

DIVERSITY, SPATIAL PATTERNS, AND COMPETITION IN CONVENTIONAL
NO-TILLAGE AND ORGANICALLY MANAGED SPRING WHEAT SYSTEMS
IN MONTANA

by

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ABSTRACT

The long term sustainability of agricultural systems has become a major concern. In light of this, interest in integrated weed management systems has increased. A better understanding of ecological processes occurring within the weed community might yield insights into how to control weeds while reducing chemical inputs. The objectives of this study were to 1) compare weed species richness and diversity between conventional no-till and organic spring wheat systems, 2) compare spatial patterns of the weed community between these two systems, and 3) examine the joint effects of weed species richness and density on spring wheat performance.

Objective 1 was carried out on experimental plots and three production farms in Montana. A nested plot sampling design was used to generate species-area curves. The intercept and slope of the species-area curves were then used to estimate relative α and β diversity respectively. Data indicated higher species richness, α and β diversity in organic systems. We concluded that levels of α and β diversity may serve as indicators of underlying processes occurring in these two systems.

Objective 2 was carried out on three production farms in Montana. Percent cover data were collected from three 100 m transects in each of six fields. Using indices of dispersion and three term local quadrat variance, we found that organic and conventional system weed communities were equally aggregated, but that patterns of aggregation differed between systems. We concluded that spatial patterns in organic systems could facilitate site-specific management, and may indicate habitat heterogeneity as a controlling force in weed community distribution.

Objective 3 was carried out at the Montana State University Arthur Post Agronomy Farm. Using four weed species and spring wheat, a completely randomized full factorial addition-series experiment was established using all possible species combinations at four density levels. The effects of diversity and density were examined on target plants within each plot. We failed to reject the null hypothesis, concluding that weed species richness does not directly affect spring wheat performance. However, relative growth rate (RGR) analysis indicated that RGRs of dominant weed species may be suppressed at higher levels of species richness.

CHAPTER 1

PROJECT BACKGROUND AND OBJECTIVES

Introduction

Agriculture is a critical component of modern human society. It is also the largest industry on the planet (Clay, 2004). Despite the lack of direct involvement with agriculture by an increasingly large segment of the world's population, it still provides the necessary basis for society to function. If agriculture were to cease, many human societies on the planet would find it necessary to shift their focus from the acquisition of luxuries to modes of survival.

The ability of agricultural systems to produce adequate food has, in general, grown in parallel with an expanding world population (Tilman et al., 2002; Trewavas, 2002). However, in recent years the negative effects of current agricultural practices, such as soil and water contamination, food borne diseases, and erosion have drawn into question its sustainability (Tilman, 1999; van der Werf and Petit, 2002; Biao et al., 2003). In addition, pest management programs using chemical or mechanical practices often represent a large economic cost to farmers. It has become clear that it is necessary to examine the ecological processes operating within agricultural systems to identify more environmentally and economically sustainable agricultural practices.

Integrated weed management systems which combine biological, cultural, mechanical, and chemical control methods have been identified as an alternative form of management that decreases costs to both the farmer and the environment and which

might lead to more sustainable systems (Clements et al., 1994). However, knowledge gaps relating to ecological processes that could guide the development of integrated weed management programs in agricultural systems still remain. For example, weeds have traditionally been assessed as an unwanted but unavoidable part of agriculture. As a result, much research has been focused on the control and effects of individual weed populations within agricultural environments (Booth and Swanton, 2002). However, relatively little is known about the potential importance of weed community characteristics under different agricultural management systems. There have been studies linking the effects of management to weed community composition (Derksen et al., 1993; Derksen et al., 1994; Swanton et al., 2006). However, few studies, if any, have investigated the implications of differences in weed communities on crop plants and weed management.

Research and casual observations have already established that weed communities of conventionally managed fields are different from those of organically managed fields (Menalled et al., 2001; Hulting, 2004). In general, weed communities of organically managed systems have higher weed species diversity (Menalled et al., 2001) and richness (Menalled et al., 2001; Hyvonen and Salonen, 2002; Hyvonen et al., 2003) than the weed communities of conventionally managed fields. It has also been observed that weeds in conventionally managed fields are distributed in “patches” (Hughes, 1990; Wiles et al., 1992; Mortensen et al., 1995; Dieleman et al., 1999; Rew and Cousens, 2001; Faechner et al., 2002). To our knowledge, there is no scientific data on the distribution of weeds in organic systems.

In addition, informal communications with producers suggest that organic farmers do not experience the drastically higher yield loss that would result from much higher levels of weed density as compared to conventional farmers. Is this just a matter of differing perceptions in the farming community, or are there processes in weed communities that are operating differently in organic and conventional input systems? This is a central question that we hope to address by assessing weed community characteristics within organic and no-tillage conventional input dry-land spring wheat farming systems. It is quite possible that the different management practices associated with organic and conventional systems could lead to differences in the way that weeds and crop species compete for resources. For example, if management practices within organic systems favored a higher level of weed diversity, one might hypothesize that competition between crop and weed species would be more diffuse, reducing adverse effects on the crop species. Alternatively, the decreased species diversity and addition of pesticides on a conventional no-tillage field could limit other interactions which may benefit crop growth.

Literature Review

Diversity of plant communities is, in general, positively associated with increased ecosystem function and stability (Tilman, 1996; Sanderson et al., 2004; van Ruijven and Berendse, 2005). Thus, diversity represents a logical starting point in the examination of the functional importance of weed communities in agricultural systems. Species diversity and richness have already been proposed as components of sustainable weed management at both the field and landscape level (Clements et al., 1994; Van Elsen,

2000). There are a number of perceived benefits that increased species diversity or species richness might bestow upon agricultural systems (Jordan and Vatovek, 2004). These range from decreasing the likelihood of developing herbicide resistance in weed communities (Clements et al., 1994), to providing resources for beneficial organisms (Thies and Tschardtke, 1999; Landis et al., 2005; Taylor and Maxwell, 2006) and enhancing soil quality (Jordan and Vatovek, 2004).

Diversity is an important attribute of plant communities. Booth and Swanton (2002) suggest that the number of species within a given general plant community is governed by certain “filters or constraints acting on the species pool”. In natural plant communities, the number of species in a given community may be determined by the heterogeneity of aspects related to the environment such as soil quality, light availability, or water availability (Crawley, 1997b). There may also be elements of chance involved, and the number of species may be somewhat controlled by their dispersal ability (Hubbell, 2001). Within agricultural systems there are several constraints on species diversity. Herbicide use, tillage, and other weed management practices are important filters controlling weed community composition in agricultural systems (Booth and Swanton, 2002). The exact mechanisms responsible for controlling the level of species diversity in agricultural systems are still poorly understood. However, equal in importance to this lack of understanding is the fact that the relationship between weed species diversity and crop yield is unclear. In order for a more ecological system of management to proceed, it will be necessary to demonstrate some knowledge of the effects of ecological attributes, such as species diversity, on crop yield. Therefore, this

study examines: 1) methods to assess weed diversity in conventional and organic spring wheat systems, and the implications of differences in different types of diversity for developing potential management strategies, 2) spatial patterns of weed communities within each of these two management systems, and, 3) the impact of weed diversity and density on crop-weed competition.

Species-Area Relationships

The species-area-relationship is a well established and much discussed method in ecological research (Arrhenius, 1921; Gleason, 1922; Connor and McCoy, 1979; McGuinness, 1984, Rosenzweig, 1995). Species-area curves have been used to estimate the total number of species present in an area (Stohlgren et al., 1997), and to determine the minimum size of sampling unit necessary to characterize the diversity of a study area (Pfeifer et al., 1996; Mulugeta et al., 2001; Cannone, 2004). In addition, species-area curves are suitable for estimating the relative α and β diversity of an area, which can then be used to infer how species are distributed within an area (Scheiner, 2003) and can serve as indicators of dispersal processes (Loreau, 2000). Competitive interactions and spatial distributions of plant species can also modify the shape of the species-area curve (Leps and Stursa, 1989). All of this suggests that the species-area curve may be a useful indicator of spatial patterns, competitive interactions, dispersal, and diversity within plant communities.

Although the use of species-area curves in non-crop systems is well established, their effectiveness has seldom been examined in an agricultural setting. A recent study utilized species-area curves and found that tillage regimes modified the minimum sample

areas needed to represent 75% of the weed species present (Mulugeta et al., 2001). However, to our knowledge, the weed species-area relationship has never been used in a comparison of weed communities of organic and conventional input systems. Examining species-area curves of organic and conventional input systems might yield valuable information for several reasons. At the most basic level, prior knowledge of the species-area curve is useful in determining the spatial scale at which species richness should be evaluated (Clements et al., 1994). The species-area curve has also been linked to general plant community processes (competition and dispersal, see above) that might be important in regard to weed management. Thus, as the examination of ecological processes becomes more prominent in agricultural research, species-area curves may be especially useful because of their ability to suggest underlying processes which may be operating within these systems.

Spatial Patterns of Weed Communities

Knowledge of the spatial distribution of weeds within a field is useful for determining where and when to carry out weed control (Thornton et al., 1990; Wiles et al., 1992) and in making accurate estimates of yield loss due to weeds (Brain and Cousens, 1990; Thornton et al., 1990). Up to this point, most research has focused on the spatial distribution of weeds within conventional input systems where weed communities tend to have patchy distributions (Hughes, 1990; Wiles et al., 1992; Mortensen et al., 1995; Dieleman et al., 1999; Rew and Cousens, 2001; Faechner et al., 2002) which are most likely due to differential mortality rates.

Despite this focus on conventional input cropping systems, there are still knowledge gaps relating to weed spatial patterns in conventional fields, especially in relation to species richness and density within weed patches. Furthermore, the effects of weed diversity on yield loss have not been adequately investigated. Cardina et al (1997) suggested that within a patch, weed intra-specific competition reduces the competition between the weeds and the crop. However, little is known about the relative importance of weed density and inter-specific competition among weeds in relation to yield loss. It follows that if weed aggregation is going to be considered as a determinant of weed impact on crop yield, the characteristics (composition, density, and diversity) of the aggregations themselves should also be considered.

Organic cropping systems, on the other hand, remain relatively unexamined with respect to weed spatial patterns. Casual field observations and anecdotal evidence suggest that weeds are not as patchy in organic systems as in conventional systems. Thus, it is reasonable to think that there might be spatial aspects of weed community structure within an organic cropping system that would influence crop-weed interactions differently than in conventional input systems. In addition, knowledge of spatial patterns in the weed communities of organic systems might allow for the implementation of site-specific management practices.

Various methods have been used to map weed populations in farm fields. Discrete sampling is the most commonly used method, and involves collecting data from quadrats distributed on a grid (Rew and Cousens, 2001). That data is then interpolated with techniques such as kriging to generate maps of weed distribution (Rew et al., 2001).

Seedling counts from 0.25-m² quadrats on a 10 m x 10 m grid have been shown to yield accurate maps of weed spatial distributions when kriging is applied (Heisel et al., 1996). However, determination of the proper grid size prior to sampling is essential for this type of technique, particularly when weeds are distributed in patches within a field, as larger grid sizes may lead to a decreased likelihood of recording any given patch of weeds (Rew and Cousens, 2001). In addition, grids are sometimes difficult to establish and the number of data points necessary to yield accurate maps is often very high (Rew and Cousens, 2001).

