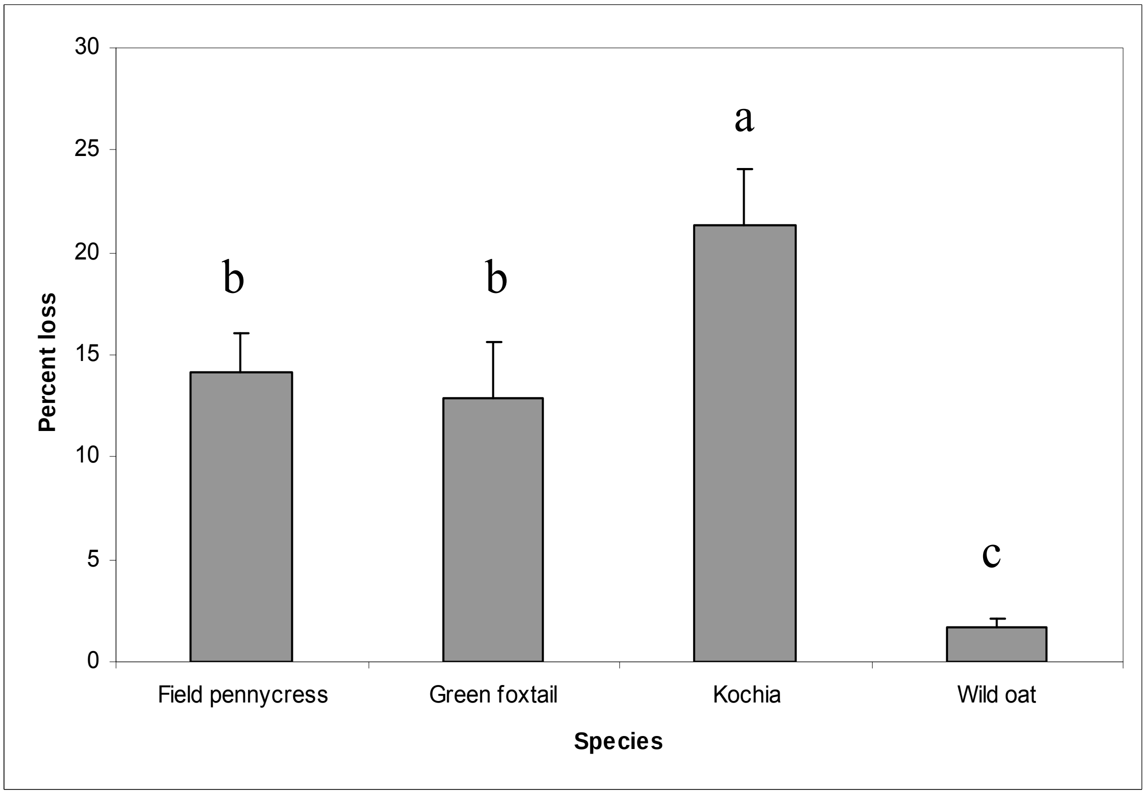

Figure 4.1. Percent loss of seeds from control cards by species. Bars represent standard error and letters show significant differences between species.

Differences in Seed Removal Between Species

Seed removal differed among weed species (*P*<0.01) (Table 4.1). Averaged across field and density, kochia had the highest seed removal in four out of six discrete sampling periods (Figure 4.2). Field pennycress had the highest rate of seed removal in the last sampling period (September 27) and green foxtail each had the highest seed removal in the first sampling period (June 20). Green foxtail had the second highest seed removal in all sampling periods where kochia had the highest seed removal (Figure 4.2). When seed loss was compared between species using multiple comparisons, all but one comparison was significantly different (Table 4.2).

Table 4.1. Proportion of seed removal averaged over fields and sampling dates.

Species	Average	Standard Error
Green foxtail	20.3	2.8
Kochia	35.6	4.5
Field pennycress	15.5	2.4
Wild oat	10.8	2.3

Table 4.2. Results of Tukey HSD test for significant differences in seed loss between all weed species.

Species comparison	P-value
Kochia-green foxtail	<0.01
Wild oat-green foxtail	<0.01
Field pennycress-green foxtail	<0.01
Wild oat-kochia	<0.01
Field pennycress-kochia	<0.01
Field pennycress-wild oat	0.22

Effects of Density, Crop Presence, and Sample Date on Seed Removal

Seed density was not a significant factor affecting percent seed removal for any of the studied species (foxtail *P*=0.42, kochia *P*=0.16, pennycress *P*=0.76, wild oat *P*=0.62). Crop presence was a significant factor in seed removal for kochia (*P*<0.01) with higher seed removal in wheat fields than in fallow fields, but was not a significant factor affecting seed removal of the remaining three species. Finally, date of sampling period was a significant factor affecting seed removal for all four species (foxtail *P*<0.01, kochia *P*<0.01, pennycress *P*=0.01, wild oat *P*<0.01) (Figure 4.2). While seed removal varied over time, some seasonal effects can be seen with lower seed removal both at the beginning and at the end of the growing season with some variability in the temporal patterns of seed removal possibly due to rain events or temperature (Table 4.3).

Table 4.3. Rainfall accumulation in centimeters and high and low temperatures in Celsius during the 48 h period when seed cards were present in the field.

Sampling date	Rainfall (cm)	Maximum temperature (C)	Minimum temperature (C)
20 June	0	22	5
5 July	0.45	28	12
17 July	0	34	13
31 July	0.23	23	9
29 August	0.02	33	7
27 September	0	24	5

Relationship Between Seed Predation and LAI

Averaged across density levels, seed removal was significantly correlated with LAI in only three cases (Table 4.4). Seed removal was not correlated with LAI for wild oat during any sampling period. Green foxtail showed a significant positive correlation in the fifth sampling period and kochia showed a significant positive correlation in the first sampling period. Field pennycress showed a significant negative correlation in the fourth sampling period.

Table 4.4. Correlations between seed removal and LAI across all fields and sampling periods. NS indicates non-significant effect; all other correlations are significant at *P*<0.05

Species	1	2	3	4	5	6
Green foxtail	NS	NS	NS	NS	0.36	NS
Kochia	0.67	NS	NS	NS	NS	NS
Field pennycress	NS	NS	NS	-0.52	NS	NS
Wild oat	NS	NS	NS	NS	NS	NS

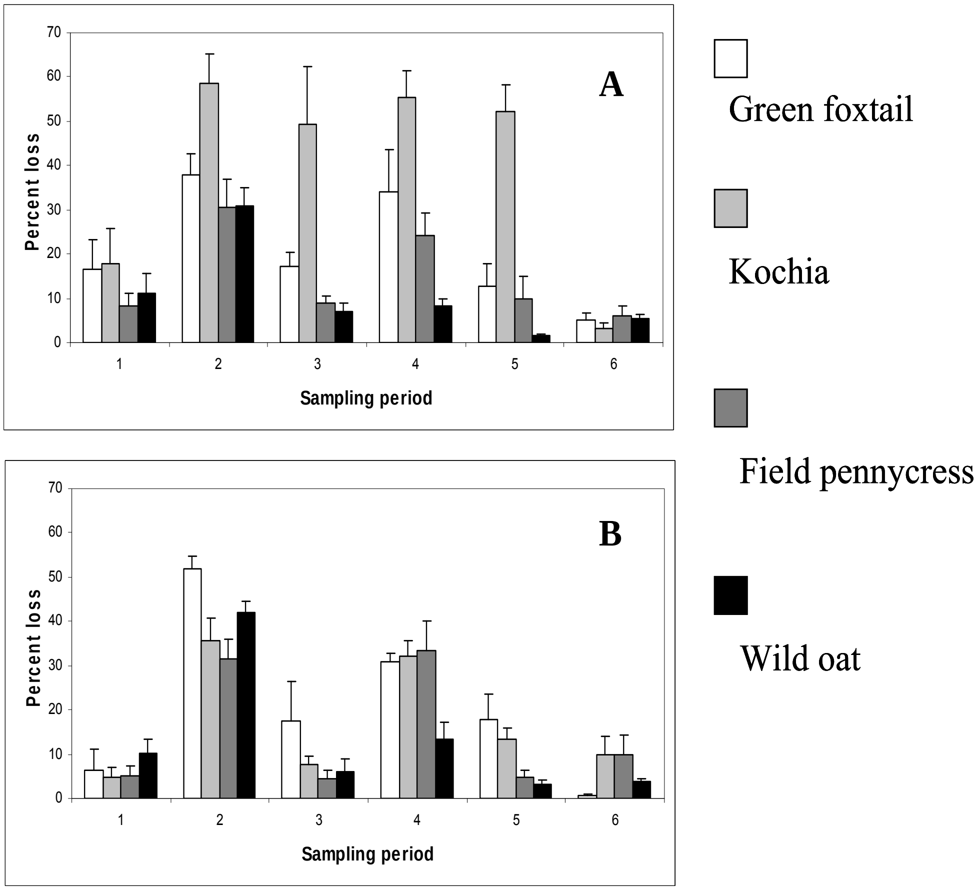

Figure 4.2 Percent seed loss from seed cards with density combined throughout the sampling season. A) wheat fields, B) fallow fields. Bars represent standard error.

Discussion

We failed to find significant differences in seed loss between wheat and fallow fields for three of the four species studied. This may have been due to edge effects from the relatively small size of the fields used as cards were between 15 and 60 m from field edge. However, other studies have found differences between management systems using small fields (Brust and House, 1988).

The four weed species studied had differing rates of seed removal. Numerous studies have shown that seed and predator characteristics affect the species predation rates, although these effects vary (Hoffmann et al., 1995; Diaz, 1996; Seaman and Marino, 2003; Heggenstaller et al., 2006). For example, while Hoffmann et al. (1995) found that predation rates were positively correlated to seed size, Seaman and Marino (2003) did not find this relationship. However, both Heggenstaller et al. (2006) and Seaman and Marino (2003) found that seed predation rates were negatively correlated with seed size. In accordance with these two studies, wild oat was the largest seed in this study and exhibited the lowest removal rates of the four species. Moreover, kochia was the most removed species in our study and has small seeds and a very thin seed covering, possibly enabling predators to eat these seeds more easily. Green foxtail and field pennycress are also small-seeded species, although both have a more robust seed coat than kochia, perhaps leading to their lower rates of loss. Despite the potential impact of seed size and cover strength on seed predator behavior, it is possible that other factors such as seed nutrient and energy contents could impact predation rates (Diaz, 1996). Seed predator abundance, identity, and activity could also impact weed seed removal rates. Potential predators at the study site include rodents, ants, ground beetles, and crickets as they were previously observed at the studied site (Taylor, 2001).

Ambient seed loss from control cards was higher than initially expected from other studies (Marino et al., 2005; Heggenstaller et al., 2006) although ambient loss was similar to losses found by Westerman et al. (2003a). Several sampling periods experienced rain, probably causing higher seed loss from all cards, including controls.

Vander Wall et al. (2005) emphasized secondary dispersal as a part of seed removal that cannot be equated with seed predation. While the exact fates of all seeds removed in this study are unknown, a number of empty seed coats and some partially consumed seeds were observed throughout the study. Thus, although secondary dispersal may have occurred, it is likely that the majority of seed removal was due to seed predation.

Seed density did not affect seed removal levels. Response of seed removal to seed density has been studied before with varying results. For example, a study in southern Ontario on the effects of crop residues on seed predation by Cromar et al. (1999) found that there was density-dependent feeding for common lambsquarters (*Chenopodium album* L.) and barnyardgrass [(*Echinochloa crus-galli)* (L.) (Beauv.)] seeds with common lambsquarters showing a higher proportional loss from higher density samples and barnyardgrass higher loss from low density samples. However, a study in the Netherlands by Marino et al. (2005) found varying density-dependent feeding responses on common lambsquarters and explained these results due to variation in the spatial scale at which densities were presented. Finally, Mittelbach and Gross

(1984) found only a minor effect of seed density on predation rates over a range of seed densities in old fields of southwestern Michigan. In our study, the spatial scale at which the cards were placed in the field was held constant and it is possible that this scale was such that no density-dependent feeding was observed. The lack of an observed density-dependent effect may also be due to the experimental design as there were only two densities that were not extremely different; this may have made it unlikely to observe a response.

Canopy cover has been shown to affect seed predation (Reader, 1991; Cromar et al., 1999; Heggenstaller et al., 2006). These studies spanned 5-7 months during the growing season. Seed removal was variably correlated with LAI in this study, with some species showing significant relationships in some sampling periods. This lack of definite correlation is not surprising, as canopy cover is only one of many factors that have been shown to affect rates of seed predation by affecting the environment in which the seed predators operate.

A number of previous studies have found seasonal changes in seed predation (Watson et al., 2003; Westerman et al., 2003b; Heggenstaller et al., 2006). In this study, sampling date was a significant factor affecting seed removal for all species studied with lower seed loss observed at the beginning and end of the season. This could be due to the patterns of natural seed availability in the field or the activity-density of seed predators. In accordance, both Westerman et al. (2003b) and Heggenstaller et al. (2006) found similar seasonal effects, although to a much larger extent than this study.

While the levels of seed loss varied among weed species, predation represented a measurable source of weed seed loss. With the increased interest in integrated weed management, knowledge about the factors affecting rates of seed predation becomes important for producers and managers. This study increases our knowledge of weed seed predation for four common agricultural weeds. This information could help producers assess how best to include seed predation as a management technique for specific problem weeds.

Conclusions

This study, in accordance with seed predation studies in other regions, indicates that postdispersal weed seed loss can represent a significant reduction of weeds in the system. This loss was not different between wheat and tilled fallow fields for three (wild oat, green foxtail, and field pennycress) of the four species studied. This result indicates that producers who use tillage for management can still expect to have some weed seed loss due to predation.