Continuous sampling is another option to assess weed spatial distribution (Rew and Cousens, 2001). With continuous sampling, the presence or absence of weeds is noted by an observer within the field while traveling in a continuous fashion. This data can then be analyzed using indices of aggregation to discern the general patterns of weed distribution. Quadrat variance techniques (Hill, 1973) can also be applied to continuous data, and can provide more insight into the spatial scale of patterns of vegetation. These types of analyses would be logical starting points in situations where the pattern of weed cover is unknown, and it is unnecessary to record discrete spatial patterns within the study area. In addition, these analyses would indicate whether the more intensive and detailed data collection were needed to produce discrete spatial maps of weed cover would be useful.

Weed-Crop Competition

Interference is an important factor that affects individual plants, plant populations, and plant communities (Harper, 1977). The effects of weed-crop competition in

agricultural settings have been assessed previously. In a model based approach using the inverse hyperbolic equation (Cousens, 1985), Garrett and Dixon (1998) determined that increasing competition resulted in a diminishing yield response. Many field studies have found that crop yield decreases with increased weed density (O'Donovan and Sharma, 1983; Tamado et al., 2002; Whish et al., 2002; Moechnig et al., 2003) and that weed biomass decreased with increased crop density (Weiner et al., 2001). Weiner et al. (2001) also found that weed density decreased as a result of planting crops in a grid pattern as opposed to a row pattern. However, the relationship between weed diversity and crop yield is unclear. Although Clements et al. (1994) questioned if increasing weed diversity at a constant density would decrease the effect of weeds on the crop, no empirical study has yet evaluated this issue. There have been recent studies that suggest that weed diversity has had either negative (Davis et al., 2005) or positive (Suarez et al., 2001) effects on crop yield. However, both of these studies were observational in nature, and did not control for weed density. Therefore, the observed yield effects could have been due to other factors besides diversity. In one study, Murphy et al. (2006) demonstrated that crop yield was not affected by management system, even in light of increased weed diversity in some systems, suggesting that weed species diversity may have no effect on yield. However, the link between weed diversity and crop yield has yet to be experimentally tested.

To study the effects of diversity on crop yield, it would be necessary to manipulate weed diversity and examine the effects of this manipulation on target crop plants as well as on the weeds themselves. The effects of neighboring plants on the

growth of an individual plant are commonly studied using a running radius neighborhood competition approach. In this approach, a target plant is centered within a circular area of fixed radius, and all other plants within that area are considered neighbor plants (Silander and Pacala, 1985). Although neighborhood size is sometimes set arbitrarily, Silander and Pacala (1985) found that the optimum neighborhood size for relating neighbor plants to target plant performance in their specific case was quite small (5 cm radius). In a separate study, Lindquist et al. (1994) found that a neighborhood size of 16 cm was optimal for measuring neighborhood effects in a small grain system. This lends support to the idea that plants only compete strongly with their nearest neighbors (Crawley, 1997a).

The effects of neighbor plants on target plants can be quantified in several ways. Using linear models, Hickman (1979) was able to account for 48 to 73% of the variation in dry weight biomass of *Polygonum spp.* using the mean distance to four neighbors. Weiner (1982) was able to account for over 80% of the variation in individual seed set using a model which incorporated both distance to neighbors and their competitive effects. The number of independent factors that could be used in these models is quite expansive, but it is usually limited by logistical considerations. One potential problem with these types of analyses is that they measure absolute differences in biomass, seed production, or yield, and generally do not account for initial size inequality due to differences in physiology between species. One measure that accounts for the efficiency of biomass accumulation of a plant given the size of the plant is the relative growth rate, or RGR (Radosevich et al., 1997). The RGR also serves as a good approximation of competitive ability (Holt and Orcutt, 1991; Hegazy et al., 2005; Wang et al., 2006).

Measurements of RGR can be achieved by accounting for plant biomass at the time of planting and then measuring plant biomass at harvest. Relative growth rate can also be measured at many points throughout the growing season by measuring an attribute of the plant which can be correlated with biomass. Bussler et al. (1995) found that plant volume was very closely correlated with plant biomass. Thus, by measuring plant volume at several points throughout the growing season, plant biomass could be estimated without actually harvesting the plant. In this way, relative growth rate of a specific target plant or species could be measured over a growing season and between points within the growing season.

Project Justification and Objectives

In order to move towards a more sustainable system of agriculture, it will be necessary to consider agricultural systems within an ecosystem framework. By doing so, it is possible that beneficial natural processes could be identified and then be used in place of current agricultural practices or to augment them. This, in turn, could alleviate some of the negative environmental, economic, social, and public health concerns associated with current agricultural practices.

There is still a long way to go in the pursuit of a more sustainable system of agriculture, and the development of appropriate scientific research programs will be critical to this aim. Although the focus of scientific research is often necessarily small in scale, the collaborative efforts and communication of members of the scientific community make the achievement of broad goals possible.

There are three main objectives to this study:

Objective 1: Compare weed diversity in conventional and organic spring wheat systems using species-area curves.

Objective 2: Compare the spatial patterns within the weed communities of organic and conventional no-tillage cropping systems, and examine weed density and species richness within weedy areas in both systems.

Objective 3: Quantify the effects of weed density and weed species richness on spring wheat yield.

In a broad sense, it is hoped that this study, which focuses on organic and conventional no-tillage dry-land spring wheat systems of the Northern Great Plains, can be used as a piece of a greater puzzle, and thus will generate hypotheses that will move our agricultural practices towards the goal of sustainability. At a more local scale, the findings of this project will provide valuable information for farmers in regard to the effects of different types of weed communities on spring wheat yield, and the applicability of site-specific management.

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CHAPTER 2

USE OF SPECIES-AREA CURVES TO EXAMINE WEED COMMUNITIES IN
ORGANIC AND CONVENTIONAL NO-TILLAGE SPRING WHEAT
CROPPING SYSTEMSIntroduction

The importance of species diversity within agroecosystems has become a point of interest within the scientific community in recent years, given the number of studies addressing the issue (Swift and Anderson, 1993; Menalled et al., 1999; Van Elsen, 2000; Lee et al., 2001; Menalled et al., 2001; Mulugeta et al., 2001; Suarez et al., 2001; Hyvonen and Salonen, 2002; Weibull et al., 2002; Albrecht, 2003; Hyvonen et al., 2003; Thrupp, 2004; Davis et al., 2005; Manhoudt et al., 2005). Weed diversity is an important component of the overall diversity of most cropping systems. However, the value of weed species diversity may be counterintuitive at the producer level, as most cropping practices favor yield maximization through the growth of monocultures. It is perhaps for this reason that the potential role of plant species diversity in the sustainability of agricultural production systems has not been well studied.

There is growing evidence that the number and relative abundance of species plays an important role in terrestrial ecosystem function. Plant diversity has been shown to be positively associated with community and ecosystem level processes such as productivity, nutrient cycling, and stability of biomass production (Tilman, 1996; Sanderson et al., 2004; Hooper et al., 2005; van Ruijven and Berendse, 2005). All of

these functional responses are desirable in agricultural systems. Unfortunately, much of the research relating diversity and ecosystem function has been conducted in natural systems or experimental grassland contexts different from agroecosystems (Hooper et al., 2005). Our ability to understand community and ecosystem function and stability as they relate to agriculture may be critical to the achievement of agricultural sustainability (Tilman, 1999). Hence, if agricultural sustainability is the goal, diversity within agroecosystems needs to be investigated more fully.

There are a number of perceived benefits that greater weed species diversity might bestow upon agricultural systems (Jordan and Vatovec, 2004). These range from decreasing the likelihood of developing herbicide resistance in weed communities (Clements et al., 1994), to providing resources for beneficial organisms (Thies and Tschardtke, 1999; Landis et al. 2005; Taylor and Maxwell, 2006) and enhancing soil quality (Jordan and Vatovec, 2004). Moreover, it has also been suggested that weed diversity would be a suitable indicator of overall diversity within agroecosystems (Albrecht, 2003).

Special methodological considerations that are not often addressed in agroecosystem research (incorporating temporal and spatial measurements) are necessary in providing useful insights into the functionality of weed community diversity. This issue will become increasingly important as more growers shift to reduced input systems that favor greater numbers of weed species and higher system complexity (Menalled et al., 2001; Hyvonen and Salonen, 2002; Hyvonen et al., 2003; Davis et al., 2005). Although it has been suggested that species richness may be the most appropriate

measure in agricultural systems (Albrecht, 2003), the methods and indices that are currently used to estimate weed diversity tend to differ among studies and there is often little justification given for the chosen method or index. A specific type of species-area curve, the log-species number log-area curve, was chosen to measure plant species diversity in different types of agroecosystems for this study. This type of curve, like all species-area curves, incorporates the spatial aspect of measurement inherently, as species area curves measure the number of species occurring at a given sample area. To incorporate the temporal aspect, two growing season measurements and one post-harvest measurement were taken each year during this two year study.

The species-area curve has several properties which make it useful to assess on-farm plant diversity. Species-area curves allow one to determine the minimum sample area necessary to characterize diversity of a general area (Arrhenius, 1921; Gleason, 1922; Williams, 1943; Mulugeta et al., 2001; Cannone, 2004), estimate the total number of species present in an area (Stohlgren et al., 1997), and compare diversity at multiple spatial scales. In addition, species-area curves can be used to estimate α and β diversity, where α diversity is plot scale diversity and β diversity is a measure of the change in species composition from plot to plot (Scheiner, 2003; Scheiner, 2004). They can also be used to gain insight into the causes and possible consequences of species diversity within a system. The first objective of this study was to determine if the log-species number log-area relationship held in a spring wheat agroecosystem and could be used to compare and interpret plant species diversity in conventional no-tillage and organic spring wheat (*Triticum aestivum L.*) systems. The second objective was to study the within season

temporal variations in plant α and β diversity within conventional no-tillage and organic spring wheat systems.

Materials and Methods

This study was conducted at two sites, both in dry-land spring wheat production systems. The first site was located in Fergus Co., MT, on the USDA Special Project, Sustainable Pest Management for Dry-land Wheat Research site (SPM site), 46°56'38" N, 109°42'46" W, 1,277 m elevation. The soil at this site is a Judith Clay Loam (Clark, 1988), and for the last 5 yrs, precipitation averaged 325 mm annually. Our second study site was located in Chouteau Co., MT, and was composed entirely of production farms in the vicinity of Big Sandy, MT 48°10'44"N, 110°06'49"W, 824 m elevation. Soils in this area ranged from Telstad-Joplin Loam to Fort Benton Fine Sandy Loam (Bronec, 2003), and over the last five years, annual precipitation averaged 288 mm.

The SPM site was established in 1999 and covers 16 ha. This study was conducted in 2004 and 2005. Since the establishment of the site, the observed plots were managed for agricultural production under conventional high input and organic regimes. Conventional plots measured 14.6 m by 30.5 m, and the organic plots measured 7.3 m by 30.5 m. Conventional plots followed a spring wheat, winter wheat, barley (*Hordeum vulgare* L.), and chemical fallow rotation. These plots were managed without tillage and both herbicides and fertilizers were applied based on local best management practices. Details regarding specific agronomic information for this site can be found in Hulting (2004). Organic plots were plowed prior to planting and followed a spring wheat, lentil (*Lens culinaris*), barley, and Austrian winter pea (*Pisum sativum*) green manure rotation.

At the SPM site, observations of plant species diversity were made during the spring wheat phase of the rotations. To assess the within season temporal patterns of plant diversity, observations were made three times during the periods from 2 June, 2004 to 4 Sept., 2004 and from 14 June, 2005 to 3 Sept., 2005. Specifically, observations were made twice during the crop growing season and once a few days following harvest each year. During each sampling effort, two sets of nested sub plots were randomly placed within each plot. Nested sub plots consisted of a 0.1 m² ring, a 1.0 m² ring, and a 10 m² ring. All non-crop plant species were identified and counted within each ring. Number of individuals and percent cover of the crop species was counted in the smallest ring. Once observations were taken from both of the nested sub plots, species richness at the whole plot scale was measured.