The seed loss seen in this study, although significant, was variable. This variability was seasonal, with lower rates at the beginning and end of the growing season. The loss due to predation was also not strongly correlated with canopy cover in wheat fields, so producers may expect to see similar rates of loss in varying stands of wheat.

As this was the first study of seed predation in Montana, future studies in the State and the northern Great Plains region should continue the observation of weed seed predation. Information on seed loss of a greater variety of species and in many cropping situations is important for producers in the region. Seed predation has been shown by other studies to be an important loss from weed seedbanks and this study has shown that this loss can occur in Montana wheat and fallow fields.

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CHAPTER 5

COMPARISON OF SEEDBANK DIVERSITY, COMPOSITION, AND RICHNESS BETWEEN CONVENTIONAL NO-TILLAGE AND ORGANIC SPRING WHEAT CROPPING SYSTEMS

Introduction

Weed seedbank abundance and composition can be viewed as indicators of the successes and failures of cropping systems and management practices (Cardina et al., 2002; Tuesca et al., 2004; Murphy et al., 2006; Sosnoskie et al., 2006). For example, tillage affects weed seed distribution in the soil profile (Mohler et al., 2006), seed survival, and seedling emergence (Roberts and Feast, 1972; Benvenuti et al., 2001; Boyd and Van Acker, 2003; Grundy et al., 2003; Tuesca et al., 2004; Davis et al., 2005). Also, higher weed seedbank diversity has been observed in more diverse crop rotations (Sosnoskie et al., 2006). Also, weed seedbank community composition was observed to differ among management systems with conventional and no-tillage systems being dominated by grasses while low input and organic systems were dominated by dicot species in two studies in Michigan (Menalled et al., 2001; Davis et al., 2005) . In accordance, a study in Ontario, Canada of three tillage systems and three rotations by Murphy et al. (2006) observed that tillage and crop rotation impact weed seedbank diversity and density, with the highest diversity found in no-tillage systems with a three-crop rotation and diversity decreasing with increased tillage intensity.

As weed seedbanks are indicative of a field's cropping systems history, it would be useful to know if weed seedbanks and the aboveground community are closely related. If this relationship were predictive, seedbank data could be used in the design of predictive weed management. Although a number of studies have evaluated the relationship between the weed seedbank and the aboveground weed communities, results are contradictory. While some studies have found strong relationships between the weed seedbank and aboveground communities (Dessaint et al., 1997; Zhang et al., 1998; Rahman et al., 2001; Tuesca et al., 2004; Rahman et al., 2006), others have found that correlations were generally low and very variable (Wilson et al., 1985; Forcella, 1992; Cardina and Sparrow, 1996; Webster et al., 2003).

Despite the importance of weed seedbanks as a propagule source for agricultural weeds (Cavers and Benoit, 1989), little is known about the impact of management systems on seedbank composition in the northern Great Plains Region. Furthermore, to my knowledge, no studies on the relationship between weed seedbank and aboveground weed community composition have been conducted in this region. Thus, the objectives of this study were first, to evaluate the effects of management systems on the weed seed abundance. Second, to compare weed seedbank diversity, richness, and species composition across cropping systems. Lastly, to assess the relationship between weed seedbanks and aboveground weed communities in representative no-tillage and organic fields of the northern Great Plains Region.

Materials and Methods

Three representative organic fields and three representative no-tillage conventional fields were selected in May 2005 and May 2006 near Big Sandy, Montana. This study was performed in conjunction with an aboveground weed assessment that was performed by Pollnac (2007). Big Sandy is located in agroecoregion 12, of which the bulk of soils are Aridic Ustolls (Brown Chernozems), with Cryerts (Vertisols), clayey glacial lake sediments (Padbury et al., 2002). All fields were planted with spring wheat (*Triticum aestivum* L.) in 2005 and 2006. Management practices utilized in each field are summarized in Table 5.1. The no-tillage conventional fields followed a wheat-fallow crop rotation. All organic fields followed a lentil (*Lens spp.*)-spring wheat-winter pea (*Lathyrus hirsutus*) -winter or spring wheat rotation. Conventional no-tillage fields had been under this regime for 3 yr previous to the study and minimum tillage for 15 yr prior. Organic fields had been under organic management for at least 15 yr.

In early to mid June 2005 and June 2006, aboveground weed diversity was assessed in each field using Simpson's diversity index as part of an independent study (Pollnac, 2007). Pollnac recorded aboveground measurements along three 100 m transects in each of three organic and three conventional fields. In each of the three no-till conventional fields, one transect was established to run through an observed weed patch. Two parallel transects were placed at random distances (between 5 and 50 m) from the initial transect in each field. In each of the three organic fields, three parallel transects were established randomly, as a visual estimation indicated that weeds were ubiquitously distributed. Along each transect, number of weed species and total percent cover by weed species were taken continuously in 1 m by 0.33 m frames.

Table 5.1. Management practices for sampled Big Sandy commercial farms

	Org A 2005	Org A 2006	Org B 2005	Org B 2006	Con 2005	Con 2006
Wheat Variety	Gold Lady	Klassik	Manna	Manna	Amadon	Amadon
Tillage Date	April 25	May 4	April 30	April 7	No-till	No-till
Plow	Flexicoil 820	Flexicoil 820	Frigstad with Honeybee rod	Frigstad with Honeybee rod	--	--
Seeding Date	May 2	May 6	May 2	April 10	May 1	April 10
Seed Treatment	None	None	None	None	Vitavax	Vitavax
Seeding Rate	120lbs/acre	65lbs/acre	100lbs/acre	100lbs/acre	70 lbs/acre	70 lbs/acre
Seeding Depth	2”	1”	2”	2”	¾”	¾”
Seeder	Flexicoil 5000 plow, 2340 Cart, 9” spacing	Flexicoil 5000 plow, 2340 Cart, 9” spacing	John Deere 9350 double disk, 6” spacing	Flexicoil 5000, 9” spacing, 3” spreader tips	John Deere 9400, 12” spacing	John Deere 9400, 12” spacing
Fertilizer application Date	--	--	--	--	April 28/ May 1	April 8/ April 10
Type-Rate	Green manure-50lbs/acre	Green manure-45lbs/acre	--	--	Anhydrous Ammonia (70 units/acre) Mono-ammonium phosphate (60lbs/acre)	Anhydrous Ammonia (70 units/acre) Mono-ammonium phosphate (60lbs/acre)
Herbicide	--	--	--	--	Roundup (24oz/acre burn-down) LV6 + LI extra (8oz + 0.25oz/acre, post)	Roundup (24oz/acre burn-down) LV6 + LI extra (8oz + 0.25oz/acre, post)

Organic sampling area was split between 2 farms (Org A and Org B). Conventional sampling area was spread across 1 farm. Post = post emergent application.

To assess weed seedbanks, eight 1m by 0.33 m areas were selected in each field to encompass a wide range of aboveground weed diversities. Seedbank samples were taken in these areas in early August of 2005 and 2006. Three cores of 4 cm in diameter were taken in each area to a depth of 20 cm and split in half at 10 cm. For each depth, the three samples were combined and a subsample of 470 cm^3 was germinated for 10-14 d under greenhouse conditions. Seedlings were identified and removed with the attached seed. After germination, the samples were elutriated (Gross and Renner, 1989; Wiles et al., 1996) to recover any dormant or dead seeds. These seeds were separated under a dissecting microscope and tested for germinability in a 20° C growth chamber for seven to ten days. Any ungerminated seeds were tested for viability using a tetrazolium solution (Sawma and Mohler, 2002).

Data Analysis

Species richness and Simpson's species diversity were calculated using PC-ORD (McCune and Mefford, 1999). Species richness was calculated as the number of species present in each plot. Simpson's index of diversity is calculated as:

$$\mathrm{D} = 1 - \sum_{i}^{s} p_{i}^{2} \qquad \text{Eq. 5.1}$$

Where S represents the number of species in the community and p_i represents the proportion S made up by the ith species. Seed abundance (seeds m^{-2}), species richness, and Simpson's diversity values were compared between organic and conventional systems using a mixed factor ANOVA with the R software program (R Development

Core Team, 2006). All ANOVAs were performed considering cropping system, aboveground weed diversity, and sampling year as fixed factors and field as a random factor. Samples were analyzed separately by sample depth as the two depths could not be considered independent from each other.

Seed abundance data were pooled by field, and a detrended correspondence analysis (DCA) was run to evaluate the impact of management systems on weed seedbank community composition. To decrease the impact of rare species, the ordination was conducted using only those species that had a relative abundance larger than 1%. This was calculated separately by field and by year. The ordination was carried out using the PC-ORD multivariate analysis program (McCune and Meffored, 1999). Rare species were downweighed and 26 segments were used to rescale the axis. Finally, the relationships between aboveground weed diversity and seedbank diversity; aboveground richness and seedbank richness; and weed percent cover and seedbank abundance for each cropping system and depth were analyzed using Pearson's product-moment correlation. All correlations were performed utilizing the R software program (R Development Core Team, 2006).

Results

Weed Seedbank Abundance

Seed density varied between field, cropping system, and year (Figure 5.1). In 2005, 18 species were recovered. Of those, three were unique to organic fields, five were found only in no-tillage conventional fields and the remaining ten were shared between cropping systems (Table 5.2). In 2006, 18 species were also recovered. Thirteen of these species were previously found in 2005 and eight were found in both conventional and organic fields. Eight of the remaining species were unique to organic fields and two species were found only in no-tillage conventional fields (Table 5.2). Three of the species unique to organic fields in 2006 were also found exclusively in conventional fields in 2005, showing that species composition was variable between years and cropping systems. Of the 18 species recovered in 2005, 12 were found in the aboveground weed community earlier in the growing season. In 2006, ten of the 18 species found in the seedbank were present in the aboveground weed community (data not shown).

The number of seeds recovered from the top ten cm of soil was significantly affected by sampling year ($P<0.001$) and an interaction between cropping system and sampling year ($P=0.02$). The seed abundance in the 10-20 cm sample was also significantly affected by sample year ($P<0.01$) and a cropping system by sample year interaction ($P=0.04$). At both sampling depths, fewer seeds were found in fields during the 2006 sample than in the 2005 sample.

Table 5.2. List of seed species by cropping system. Species list is broken down into those species common to both systems (shared), those found only in conventional no-tillage fields (conventional), and those found only in organic fields (organic).

2005			2006		
Shared	Organic	Conventional	Shared	Organic	Conventional
Amaranthus spp. *Astragalus spp.* *Chenopodium album* *Convolvulus arvensis* *Euphorbia nutans* *Polygonum aviculare* *Polygonum convolvulus* *Salsola kali* *Setaria viridis* *Triticum aestivum*	*Aropyron cristatum* *Descuriana Sophia* *Thlaspi arvense*	*Helianthus annuus* *Medicago sativa* *Polygonum ramosissimum* *Taraxacum officinale* *Vaccaria hispanica*	*Amaranthus spp.* *Astragalus spp.* *Avena fatua* *Chenopodium album* *Polygonum aviculare* *Polygonum convolvulus* *Setaria viridis* *Triticum aestivum*	*Brassica nigra* *Chenopodium spp.* *Euphorbia nutans* *Medicago sativa* *Sisymbrium altissimum* *Salsola kali* *Thlaspi arvense* *Vaccaria hispanica*	*Echinocloa crus-gali* *Kochia scoparia*