To assess the validity of the plot-level study, separate surveys on three farms located near Big Sandy, Montana were conducted during the summer of 2005. Measurements were taken three times between 18 June, 2005 and 9 Sept., 2005. For this survey, three spring wheat fields on one conventional farm and three spring wheat fields on two organic farms were utilized. The conventional fields followed a winter wheat, fallow, spring wheat, fallow rotation. And these fields were managed as no-tillage systems and were subject to both fertilizer and herbicide use (Table E.1). The organic fields followed a spring wheat, Austrian winter pea sequence with no fertilizer or pesticide inputs, and were plowed on a regular basis prior to planting. At each field, data were collected from six sets of randomly placed nested plots in the same fashion as described for the SPM site, with the exception that the entire field was not surveyed after

gathering data from the nested plots. Instead, an additional 100 m² area was established around each nested plot to account for the largest scale of sampling. Within these 100 m² plots, occurrences of all non-crop species were identified. As with the SPM site, data were collected twice during the growing season and once a few days following harvest.

Data Analysis

Prior to analysis, one was added to all non-crop species richness values to allow for log transformation of samples that contained no non-crop species. This essentially converted our data to total plant diversity (including crop). Data from each study area and management system were pooled for each of the three sampling periods. Species-area curves were obtained for each sample site, management system, and sampling period by performing a linear regression between the log₁₀ of species richness (dependent variable) and the log₁₀ of sampled area (independent variable). All regressions were performed using R 2.2.1 (CRAN, 2005). At each study site, the regression lines and their respective slopes and intercepts for the different management systems and sampling periods were compared using the extra sum of squares method for regression comparison (Draper and Smith, 1981). Slope and intercept values from each regression were used as estimates of the α and β diversity in each combination of system and sample period (Scheiner, 2003; Scheiner, 2004). Since the regression parameter estimates were based on a log transformed scale, our intercept and α diversity estimates represent the 1 m² scale of sampling. A single factor ANOVA using time of season as the independent variable followed with a Tukey procedure (R 2.2.1) was performed for each sample site

at the first three scales of measurement (0.1 m², 1 m², 10 m²) to test for the effects of sampling period on the number of weed species found.

Results

All regressions of log species richness on log area sampled were significant except for the conventional no-tillage late summer sampling period in Big Sandy (Table 2.1).

Table 2.1. Table of comparisons for organic and conventional no-tillage species-area curves at each sample site for each sample period.

		<i>p</i> -value	<i>b</i> ₀	<i>b</i> ₁	F	CI(<i>b</i> ₀ con - <i>b</i> ₀ org)	CI(<i>b</i> ₁ con - <i>b</i> ₁ org)
SPM Site 2004							
Early Summer	Con	3.2e-5	0.3	0.14	11.5*	(-0.28, -0.03)	(-0.17, -0.02)
	Org	2.7e-7	0.5	0.23			
Mid Summer	Con	6.0e-6	0.3	0.17	2.7	(-0.18, 0.07)	(-0.14, 0.01)
	Org	7.2e-8	0.4	0.24			
Late Summer	Con	8.2e-5	0.04	0.08	16.2 *	(-0.26, -0.06)	(-0.14, -0.01)
	Org	2.3e-5	0.2	0.16			
SPM Site 2005							
Early Summer	Con	2.7e-7	0.5	0.20	19.2*	(-0.34, -0.13)	(-0.01, 0.12)
	Org	1.9e-4	0.7	0.15			
Mid Summer	Con	6.3e-4	0.1	0.14	50*	(-0.06, -0.33)	(-0.15, 0.02)
	Org	3.3e-7	0.6	0.20			
Late Summer	Con	3.0e-3	0.01	0.05	107.5*	(-0.47, -0.29)	(-0.22, -0.11)
	Org	8.9e-8	0.4	0.21			
Big Sandy 2005							
Early Summer	Con	2.2e-11	0.4	0.15	67.5*	(-0.38, -0.11)	(-0.09, -0.01)
	Org	2.2e-16	0.7	0.19			
Mid Summer	Con	1.6e-2	0.01	0.02	56.1*	(-0.73, -0.17)	(-0.21, -0.04)
	Org	1.7e-3	0.5	0.15			
Late Summer	Con	0.4	0.02	0.01	42.3*	(-0.51, -0.04)	(-0.21, -0.07)
	Org	1.5e-4	0.3	0.15			

org = organic system regression, con = conventional no-tillage system regression, *p*-value = *p*-value of regression, *b*₀ = *y* intercept, *b*₁ = slope, * = greater than critical value of F at $\alpha = 0.05$. Critical values of F = 3.24 (SPM Site) and 3.09 (Big Sandy), confidence intervals calculated at $\alpha = 0.05$.

The extra sum of squares analysis indicated differences in eight out of the nine comparisons of organic and conventional no-tillage system regressions based on the critical value of F at $\alpha = 0.05$. When curves were significantly different, intercepts (α -diversity) were higher for the organic systems than for conventional no-tillage systems in all cases. Slopes (β -diversity) were higher for the organic system in six out of eight comparisons. For the other three comparisons, slope did not differ. This suggests higher levels of plant species richness at all scales of measurement (Figure 2.1).

When crop species was not taken into account, the weed community indicated the same general trend as for the whole community (Table 2.2). Weed species richness decreased between the early and late season sampling periods in all cases for the organic systems and 8 out of 9 cases for the conventional no-tillage systems (Table 2.3). There was evidence of non-constant variance between periods within the conventional no-tillage systems. These were due to the fact that, in the late summer sampling period, no weeds were found (richness = 0), and thus there was thus no variance.

A total of 27 non-crop species were recorded at the SPM site, and 32 at Big Sandy (Table 2.4). At the SPM site, the bulk of non-crop species were shared between systems, with organic and conventional no-tillage systems having a lesser and equal number of exclusive species. In contrast, most non-crop species at Big Sandy were found exclusively in the organic system with a smaller number of shared species and only two species found exclusively in the conventional no-tillage system.

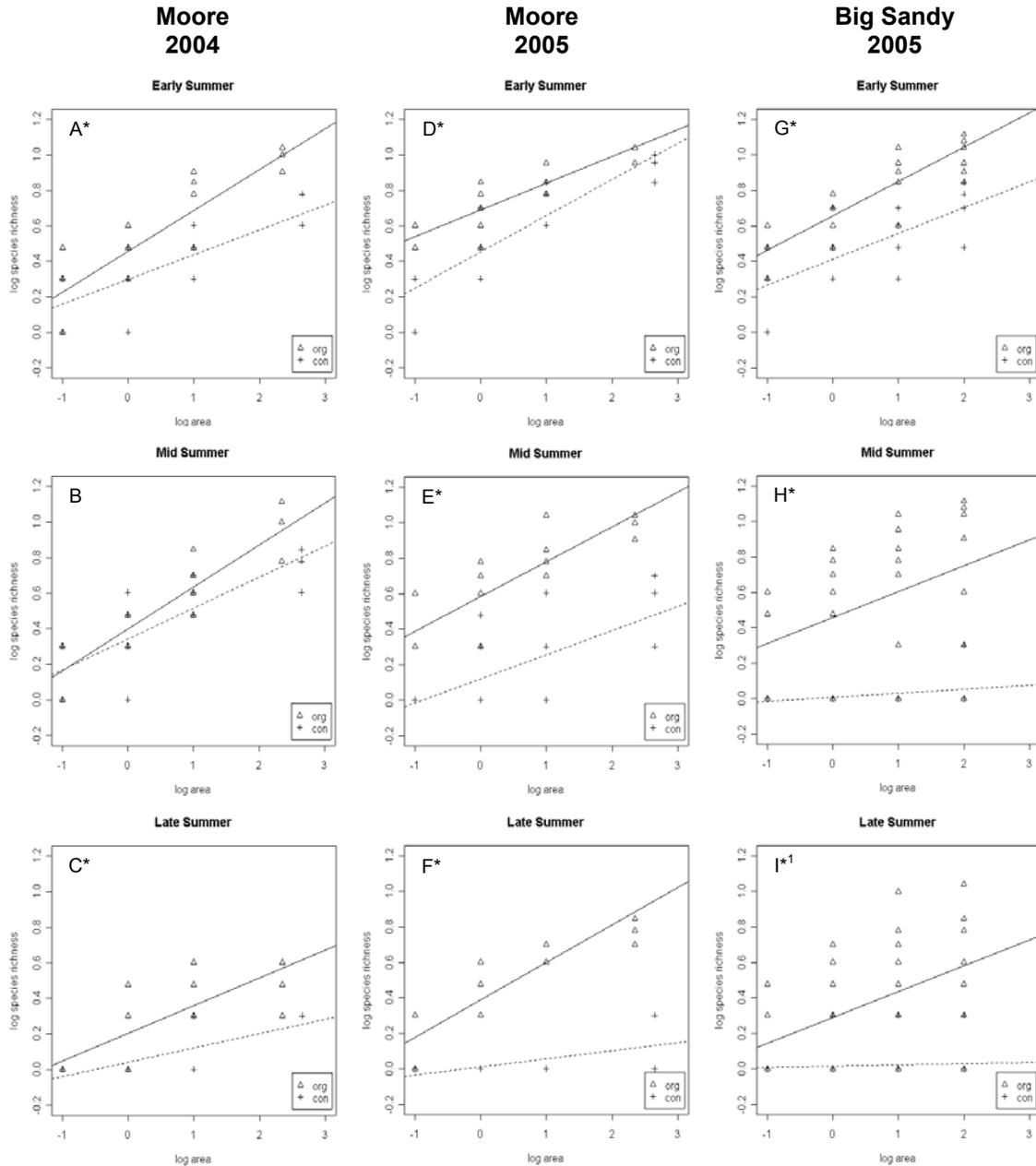


Figure 2.1. Comparative species-area curves for all sample periods: org = organic, con = conventional, * = F-statistic indicates significant difference between curves ($p < 0.05$), 1 = conventional system curve not significant ($p > 0.05$).

Table 2.2. Mean non-crop plant species richness (sd) for organic and conventional no-tillage systems by site and year for each samplingscale. For the SPM site, n=6 for 0.1, 1, and 10 m² scales and n=3 for 223 and 445 m² scales. For Big Sandy, n=12 for all scales.

	System	0.1	1	10	100	223	445
SPM Site 2004							
Early Summer	Con	0.5(0.55)	1.2(0.75)	1.8(0.75)	-	-	3.7(1.15)
	Org	0.8(0.75)	1.8(0.75)	4.5(2.07)	-	8.7(1.53)	-
Mid Summer	Con	0.5(0.55)	1.3(1.03)	2.8(0.75)	-	-	4.7(1.53)
	Org	0.7(0.52)	1.2(0.41)	3.8(1.83)	-	8.7(3.5)	-
Late Summer	Con	0	0	0.5(0.55)	-	-	1(1)
	Org	0	0.8(0.75)	1.8(0.75)	-	2(1.53)	-
SPM Site 2005							
Early Summer	Con	0.8(0.41)	1.7(1.21)	4.7(1.37)	-	-	7.7(1.53)
	Org	2.3(0.52)	4.3(1.63)	6.3(1.37)	-	9.3(1.15)	-
Mid Summer	Con	0	0.5(0.84)	0.8(1.16)	-	-	2.7(1.53)
	Org	1.3(0.82)	3.3(1.37)	5.8(2.14)	-	8.7(1.53)	-
Late Summer	Con	0	0	0	-	-	0.7(0.57)
	Org	0.3(0.52)	2(0.63)	3.5(0.55)	-	5(1)	-
Big Sandy 2005							
Early Summer	Con	0.9(0.67)	1.8(0.83)	2.6(1)	4.2(0.94)	-	-
	Org	1.9(0.67)	3.5(1)	7.1(1.68)	9.5(1.88)	-	-
Mid Summer	Con	0	0	0	0.3(0.45)	-	-
	Org	1.6(1.24)	2.3(2.05)	4(3.27)	6.9(4.48)	-	-
Late Summer	Con	0	0.1(0.29)	0.1(0.29)	0.1(0.29)	-	-
	Org	0.5(0.80)	1.3(1.30)	2.6(2.57)	3.6(2.84)	-	-

Table 2.3. Results of ANOVA and Tukey procedure. *p*-value is for omnibus test for effects of period on weed species richness at the specified scale (0.1 m², 1 m², or 10 m²). Confidence intervals are for $\alpha = 0.05$ and represent the 95% confidence interval for the difference between the specified pair of periods.