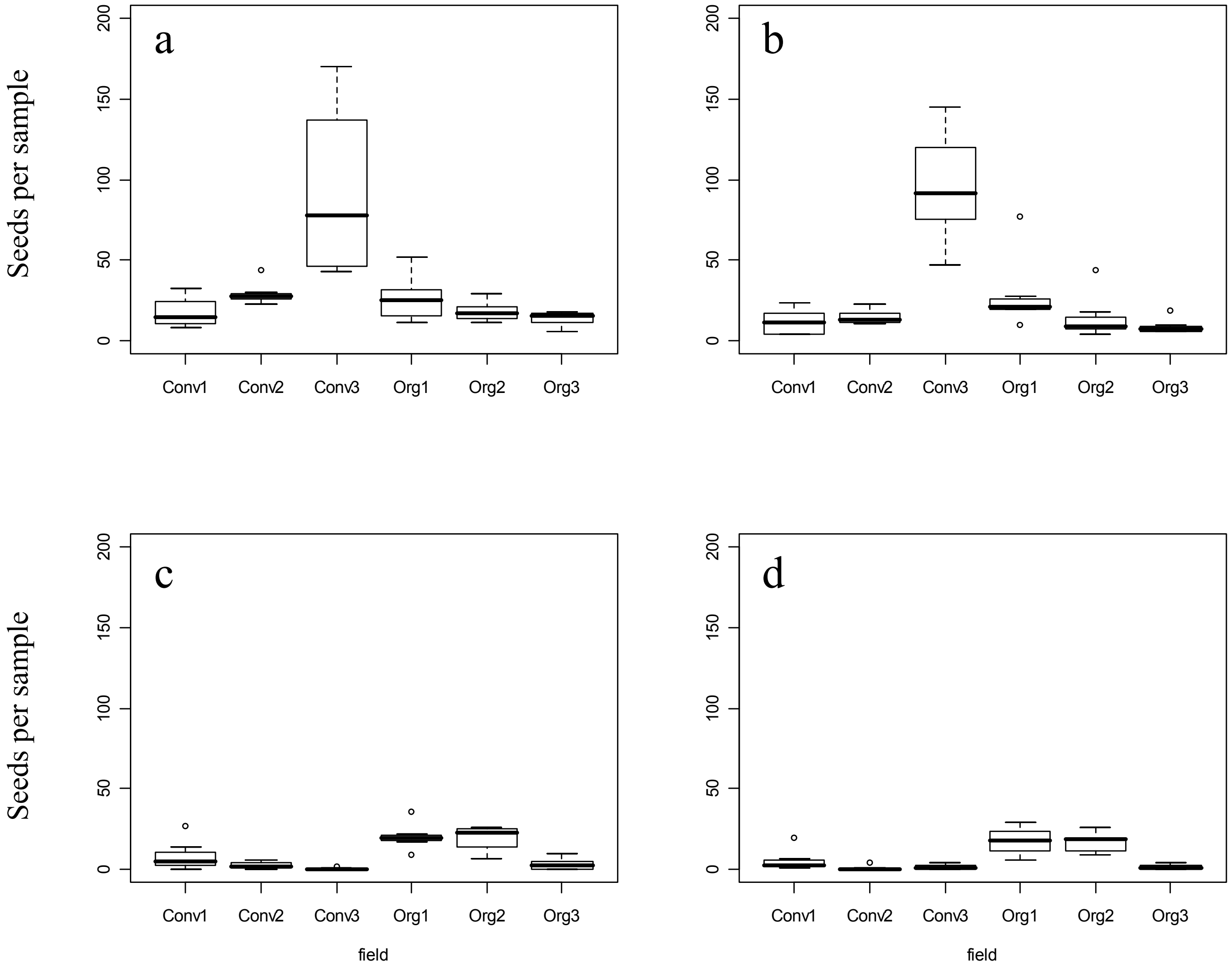

Figure 5.1: Average seed number per field in conventional no-tillage and organic fields near Big Sandy, Montana. Boxes contain the first to third quartiles and dots represent outliers a) 2005 0-10cm depth, b) 2005 10-20cm depth, c) 2006 0-10cm depth, d) 2006 10-20cm depth

Weed Seedbank Diversity and Community Composition

Year was the only significant predictor affecting belowground weed seed diversity at both depths (*P*=0.01). At the 10 to20 cm sampling depth, there was also a significant interaction between management system and year (*P*=0.04). Weed seedbank diversity was extremely variable between and within years (Figure 5.2). Although the two depths were not compared statistically because the lower sample was a continuation of the upper sample and therefore not independent, there was little difference observed between their mean weed seedbank diversity (Figure 5.2).

At the 0-10 cm sampling depth, year was the only significant factor affecting seedbank richness (*P*=0.002). At the 10 to 20 cm sampling depth, seedbank richness was affected by year (*P*<0.001), cropping system (*P*=0.05), and an interaction between cropping system and year (*P*=0.01). Seedbank richness varied between years and systems, with generally higher values in 2005 than 2006 (Figure 5.3). In 2005, mean richness was generally lower in the 0 to 10 cm samples in no-till conventional fields and generally higher in 0 to 10 cm samples in organic fields. In 2006, weed seedbank richness did not show any distinct trends at either depth.

The DCA ordination indicated that while year played a significant role in determining weed seedbank communities, management system had a significant role only during 2006. The first DCA axis of the upper seedbank sample had a length of 1.89 SD (standard deviation) units and an eigenvalue of 0.55. The second DCA axis had a length of 1.21 SD units and an eigenvalue of 0.094. The first DCA axis of the lower seedbank sample had a length of 2.07 SD units and an eigenvalue of 0.59. The second DCA axis

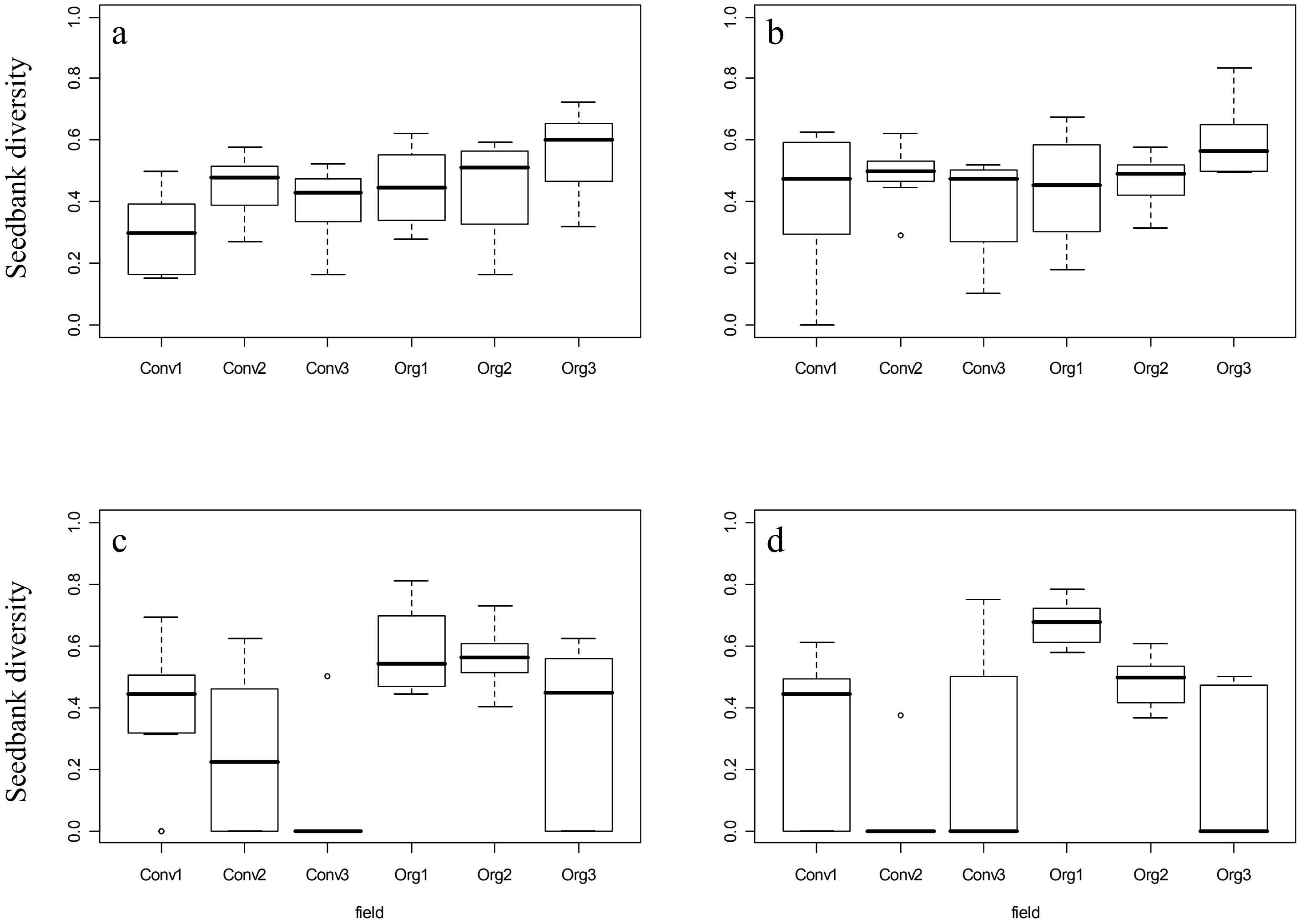

Figure 5.2: Average seedbank diversity per field in conventional no-tillage and organic fields near Big Sandy, Montana. Boxes contain the first to third quartiles and dots represent outliers. a) 2005 0-10cm depth, b) 2005 10-20cm depth, c) 2006 0-10cm depth, d) 2006 10-20cm depth

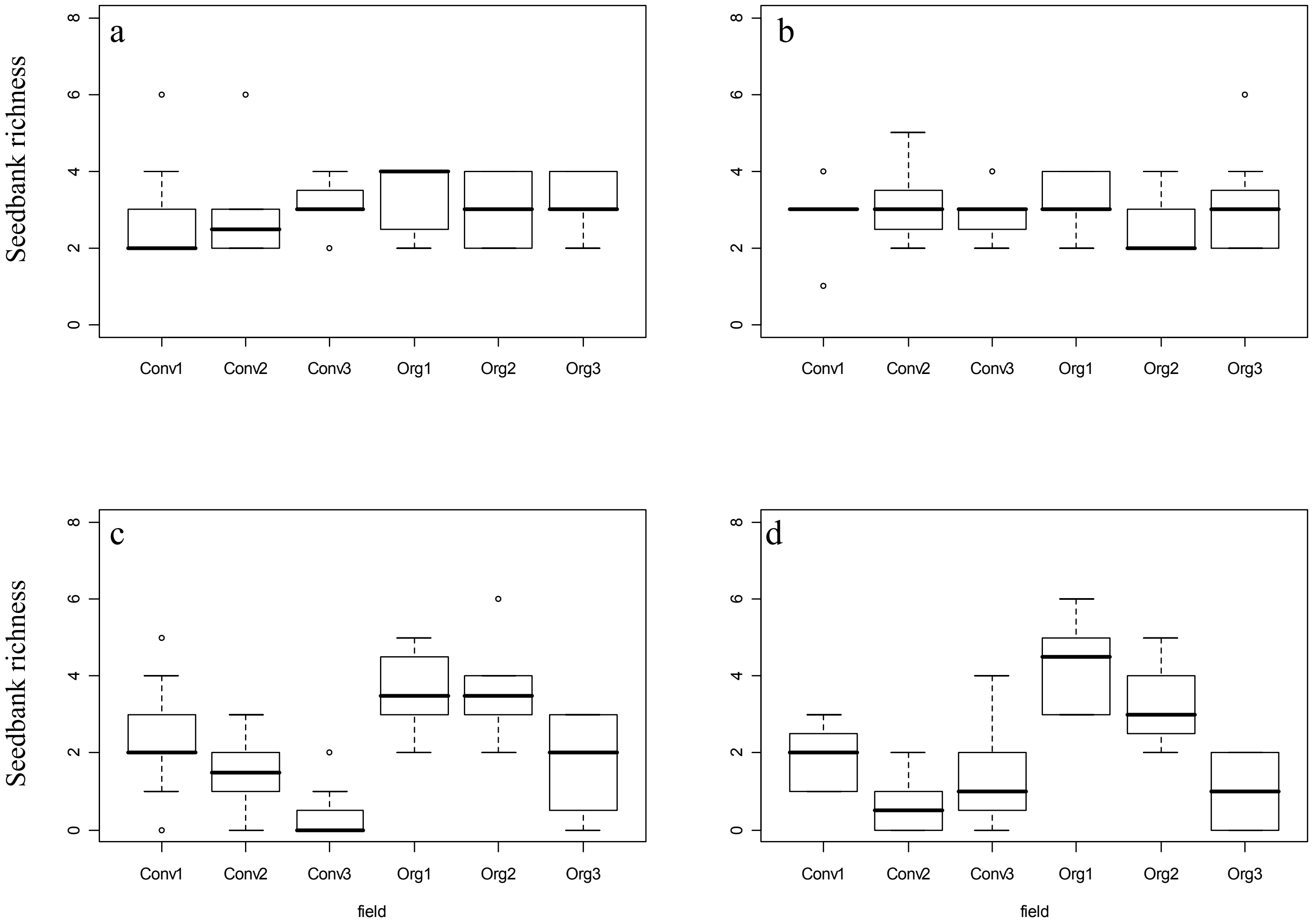

Figure 5.3: Average seedbank richness per field in conventional no-tillage and organic fields near Big Sandy, Montana. Boxes contain the first to third quartiles and dots represent outliers.. a) 0-10cm 2005, b) 10-20cm 2005, c) 0-10cm 2006, d) 10-20cm 2006

had an eigenvalue of 0.05 and a length of 1.02 SD units. In both the upper and lower seedbank samples, the first axis of the DCA ordination divided the data between years (Figure 5.4). In the lower sample, the first axis also divided conventional samples from organic samples in 2006. When weed species were plotted in relation to cropping systems and years, some possible associations were seen, with these relationships being more by year than by cropping system (Figure 5.5). Specifically, pigweed species (*Amaranthus spp.*) and wild buckwheat (*Polygonum convolvulus*) were associated with both cropping systems in 2005, while wild oat and wheat were associated with both cropping systems in 2006.

Correlation between above- and belowground weed communities

Weed seedbank diversity, richness, and abundance were variable over the two years sampled and I failed to detect strong correlations between the aboveground and belowground weed communities. The only significant relationship was observed in organic fields between weed percent cover and seed abundance at the 0-10 cm depth (Tables 5.3 and 5.4). All other correlations were not statistically significant at the P=0.05 level.

Table 5.3. Correlation between aboveground community characteristics and seedbank diversity, richness and abundance at each sampling depth in organic fields.

	0-10 cm		10-20 cm	
	Correlation	*P*	Correlation	*P*
Seedbank diversity with weed diversity	0.11	NS	0.16	NS
Seedbank richness with weed richness	0.16	NS	0.23	NS
Seed abundance with weed percent cover	0.34	0.02	0.05	NS

Table 5.4. Correlation between aboveground community characteristics and seedbank diversity, richness, and abundance at each sampling depth in conventional no-till fields.