Site	System	Scale	P	CI (late-early)	CI (mid-early)	CI (mid-late)
Moore 2004	Org	0.1	0.04	-1.62, -0.04	-0.96, 0.62	-0.12, 1.46
	Org	1	0.05	-1.99, -0.01	-1.65, 0.32	-0.65, 1.32
	Org	10	0.04	-5.15, -0.18	-3.15, 1.82	-0.48, 4.48
	Con	0.1	0.12	-1.17, 0.17	-0.67, 0.67	-0.17, 1.17
	Con	1	0.01	-2.27, -0.06	-0.94, 1.27	0.23, 2.44
	Con	10	<0.01	-2.37, -0.30	-0.04, 2.04	1.30, 3.37
Moore 2005	Org	0.1	<0.01	-2.95, -1.05	-1.95, -0.05	0.05, 1.95
	Org	1	0.02	-4.26, -0.41	-2.92, 0.92	-0.59, 3.26
	Org	10	0.01	-5.08, -0.59	-2.75, 1.75	0.09, 4.58
	Con	0.1	<0.01	-1.19, -0.48	-1.19, -0.48	-0.35, 0.353
	Con	1	0.01	-2.94, -0.39	-2.44, 0.11	-0.774, 1.77
	Con	10	<0.01	-6.22, -3.11	-5.39, -2.28	-0.72, 2.39
Big Sandy 2005	Org	0.1	<0.01	-2.35, -0.48	-1.27, 0.60	0.15, 2.02
	Org	1	0.01	-3.69, -0.65	-2.77, 0.27	-0.60, 2.44
	Org	10	<0.01	-7.10, -1.90	-5.68, -0.49	-1.18, 4.01
	Con	0.1	<0.01	-1.30, -0.53	-1.30, -0.53	-0.39, 0.39
	Con	1	<0.01	-2.26, -1.24	-2.34, -1.32	-0.59, 0.43
	Con	10	<0.01	-3.10, -1.90	-3.18, -1.98	-0.68, 0.52

Table 2.4. List of non-crop species by site. Species list is broken down into those species common to both systems (shared), those found only in conventional no-tillage plots (conventional), and those found only in organic plots (organic).

Big Sandy			Moore (SPM Site)		
Shared	Organic	Conventional	Shared	Organic	Conventional
<i>Cirsium arvense</i>	<i>Medicago sativa</i>	<i>Androsace septentrionalis</i>	<i>Cirsium arvense</i>	<i>Solanum rostratum</i>	<i>Medicago sativa</i>
<i>Melilotus sp.</i>	<i>Hordeum vulgare</i>	<i>Lolium perenne</i>	<i>Brassica napus</i>	<i>Chenopodium album</i>	<i>Malva neglecta</i>
<i>Kocia scoparia</i>	<i>Cichorium intybus</i>		<i>Taraxacum officinale</i>	<i>Solanum triflorum</i>	<i>Descurania pinnata</i>
<i>Lactuca serriola</i>	<i>Chenopodium album</i>		<i>Bromus tectorum</i>	<i>Panicum miliaceum</i>	<i>Alyssum alyssoides</i>
<i>Amaranthus retroflexus</i>	<i>Vaccaria pyramidata</i>		<i>Thlaspi arvense</i>	<i>Helianthus annuus</i>	<i>Tragopodon dubius</i>
<i>Salsola iberica</i>	<i>Bromus tectorum</i>		<i>Lens culinaris</i>		
<i>Polygonum convolvulus</i>	<i>Camelina microcarpa</i>		<i>Pisum sativum</i>		
<i>Avena fatua</i>	<i>Thlaspi arvense</i>		<i>Lolium persicum</i>		
	<i>Solidago canadensis</i>		<i>Lactuca serriola</i>		
	<i>Setaria viridis</i>		<i>Polygonum aviculare</i>		
	<i>Solanum triflorum</i>		<i>Amaranthus retroflexus</i>		
	<i>Pisum sativum</i>		<i>Lolium perenne</i>		
	<i>Descurania pinnata</i>		<i>Polygonum convolvulus</i>		
	<i>Chorispora tenella</i>		<i>Brassica kaber</i>		
	<i>Asclepias speciosa</i>		<i>Avena fatua</i>		
	<i>Lygodesmia juncea</i>				
	<i>Helianthus annuus</i>				
	<i>Sisymbrium altissimum</i>				
	<i>Vicia villosa</i>				
	<i>Brassica kaber</i>				
	<i>Centaurea solstitialis</i>				

Discussion

Differences Between Organic and Conventional No-Tillage Systems

Our results lend further support to previous studies that have found higher plant species richness in organic agricultural systems when compared to conventionally managed systems (Menalled et al., 2001; Hyvonen and Salonen, 2002; Hyvonen et al., 2003; Davis et al., 2005). Moreover, our data indicate that organic spring wheat systems have higher plant species richness than conventional ones at all the tested time periods during the growing season, and across all scales of measurement. We also observed higher levels of α diversity and β diversity in the organic system than in the conventional no-tillage system.

Differences in α and β diversity suggest that the processes controlling plant diversity within agricultural systems operate in different ways within organic and conventional no-tillage systems. Loreau (2000) suggested that, in general, an increase in species dispersal within the community is associated with increasing α and decreasing β diversity. Whether or not this pattern holds in agricultural systems has not been studied. Although this study does not allow us to draw any specific conclusions regarding the mechanisms responsible for the relative levels of weed dispersal in organic and conventional no-tillage systems, it is possible to speculate on their relative importance. The observed increase in both α and β diversity in organic spring wheat systems suggests that the higher diversity rotations (more crops) and different associated management practices (tillage, planting time, harvest time, etc.) within the organic system may select

for a broad array of life history strategies for weeds. This, in turn, results in the higher plant species diversity found in the organic systems at both the α and β scale of analysis.

β diversity in particular may be inhibited in conventional no-tillage systems, where weeds tend to be distributed in patches (Hughes, 1990; Wiles et al., 1992; Mortensen et al., 1995; Dieleman et al., 1999; Rew and Cousens, 2001; Faechner et al., 2002). Thus, one would expect higher β diversity in the weed community of the conventional no-tillage system, due to aggregation (patchiness) of the weeds (Dieleman et al., 2000), and decreased dispersal (Loreau, 2000) from decreased tillage. However, the combination of broad spectrum herbicide use (i.e. glyphosate) and low diversity rotations could select for a narrow range of weed life history types, limiting diversity at all scales. Thus, β diversity in conventional no-tillage systems will still be lower than in organic systems, even with the higher degree of aggregation observed in conventional no-tillage systems and decreased dispersal due to lack of tillage.

The unexpected higher β diversity observed in the organic system may also indicate that there is a degree of patchiness within the weed community at the middle scales that were measured (1-10 m²). This could be related to habitat heterogeneity. If there were a wider variety of microsites present within organic fields, local populations of different weed species would be more likely to establish throughout the field, increasing β diversity. Interestingly, the persistence of this patchiness would suggest that heterogeneity of habitat (due to differences in nutrient availability or microhabitats favoring certain species) may be a more powerful force in determining weed community composition than dispersal within organic systems. Cultivation implements generally

move seeds within the soil less than 2 m from their source (Rew and Cussans, 1997; Marshall and Brain, 1999), although distances up to 15 m (Marshall and Brain, 1999) and 23 m (Mayer et al., 1998) have been reported. However, weed seeds can also be dispersed longer distances when mature plants are caught on farm machinery such as combines (Ballare et al., 1987; McCanny and Cavers, 1988), sprayers, and seed drills, and moved in this manner. If dispersal was the main factor determining community composition, one would expect that, over time, the level of β diversity would decrease due to seed dispersal. This would further suggest that organic systems may be encouraging heterogeneity of weed habitat at relatively small scales.

Measuring Agroecosystem Diversity

Scale of Measurement. One implication of our results relates to the scale at which species richness should be measured within agricultural systems. Following the theory of the species-area curve (Arrhenius, 1921; Gleason, 1922; Rosenzweig, 1995), our results indicated that as the scale of sampling increased, species richness also increased. Therefore, prior to sampling for species richness in agricultural fields, investigators should determine whether or not the proposed scale of sampling will adequately describe the richness present within the system. Previous studies have also highlighted the need for this type of exploratory sampling within agricultural systems as well as within non-cropping ones (Stohlgren et al., 1997; Mulugeta et al., 2001; Cannone, 2004; Manhoudt et al., 2005). Despite this suggestion, many studies (Pysek and Leps, 1991; Doucet et al., 1999; Kleijn and Verbeek, 2000; Menalled et al., 2001; Suarez et al., 2001; Hyvonen and Salonen, 2002; Weibull et al., 2002; Davis et al., 2005; Legere et al., 2005; Poggio, 2005;

Murphy et al., 2006) base estimates of diversity on data collected at one scale, and the scale at which the variations in diversity can be adequately captured was not considered. We have speculated that the patterns of weed species diversity across scales may reveal the degree to which particular processes are acting to cause these patterns. This is something that diversity measurements taken at a fixed scale would not adequately reveal.

An interesting aspect of the scale of observation was evident when comparing the distribution of species between systems at each site. At the SPM site, the majority of non-crop species were shared between systems, with an equal and lesser number being exclusive to either the organic or conventional no-tillage system. At Big Sandy, the organic system contained the bulk of the species, with a relatively low number of shared species, and very few species exclusive to the conventional no-tillage system. The discrepancy in number of shared species is probably a result of the scale of the sample area. At the SPM site, all observations were taken within a 16 ha area. The high number of shared species may be a result of the ability of most species to be dispersed within that small area. In contrast, many of the fields sampled in Big Sandy were over 40 ha, and located within a much larger area. Thus, the number of shared species was decreased due to decreased dispersal among fields. This certainly suggests that it would be wise to verify results from the experimental plot scale at larger farm scales.

The difference in the number of species exclusive to each type of system is probably a result of time. At the SPM site, plots had only been established 4 years prior to sampling. Thus, they had only been subject to their management systems for a

relatively short period of time. In contrast, the fields at which observations were made at the Big Sandy study area had been under the same types of rotation for at least 10 years. It is possible that continued conventional management practices with low diversity rotations at the SPM site would select for a more narrow range of species. This would effectively decrease the number of species shared between the two systems as well as the number of species exclusive to the conventional system. At the same time, this would result in a higher number of species being exclusive to the organic system. Despite the species composition differences between the two study areas, the differences in species richness, α , and β diversity between systems were relatively constant across the two study areas. This suggests that the processes responsible for the observed differences in diversity can be effective at producing these differences across a range of scale, from the relatively small < 0.5 hectare experimental plot scale to the large 2,400+ hectare production farm scale.