	0-10 cm		10-20 cm	
	Correlation	*P*	Correlation	*P*
Seedbank diversity with weed diversity	0.14	NS	0.09	NS
Seedbank richness with weed richness	0.11	NS	0.05	NS
Seed abundance with weed percent cover	-0.01	NS	-0.02	NS

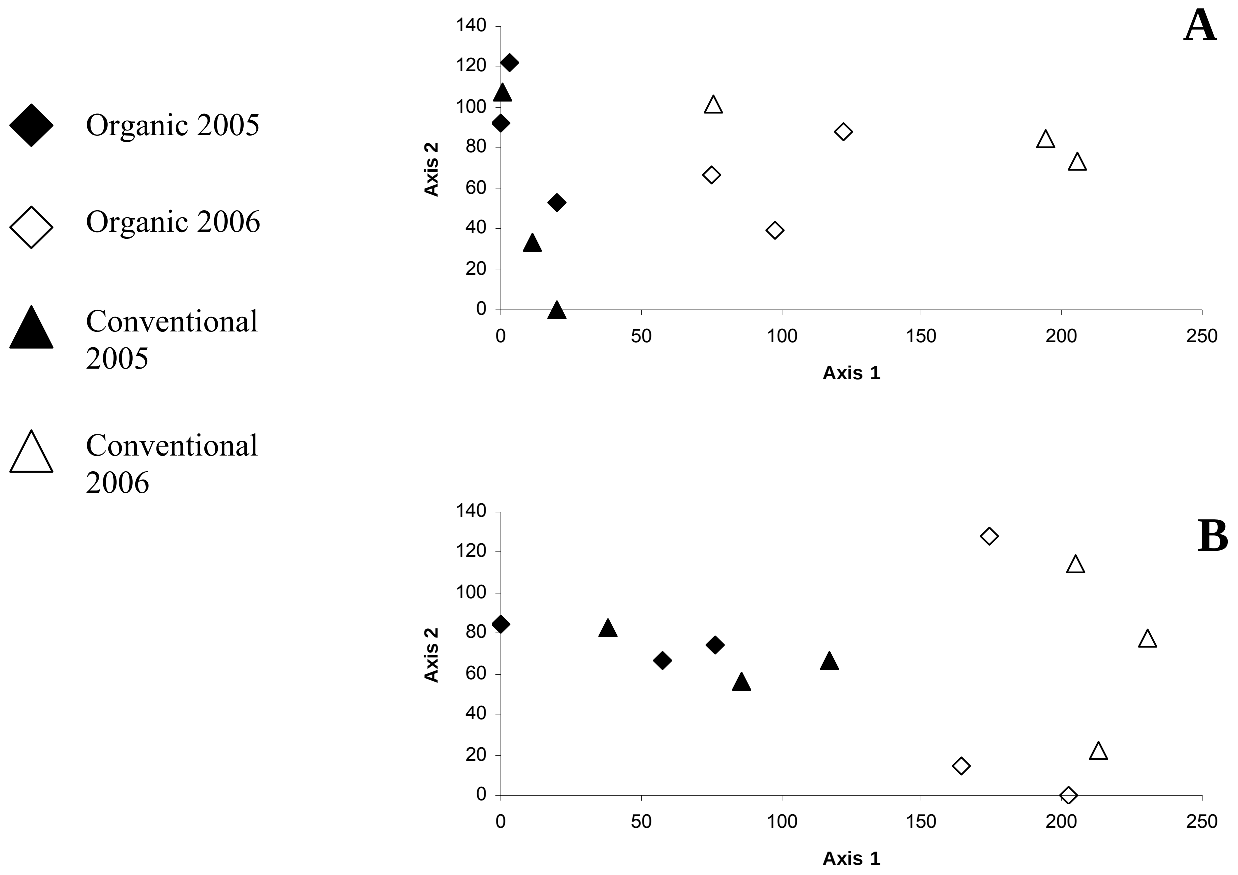

Figure 5.4. Detrended correspondence analysis (DCA) ordination of upper (A) and lower (B) seedbank samples taken in 2005 and 2006 in conventional and organic fields near Big Sandy, MT.

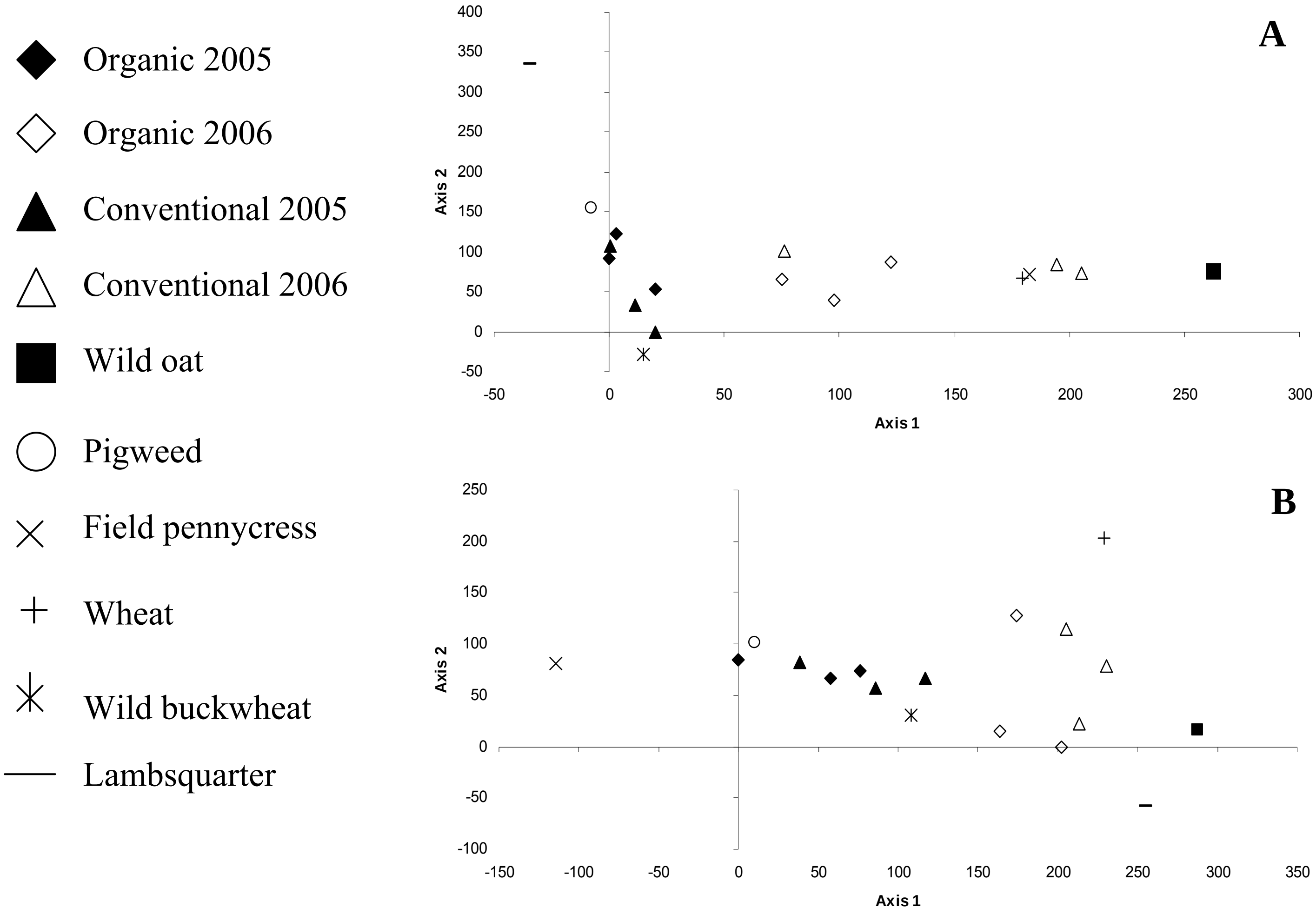

Figure 5.5. Detrended correspondence analysis (DCA) ordination of systems and species in both upper (A) and lower (B) seedbank samples taken in 2005 and 2006 in conventional and organic fields near Big Sandy, MT.