Time of Measurement. It is reasonable to expect that certain species may be present at different times during the growing season, representing a range of phenologies corresponding to different rotational crops and associated weed management practices. While previous studies have measured diversity within agricultural systems at one time during the growing season, the exact time varies among studies. Our results showed that the species richness tended to decrease within both systems as the growing season progressed. Thus, if the goal is to measure the maximum amount of species richness present within either one of these systems, it would be best to do so earlier in the growing season to maximize the number of total species observed. Also, if the goal of the species

diversity assessment relates to practical considerations, then it would be best to make observations earlier in the season when the effects of weeds on crop growth are most pronounced (Zimdahl, 1988).

Conclusions

We have confirmed previous observations that the level of plant species richness in organic spring wheat systems is higher than for their conventional no-tillage counterparts using species richness as our index (insert citations). In addition, we have also shown that both α and β plant diversity are higher within organic spring wheat systems. The incorporation of the spatial aspect of diversity through use of the species-area curve has allowed for some speculation as to the possible causes for the observed differences in general plant diversity patterns between conventional no-tillage and organic spring wheat systems. If these observations at first seem trivial, one need only consider the current interest in sustainable agriculture as a future direction for agriculture and the understanding of ecological processes that will be necessary to follow that path. If the idea of sustainable agriculture is ever to come to fruition, it will do so on a firm base of ecological understanding, and our methods of observation must necessarily change to account for a wide array of biological interactions. It is therefore critical that the direction of agroecological research continues to progress from the narrow focus on the establishment of differences between systems to the possible reasons and consequences of these differences.

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CHAPTER 3

SPATIAL PATTERNS IN WEED COMMUNITIES OF ORGANIC AND
CONVENTIONAL NO-TILLAGE SPRING WHEAT SYSTEMSIntroduction

Heterogeneous field conditions are inherent in most agricultural fields (Cook and Bramley, 1998; Robert, 2002). This heterogeneity can be manifested in soil fertility (Alvarez and Grigera, 2005; Reyniers et al., 2006), hydrologic properties (Reyniers et al., 2006), and/or weed communities (Auld and Tisdell, 1988; Cardina et al., 1995; Cardina et al., 1997; Rew and Cousens, 2001). Heterogeneous field conditions can lead to differences in crop yield, and most management practices are aimed at minimizing heterogeneity to ensure maximum yield. Of the three factors mentioned above, soil fertility and weed management usually rely heavily on expensive chemical inputs, usually applied on a field-wide basis in an effort to favorably homogenize conditions for crop growth.

The recognition that yield affecting factors are spatially variable, coupled with adequate means to measure this variability, gave rise to site-specific weed and nutrient management practices (Cook and Bramley, 1998; Robert, 2002; Rickman et al., 2003). Of all the yield affecting factors present in agricultural systems, weed communities are perhaps the most readily observed. It is widely recognized that crop yield decreases with increased weed density or biomass (O'Donovan and Sharma, 1983; Tamado et al., 2002; Whish et al., 2002; Moechnig et al., 2003; Milberg and Hallgren, 2004). Therefore, the

presence of weeds can serve as a visual indicator of potential yield loss. Consequently weed control has become a major cost for those wishing to maximize crop yield.

Knowledge of the spatial distribution of weeds within a farm field is important because it has proven useful for making estimates of yield loss due to weeds (Brain and Cousens, 1990; Thornton et al., 1990) and in determining how and when to carry out weed control (Thornton et al., 1990; Wiles et al., 1992). It has been observed that weeds in conventionally managed fields are often distributed in “patches” (Hughes, 1990; Wiles et al., 1992; Mortensen et al., 1995; Dieleman et al., 1999; Rew and Cousens, 2001; Faechner et al., 2002). Therefore, information regarding the spatial distribution of weeds can simultaneously give a farmer a better idea of what profit to expect and a way to reduce input costs by applying weed control only where weeds are present. Although the potential of precision agriculture and yield mapping to refine the economics of farming in conventionally managed systems has been recognized and used for some time, these ideas have not taken hold in organic agriculture. To our knowledge, there is no scientific data on the distribution of weeds in organic systems. As a result, there is no information that could be useful in determining the feasibility of site-specific weed management or precise yield mapping in organic systems.

The implementation of site-specific management and use of yield mapping on organic farms might require adoption of new technologies or modification of existing technology, and its costs must be weighed against its potential benefits (Robert, 2002). However, the necessary first step is to determine if there are any patterns in the weed communities of organic systems that might lend themselves to site-specific weed

management and make yield mapping a useful tool. The goal of this study was to investigate the spatial pattern of weed communities in organic spring wheat systems and to compare them to the ones found in conventional no-tillage spring wheat systems.

Many factors contribute to the spatial pattern of weeds within cropping systems. One consideration is tillage. Tillage implements generally move seeds within the soil less than 2 m from their source over the course of a season (Rew and Cussans, 1997; Marshall and Brain, 1999), although distances up to 15 m (Marshall and Brain, 1999) and 23 m (Mayer et al., 1998) have been reported. However, weed seeds can also be dispersed longer distances when mature plants are caught on farm machinery such as combines (Ballare *et al.*, 1987; McCanny and Cavers, 1988), spraying equipment, and seed drills. Another factor that can affect the distribution of weeds within agricultural systems is herbicide application, and aggregation of weeds within conventional systems is thought to be enhanced by herbicide use due to uneven herbicide application i.e. sprayer skips (Dieleman et al., 2000). In addition, the lower rate of herbicide induced mortality in high density weed patch centers leads to patch persistence when uniform herbicide applications are applied (Dieleman et al., 1999).

This study was primarily concerned with a comparison of the spatial distribution of weeds in conventional no-tillage and organic spring wheat production systems. In no-tillage conventional systems, mechanical manipulation of the soil is decreased, thereby limiting weed seed dispersal within the system. Furthermore, the use of herbicides in conventional no-tillage systems decreases the likelihood of individual weeds surviving to maturity after being introduced to the system from outside sources such as unclean farm

machinery, unclean seed, and natural forms of seed transport. In organic systems, where tillage is the primary method of weed control, mechanical manipulation of the soil is greatly increased. Since herbicides are not used, individual weeds have an increased probability of surviving to maturity after moving into the system. Over time, increased tillage coupled with decreased weed mortality rates in organic systems could lead to a more dispersed weed community. Therefore, we hypothesized that weed populations within organic systems would be less aggregated than in conventional no-tillage systems. Although the patterns of distribution may not clearly identify the processes creating them with complete certainty, they can provide for clarified and testable hypotheses about the processes driving distribution within these systems.

Several methods have been used to investigate spatial patterns of weeds in cropping systems. Discrete sampling is the most commonly used method, and involves collecting data from quadrats distributed on a grid (Rew and Cousens, 2001). That data is then interpolated, usually by means of kriging (Rew and Cousens, 2001), to generate maps of weed distribution. A limitation of this approach is that it is necessary to determine the proper grid size prior to sampling (Rew and Cousens, 2001). In addition, grids are sometimes difficult to establish and the number of data points necessary to produce accurate maps is often very high. Thus, grid sampling is often very time consuming and expensive, particularly in large agricultural fields (Rew and Cousens, 2001; Barroso et al., 2005; Hornung et al., 2006).

Continuous sampling is another option for assessing weed spatial distribution (Rew and Cousens, 2001). In continuous sampling, the presence/absence or percent

cover of weeds is noted while traveling in a continuous fashion i.e. along a transect. Data can then be analyzed using indices of aggregation to discern the general patterns of weed distribution within the field. The disadvantage of using an index of aggregation is that it is not a spatially explicit measure. However, there are also spatially explicit methods of analysis, such as quadrat variance techniques (Hill, 1973), which can be applied to continuous data. In this study, we utilized a combination of these approaches to test the null hypothesis that the weed communities of conventional no-tillage and organic systems do not vary in terms of their degree of aggregation, and to more fully explore the spatial scale of any patterns detected in hopes of elucidating processes driving the observed patterns. In addition to spatial patterns, weed species richness and weed percent cover were also examined solely within the weedy areas of each field.

Materials and Methods

This study was conducted on three production farms near Big Sandy, MT, 48°10'44"N, 110°06'49"W, 824 m elevation. Soils in this area ranged from Telstad-Joplin Loam to Fort Benton Fine Sandy Loam (Bronc, 2003), and over the last 5 yrs annual precipitation averaged 288 cm. The study sites were spread across one conventional no-tillage and two organically managed farms, and all sampled fields were in spring wheat (*Triticum aestivum L.*) production at the time of sampling. Sampling took place in the early summer of 2005 and 2006. Each year, three conventional no-tillage and three organic fields were observed. The same farms were used for both years, but the location of fields changed between years due to crop sequence. The conventional no-tillage fields followed a winter wheat, fallow, spring wheat, fallow crop sequence and

were subject to both fertilizer and herbicide use (Table E.1). The organically managed fields followed a spring wheat, Austrian winter pea (*Pisum sativum L.*) crop sequence with no fertilizer or pesticide inputs, and were cultivated just prior to planting in both 2005 and 2006. All sampling in the conventional no tillage fields took place before the fields had been sprayed with herbicides. Specifically, observations were made between 16 June and 24 June 2005, and between 4 June and 7 June 2006.

Since the primary goal of this study was to investigate the spatial distribution of weed communities in conventional no-tillage and organic spring wheat systems, it was necessary to ensure that the weed community would be sampled. Thus, the first transect was established parallel to crop rows such that it would intersect a portion of the field including a representative weed community. Two additional transects were then established at random distances greater than 15 m to the left or right of and parallel to the original transect. Each of the three transects measured 100 m in length and was approximately parallel to the orientation of the crop rows. Sampling along each transect was continuous using a 0.3 m wide by 0.99 m long frame. Within each frame, the percent cover of each weed species present was measured using ocular estimation by one observer, with the same observer making all estimates in both years. After sampling within a given field was completed, the location of each transect was geo-referenced using a Trimble Pro XRS Global Positioning System unit.

Data Analysis

Species richness and percent cover were compared between farming systems using a nested analysis of variance (ANOVA) where field was nested within system. Since year had no effect on either one of these variables, the species richness and percent cover data was pooled for 2005 and 2006. Two indices were used to test the null hypothesis that weeds were distributed randomly in both conventional no-tillage and organic spring wheat systems; the index of dispersion, ID (Krebs, 1999) and the index of aggregation, I_a (Perry, 1998). Both of these indices were calculated based on percent cover data. The index of dispersion (ID) is calculated as follows:

$$ID = \frac{s^2}{\bar{x}} \quad \text{Eq 3.1}$$

where s^2 and \bar{x} are the variance and mean of the data respectively. The index of aggregation (I_a) was calculated as follows:

$$I_a = D/E_a \quad \text{Eq 3.2}$$

where D = the observed distance to regularity of the data and E_a = the mean distance to regularity based on several randomizations of the data. Values of ID and I_a were calculated for each transect in each field for 2005 and 2006. This allowed for a detailed examination of each transect to determine if the spatial pattern of weed cover present varied from random. For a random population, the expected values for ID and I_a are 1. An ID or I_a value above or below 1 indicates aggregation or uniformity respectively. To

test for more general differences in the ID or I_a values between fields, systems, and years, a nested ANOVA was used where field was a nested factor within farming system and the effects of year were investigated. Since year had no effect on ID or I_a values, data from 2005 and 2006 were pooled for the ANOVA and analyzed with field nested within cropping system. Data were transformed using the BoxCox routine in R 2.2.1 (CRAN, 2005) to minimize problems associated with non-constant variance and non-normality.

A combination of graphs of percent cover and three term local quadrat variance (3TLQV) plots (Hill, 1973) were then used to examine the spatial scale of pattern for each transect in each field. The 3TLQV method functions by calculating the average of the squared difference between block totals of adjacent trios at differing block sizes (b) using the following formula:

$$V_3(b) = \frac{\sum_{i=1}^{n+1-3b} \left(\sum_{j=i}^{i+b-1} y_j - 2 \sum_{j=i+b}^{i+2b-1} y_j + \sum_{j=i+2b}^{i+3b-1} y_j \right)}{8b (n+1-3b)} \quad \text{Eq 3.3}$$

Plotting the variance at differing block sizes allows one to examine the spatial pattern of the data in question. The 3TLQV plots for this study were generated using a maximum block size of 25 m. The maximum possible block size for this technique is 33% of the transect length, or 33 m in our case. We chose to use 25 m as the maximum block size to avoid smoothing of variance peaks at smaller block sizes, as we were interested in patterns occurring from the small to intermediate scale. Semivariance analysis was not utilized due to the large number of vacant quadrats in the conventional no-tillage system. In such a case, when the data cannot be transformed to an approximately normal distribution, the validity of semivariance analysis is questionable (Rew et al., 2001). The

ID, percent cover plots, and 3TLQV plots were all produced using PASSAGE 1.0 (Rosenberg, 2001). I_a values were generated using SADIE 1.22 (Perry, 2001) with 5967 randomizations. Nested ANOVAs were performed using R 2.2.1.

Results

Weed percent cover and species richness were significantly higher in the organic system than in the conventional no-tillage system when considering either data from all quadrats, or data from quadrats in which weed species were present based on the results of the nested ANOVA (Figs 3.1 and 3.2). The un-pooled *ID* values (Table 3.1) indicate that weed percent cover was generally aggregated along transects in both the conventional no-tillage and organic systems.

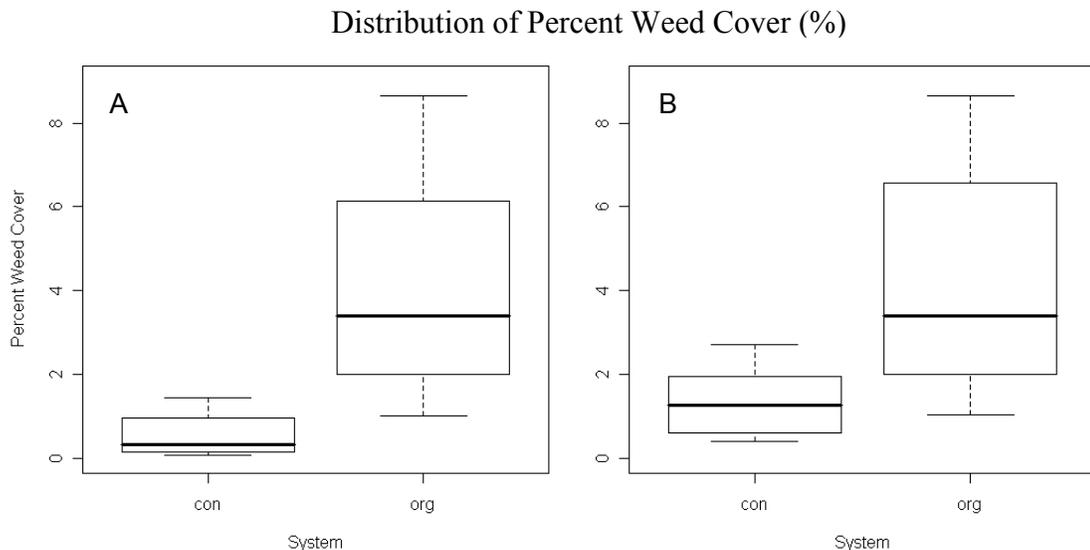


Figure 3.1. (Distribution of percent weed cover for conventional no-tillage (con) and organic (org) systems. A = data from all quadrats, $p < 0.001$. B = data from quadrats containing weed cover, $p < 0.001$).

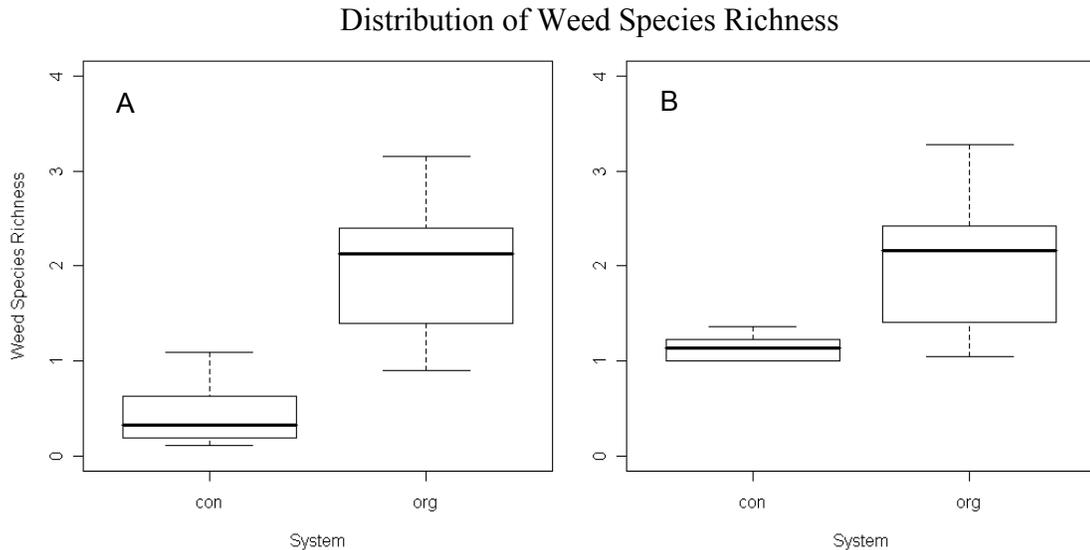


Figure 3.2. Distribution of weed species richness for conventional no-tillage (con) and organic (org) systems. A = data from all quadrats, $p < 0.001$. B = data from quadrats containing weed cover, $p < 0.001$.

In 2005, percent cover for all of the conventional no-tillage transects and seven of nine organic transects had patterns that were significantly different than random ($p < 0.001$), with mean ID values of 2.9 and 4.8 for the conventional no-tillage and organic systems respectively. An outlying ID at Org-2, transect 3 (Table 3.1) was left in the analysis for 2005 because it represented a large patch of Canada thistle (*Cirsium arvense*). In 2006, percent cover in seven of nine conventional no-tillage transects and all of the organic transects had patterns that were significantly different from random ($p < 0.001$) with mean ID values of 3.4 and 4.2 for the conventional no-tillage and organic systems respectively.

The un-pooled I_a values (Table 3.1) generated by the SADIE analysis suggest a general trend towards aggregation along both the conventional no-tillage and organic transects. However, only two of nine conventional no-tillage transects and four of nine

organic transects showed significant differences from a random distribution ($0.025 > P_a > 0.975$) in 2005 based on SADIE analysis methods (Perry, 1998). The significant departures from the random distribution all indicated an aggregated distribution ($P_a < 0.025$). In 2006, three of nine conventional no-tillage transects and three of nine organic transects indicated significant departures from the random distribution ($0.025 > P_a > 0.975$). Of these significant departures, all indicated an aggregated distribution ($P_a < 0.025$).

When the 2005 and 2006 transect data were pooled after determining that there were no year effects, there was no difference in mean ID between the conventional no-tillage and organic systems based on the nested ANOVA ($p = 0.31$) (Figure 3.3). In addition, the mean I_a values were not significantly different for the organic and conventional no-tillage systems ($p = 0.11$) (Figure 3.4).

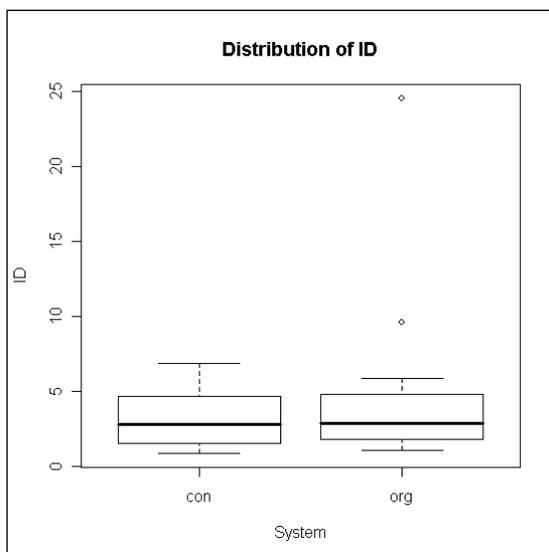


Figure 3.3. Box and whisker plot of Index of Dispersion (ID) values by system. con = conventional no-tillage system, org = organic system. $p = 0.31$

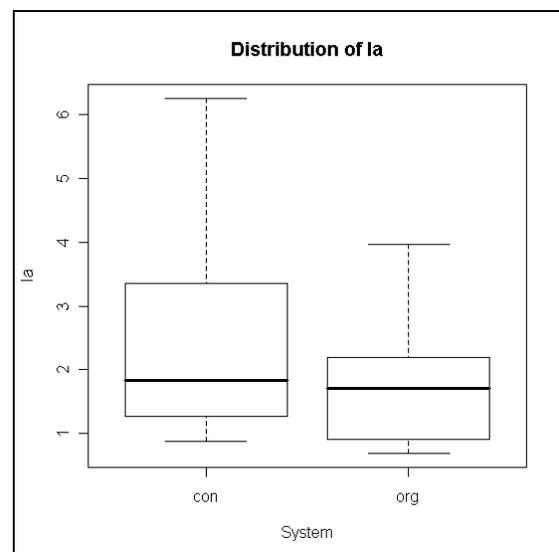


Figure 3.4. Box and whisker plot of Index of Aggregation (Ia) values by system. con = conventional no-tillage system, org = organic system. $p = 0.11$.

Table 3.1. Mean percent cover, standard deviation, index of dispersion values (ID), and index of aggregation (I_a) values for each transect in 2005 and 2006.

Big Sandy 2005								Big Sandy 2006					
Field	Tran.	Mean	S ²	ID	p	I_a	P _a	Mean	S ²	ID	p	I_a	P _a
Con-1	1	0.2	0.27	1.5	<0.01	1.1	0.298	1.0	5.46	5.3	<0.001	2.6	0.006
	2	0.7	2.85	4.2	<0.001	0.8	0.585	1.1	3.65	3.2	<0.001	1.7	0.066
	3	0.1	0.26	1.9	<0.001	0.9	0.488	0.7	1.62	2.4	<0.001	4.0	<0.001
Con-2	1	0.1	0.11	1.9	<0.001	0.7	0.752	0.4	1.58	4.2	<0.001	2.2	0.016
	2	0.3	1.35	4.8	<0.001	1.1	0.307	0.1	0.09	1.1	0.21	1.7	0.067
	3	1.4	7.99	5.6	<0.001	2.0	0.034	0.1	0.06	0.9	0.82	0.8	0.651
Con-3	1	0.2	0.26	1.5	<0.01	1.7	0.073	1.0	6.51	6.9	<0.001	0.8	0.635
	2	1.4	4.39	3.1	<0.001	2.7	0.003	0.1	0.16	1.5	<0.001	1.3	0.216
	3	0.6	1.17	2.1	<0.001	2.8	0.002	0.3	1.33	4.6	<0.001	1.7	0.072
Org-1	1	6.9	29.74	4.3	<0.001	6.3	<0.001	3.0	14.92	4.9	<0.001	1.1	0.350
	2	5.1	12.78	2.4	<0.001	3.8	<0.001	2.7	11.88	4.5	<0.001	3.7	<0.001
	3	7.0	33.33	4.8	<0.001	1.1	0.339	2.3	21.99	9.6	<0.001	2.9	0.001
Org-2	1	3.8	9.12	2.4	<0.001	1.9	0.474	1.0	2.85	2.8	<0.001	1.3	0.184
	2	4.0	4.44	1.1	0.20	2.0	0.277	2.0	6.64	3.4	<0.001	1.6	0.099
	3	8.7	212.15	24.5	<0.001	4.9	<0.001	2.5	6.12	2.5	<0.001	1.3	0.218
Org-3	1	1.5	2.73	1.8	<0.001	1.2	0.245	6.1	35.65	5.8	<0.001	3.4	0.001
	2	1.8	1.88	1.0	0.37	1.7	0.071	6.5	18.73	2.9	<0.001	1.8	0.061
	3	1.6	2.18	1.3	0.01	2.2	0.020	4.3	7.51	1.8	<0.001	0.9	0.521

con = conventional no-tillage, org = organic. ID is calculated as mean/variance. Associated p -values are based on a chi-square test for departures from a Poisson distribution. Values of 1, <1, and >1 represent random, uniform, and aggregated distributions. Values of I_a were calculated based on 5967 randomizations. Associated P_a values are the proportion of randomized samples with distance to regularity as large as or larger than the observed value, D . P_a values < 0.025 and > 0.975 favor alternative hypotheses of aggregation and regularity at $\alpha = 0.05$ respectively. I_a values of 1, <1, and >1 represent random, uniform, and aggregated distributions.