Discussion

In accordance with previous research (Davis and Liebman, 2003; Teasdale et al. 2004; Fenner and Thompson, 2005), this study indicated that weed seedbank abundance varied extremely across years. This may have been due to the effectiveness of weed control in both systems and possibly variations in environmental conditions. This pattern was also seen in the aboveground weed community where fewer weeds were found in fields in 2006 than in 2005 (Pollnac, 2007). Because the studied fields have been managed either conventionally or organically for at least 10 years, it is logical to predict that differences between cropping systems should have accumulated. Nevertheless, it appears that in the studied region, other environmental variables such as weather may have more of an effect on weed seedbank abundance and diversity than management practices.

While there was some overlap in both years, the species in the aboveground weed community were not always found in the seedbank and not all species observed in the seedbank were found in the aboveground community. In accordance, Torresen (2003) found that the relationship between the weed seedbank and the aboveground weed community varies between species. Also, Wilson et al. (1985) found that the relationship between the above- and below-ground weed community explained 42-58% of the variability of specific weed populations.

In this study, conventional fields followed a wheat-fallow crop sequence, while the organic rotation was more diverse, including winter peas, lentils, and winter or spring wheat. Although Sosnoskie et al. (2006) found an increase in weed seed diversity with increasing diversity of crop rotation, in our study cropping system was not a significant predictor of weed seedbank diversity. Nevertheless, and supporting our results, Smith and Gross (2006) found that the weed seedbank was strongly influenced by the most recent crop. As all the fields studied were planted to spring wheat in the spring of the seedbank sampling year, this may have overcome differences in the seedbank due to differing crop rotation.

Cropping system was not a significant factor in predicting weed seedbank richness. As the weed seedbank was sampled in the fall, it should have been well-related to the aboveground weed community of the growing season. However, in a similar study in Quebec, Canada, the relationship between the aboveground weed community and the weed seedbank were tenuous and varied greatly between years (Legere et al., 2005). Also, Smith and Gross (2006) found that management system was not a significant predictor of weed seedbank richness, but was a factor of the of the crop rotation phase.

The result of the multivariate ordination analysis agrees with the general seedbank characteristics that showed differences between years but not generally between management systems. In accordance with this trend, when studying aboveground weed communities in zero-, minimum-, and conventional-tillage systems in Saskatchewan, Canada, Derksen et al. (1993) found that patterns were more influenced by location and year than by tillage systems. However, other studies have observed that management systems affect weed seedbank composition (Clements et al., 1996; Unger et al., 1999).

Conclusions

The weed seedbank abundance of composition varies both spatially and temporally. This shows how much a weed seedbank can be affected by one year of management, highlighting the importance of good management planning. Although a number of studies have found differences between the weed seedbanks of organic and no-till conventional cropping systems, no distinct difference was found in this study.

Future studies should complement the information presented here with an evaluation of the long-term relationships between the aboveground and belowground weed communities in conventional and organic cropping systems within the context of the entire rotation.

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CHAPTER 6

SUMMARY OF FINDINGS/FUTURE RESEARCH

This study highlighted the importance of understanding weed seedbank composition and dynamics for improving an integrated weed management plan in the northern Great Plains region. First, this study showed that weed seedling emergence can be affected by burial depth and seedbank density. Also, the strong correlations observed between weed seedling emergence and both rainfall and crop canopy cover highlight the importance of environmental factors.

Second, this study has demonstrated that if seed inputs are minimized, the seedbanks of wild oat and green foxtail decline to very low levels. In the case of wild oat seeds mixed within the top 10 cm of the soil profile, this decline in viable seeds abundance came after a spike in the number of germinable seeds, which has strong management implications for producers. If a producer using tillage for management experiences an increase of wild oats in one year, management of wild oat seedlings will be of utmost importance in the next spring as the seeds from the previous fall could germinate at high levels.

Third, this study indicated that post-dispersal weed seed predation represents a significant loss of weed seeds from an agricultural system. Also, and contrary to our expectations, weed seed loss presumably primarily due to predation in tilled fallow fields had a comparable magnitude to that observed in cropped fields. While there were differences in seed loss between the studied species, there was no evidence of density-dependent feeding. The lack of density-dependent feeding suggests that weed seed predation could be a part of weed management even at low seed levels.

Lastly, this study involved the first characterization of weed seedbanks in production systems in Montana. It has shown that the seedbank composition of organic and conventional no-tillage systems do not differ significantly and most differences can be explained by year to year variation. Also, in support with previous research, our results indicated only a weak relationship between aboveground and belowground weed community characteristics.

In light of these observations, there is much potential for further future study. While a large body of agronomic research on weed seedbanks can be found relating to areas in the Midwest USA, relatively few studies have been performed in the northern Great Plains Region. Specifically, the assessment of seedbank responses to management systems should continue with additional species that are common weeds in the NGP region. Also, future studies should look at the impact of crop diversification on weed seedbanks.

While the results of this study were used to estimate the yield loss caused by wild oat seedlings at different seedbank depths and density levels, extensive information on the critical weed free period in the NGP region is lacking. Future studies should focus on determining the critical weed free period in this region for multiple weed and crop species to increase the efficiency of weed management in the region.

With a view to increasing the integration of ecological aspects into weed management, future studies should increase the knowledge about seed predation’s effects on the weed seedbank. Aspects that need to be evaluated include the effects of management systems, species, and seed density on pre- and post-dispersal seed removal and the overall impact of this mortality factor on subsequent weed abundance.

Although this study gave information about the weed seedbank composition in organic and conventional no-tillage fields representative of Montana cropping systems, these data are only the beginning of the information that would be useful for both researchers and producers. Future studies should work to characterize weed seedbanks in more cropping systems and more areas of the state and region. As the seedbank evaluation in this study represented only two years and one time point during each year, more information is needed on the seedbank composition and characteristics within the year and over the long-term. This would help to understand spatial and temporal variations in weed seedbank composition and characteristics.

For many years, weed management has focused on a few stages in a weed's life cycle. However, as it is becoming clearer that agricultural systems are ecological communities in their own right, it becomes more important to focus on all parts of the life cycle of weeds in croplands. This study provides another small piece of information about the ecology of weeds. Hopefully, the information gathered in this study will help to improve integrated weed management and, ultimately, the sustainability of food, fiber, and bioenergy production systems.