The 3TLQV analysis indicated that for both conventional no-tillage and organic systems, percent cover showed multiple scales of pattern (Figs. 3.5 - 3.8). Examination of the graphs of percent cover for each transect (Figs. 3.5 - 3.8) reveals that the spatial patterns of weed percent cover exhibited by the conventional no-tillage system are different than the organic system. Additional 3TLQV and percent cover plots are located in Appendix A. In both 2005 and 2006, the conventional no-tillage system transects had a baseline percent cover of zero, from which there were intermittent peaks in percent cover along each transect. The organic system transects were characterized by an oscillating pattern of percent cover with very few zero cover quadrats. This suggests that the peaks in variance in the 3TLQV plots for conventional systems represent the scales of patchiness of weed cover as well as the scale of gaps in between patches. This pattern is most likely due to local dispersal from the relatively few plants that survive herbicide application and produce seed. For the organic systems, the peaks in the 3TLQV plots most likely represent multiple scales of peaks in percent cover along each transect. This pattern could be caused by increased dispersal from parent plants or from heterogeneous soil conditions leading to more favorable growth conditions in some areas.

Discussion

Our results concur with previous studies which indicated that species richness was higher in organic systems than in conventional systems (Menalled et al., 2001; Hyvonen and Salonen, 2002; Hyvonen et al., 2003). Although this does not indicate that the sites used for this project are representative of conventional no-tillage and organic systems everywhere, it may allow for some generalizations. We can, at the least, demonstrate that

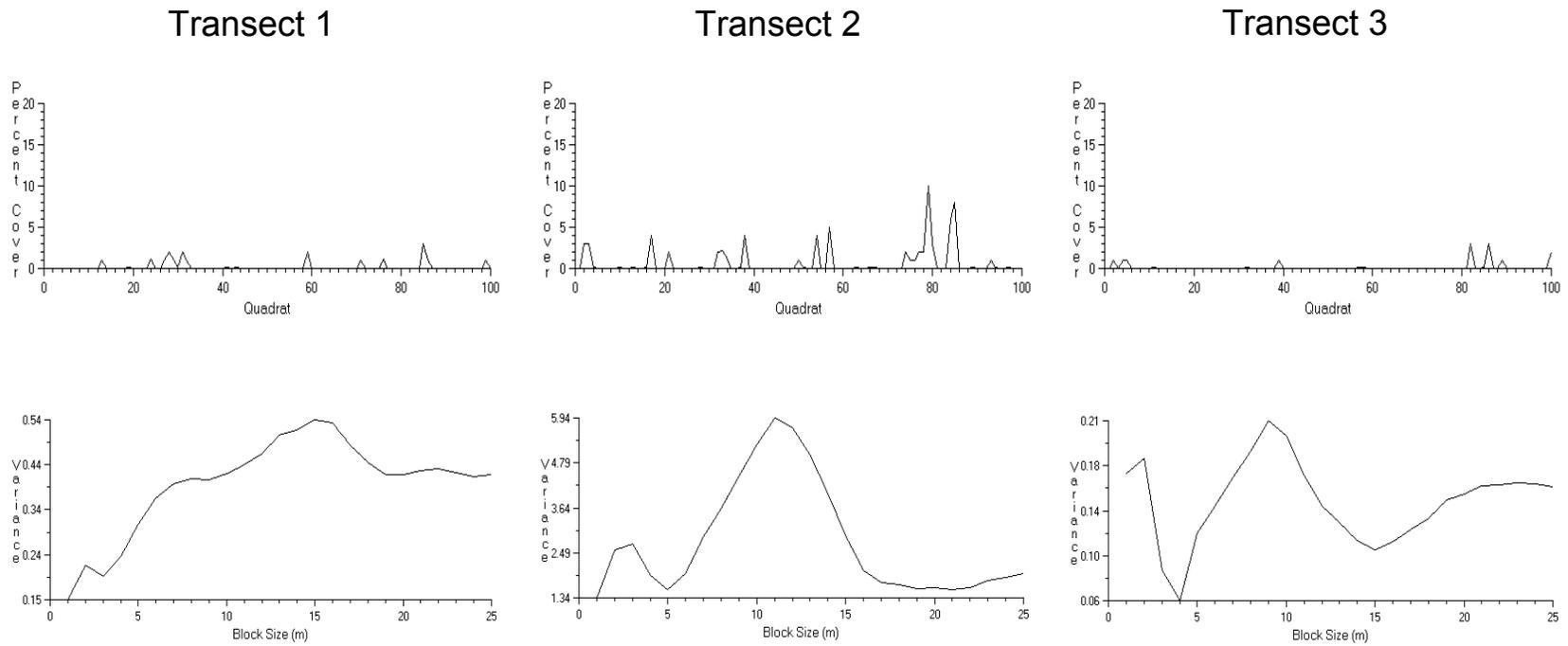
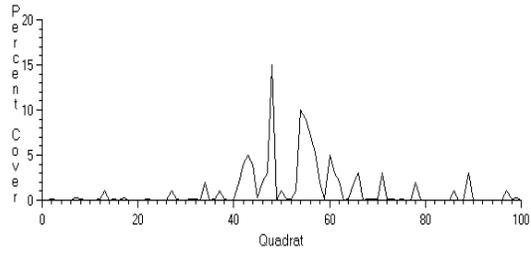
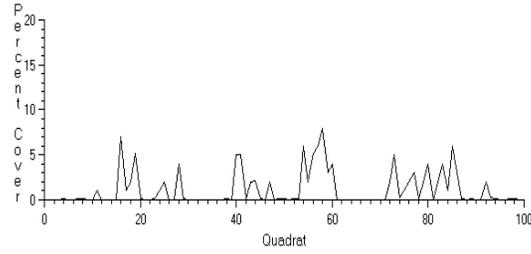


Figure 3.5. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Conventional No-Till Field 1, 2005. 3TLQV calculated based on 25m maximum block size.

Transect 1



Transect 2



Transect 3

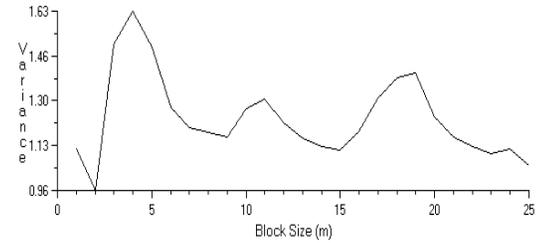
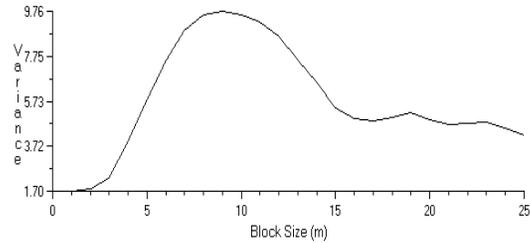
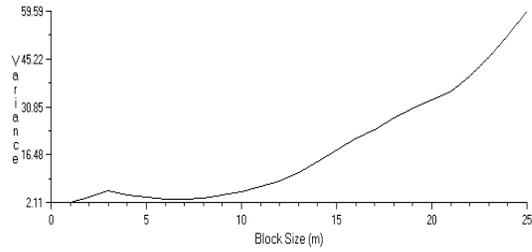
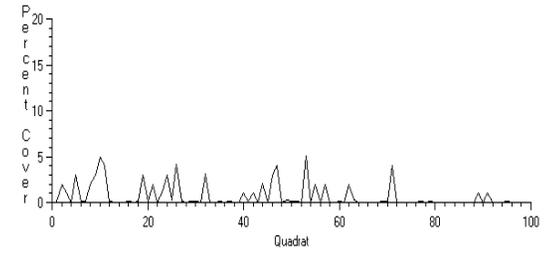


Figure 3.6. Percent cover and three term local quadrate variance (3TLQV) plot for each transect in Conventional No-tillage Field 1, 2006. 3TLQV calculated based on 25m maximum block size.

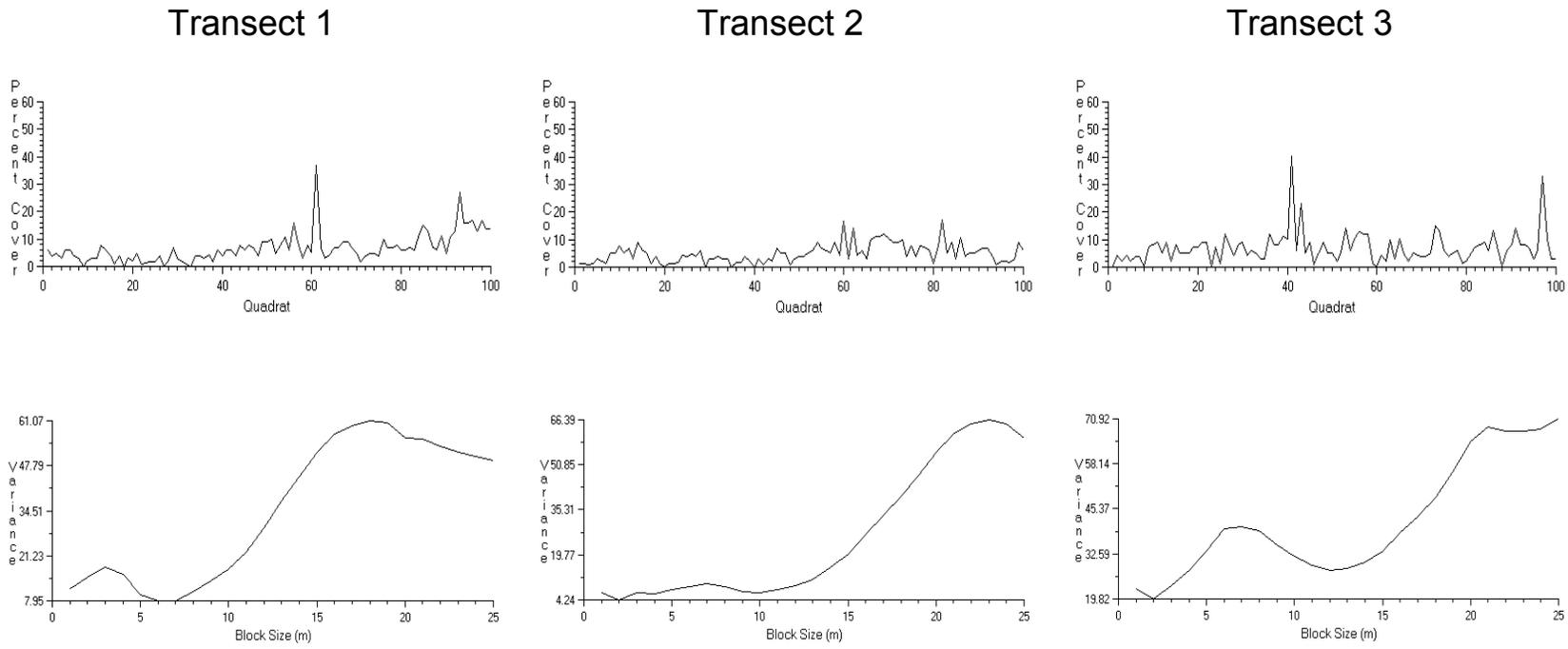


Figure 3.7. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Organic Field 1, 2005. 3TLQV calculated based on 25m maximum block size.

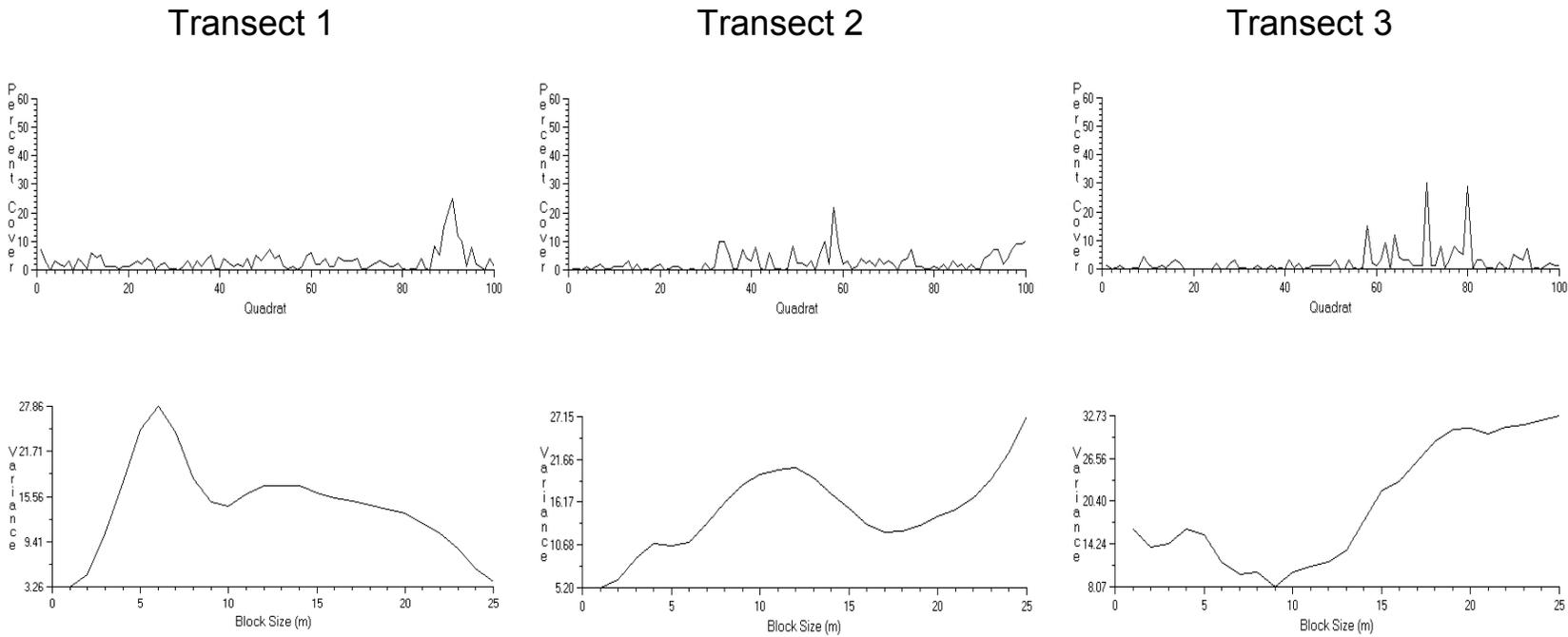


Figure 3.8. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Organic Field 1, 2006. 3TLQV calculated based on 25m maximum block size.

the fields used in this study were displaying a trend in species richness between conventional and organic systems that has been noted previously. In this regard, these fields appear to be good representations of typical organic and conventional fields, given their differences in species richness.

We also showed that the percent cover of weeds is generally higher in organic systems. This was expected. In addition to these study area scale differences in weed species richness and percent cover, we also found that these same trends were evident when the analysis was limited to those quadrats where weeds were present. This suggests that these differences apply at both the field scale and specifically within weedy areas as well. It further suggests that the differences in weed species richness and percent cover that were observed at the study area scale were not just an artifact of the large number of quadrats in the conventional no-tillage system that were lacking any weedy flora. Therefore, these trends are evident at all scales within these systems, from the broader context of the study areas down to quadrats in which weeds were present.

The results of the ID and I_a analyses for the conventional no-tillage system also concur with previous observations of weed patchiness in conventionally managed fields (Hughes, 1990; Wiles et al., 1992; Mortensen et al., 1995; Dieleman et al., 1999; Rew and Cousens, 2001; Faechner et al., 2002). The presence of patterns other than random in the organic system, as indicated by the ID and I_a analyses, has never been documented. Although both systems displayed general trends towards aggregation, this aggregation was manifested differently. This is evident upon examination of the 3TLQV and percent cover plots. The main difference between the two systems was that in the conventional

no-tillage system, these aggregations were in the form of patches of weeds within a matrix where weeds were generally not present. In the organic system, the aggregations were spikes of percent weed cover within a matrix where weeds were present at lower levels. This suggests that organic systems can be characterized as a matrix of favorable conditions for weed establishment (baseline percent cover) in which there may be several microsites in which weeds are particularly abundant (spikes in percent cover).

This difference in the type of aggregation is most likely due to differences in opportunity for dispersal combined with differential mortality rates. The patterns suggest that dispersal processes within conventional no-tillage systems are occurring mostly at a local (close to the parent plant) scale, whereas in organic systems they may be occurring at both the local and broad (field wide) scales. The pattern of weed abundance in the organic system could be driven by a set of species specific dispersal mechanisms. In addition to this, tillage could be playing a part in the dispersal of species within fields, modifying the spatial pattern of weeds within organic systems. Lack of herbicide use would also decrease the mortality rate of newly introduced individual weeds, allowing more individuals to mature and produce seeds. Thus, dispersal within the organic system is less limited over time due to frequent tillage, decreased mortality, and an increased opportunity for natural seed dispersal from parent plants. In contrast, the spatial distribution of weeds within conventional no-tillage systems may be driven by broad spectrum mortality due to herbicide use which has consistent spatial variability (Dieleman et al., 1999; Dieleman et al., 2000; Rew and Cousens, 2001). Therefore, individual weeds have a much lower probability of producing seed, since tillage is not a

factor in no-tillage systems, dispersal of seed from a lower number of individuals will tend to be limited to the local scale. This is not to say that long distance dispersal via other farm equipment does not occur in no-tillage systems. In general, however, dispersal would be more limited due to lack of tillage and dispersed individuals at low densities would be more likely to suffer mortality from herbicide application (Dieleman et al., 1999). Overall, this would lead one to expect a broad distribution of weeds in organic systems, and a patchy distribution of weeds in conventional no-tillage systems, at least in terms of presence of weeds. Our data support this speculation. Weed cover was much more spatially continuous in the organic system than in the conventional no-tillage system. However, there was still evidence of local patterns in the weed cover in the organic system.

The findings of this study have several implications for weed management in agricultural fields. First, they illustrate how useful precision management and careful operational procedures are in a conventional no-tillage system. A farmer could reduce control costs by using site-specific herbicide applications to target localized weed populations (Cook and Bramley, 1998; Robert, 2002; Rickman et al., 2003; Barroso et al., 2005) and limiting non-crop seed input into the system via contaminated crop seed or unclean farm equipment to prevent the establishment of new populations or expansion of existing ones. This essentially amounts to targeting the peaks in our percent cover data with herbicides and preventing the gaps from filling with plants from internal (local population) or external (unclean seed and equipment) sources.

The options for an organic farmer are more limited. In order to effectively control weeds in an organic system, management practices would have to target both local and broad scale dispersal processes. There are no easy solutions for limiting broad scale dispersal of weed seed in organic fields, since tillage is an integral part of the system. Furthermore, since there is an increased chance of individual non-crop plants going to seed within the system, this may exacerbate the situation. However, there are some options for controlling particularly problematic localized populations of non-crop species within organic systems. One option would be to increase crop seed rate and/or decrease crop row spacing in high weed abundance areas to maximize crop competition with the weed species and therefore suppress the non-crop species to some extent (Jordan, 1993; Doll, 1997; Olsen et al., 2005; Olsen et al., 2006). It might also be possible to plant highly competitive but less problematic species in an area where the suppression of a particularly problematic population of weeds was more important than the limited yield that would be produced in that same area. Once the level of the weed population was decreased, any future crop species planted in the area might then be more competitive with that weed population. Another option, particularly if the non-crop species can reproduce vegetatively, is to modify tillage to limit the spread of vegetative material away from the current population. Therefore, although local scale control is feasible in organic systems, there will always be an increased likelihood of broad scale dispersal of weed seed within organic systems under current organic management practices. Using our data as an example, the organic farmer would thus be able to truncate the highest peaks in percent cover by site-specific weed management. However, given current

methods, the elimination of the baseline weed cover shown on our percent cover graphs is highly unlikely.

Conclusions

The next logical question to ask is how necessary is it to institute attempts to better control weeds within organic systems? It is possible that the different management practices associated with organic and conventional no-tillage systems could lead to differences in the way that weeds and crop species compete for resources. For example, if management practices within organic systems favored a higher level of weed diversity as has been shown by some studies (Menalled et al., 2001; Hyvonen and Salonen, 2002; Hyvonen et al., 2003), one might hypothesize that perhaps competition between crop and weed species would be more diffuse, and have less of an effect on the crop species (Clements et al., 1994). In order to make a more informed decision on this matter, it will be necessary to determine if there are any differences in crop/weed competition for resources between these two types of systems. In the end, it might not be economically advantageous for organic farmers to adopt new methods to control spatially heterogeneous populations of weeds. The extra time and money needed to implement such site-specific weed control measures would not be justifiable if the resulting level of economic gain was negligible. One would have to consider the cost of decreased yield and the cost of cleaning weed seed from grain harvest and weigh those against the cost modifying management practices to implement site-specific management

The spatial patterns of the weed communities of organic systems could have implications beyond the context of site-specific management as well. In the pursuit of

sustainable agriculture, it will be necessary to employ new ways to manage farm fields in order to reduce inputs. Perhaps a more detailed examination of the spatial pattern in weed communities of organic systems would yield some useful insights. It is possible that weed communities of organic systems might be more stable in the long run, with separate populations of different weed species being held in check by one another. A more detailed examination of weed population dynamics and spatial structure over a period of time could be used to investigate this. If it were the case, then the weed community could essentially control itself to some extent, and the danger of severe outbreaks of any one weed species would be greatly diminished. If producers were willing to take a known reduction in yield in trade for a more temporally stable weed community and reduction in input costs, this could represent a more sustainable weed management strategy. While this is all speculation, it can certainly be said that the structure of weed communities of organic systems deserves more investigation. We have shown that there is a basic spatial structure within weed communities of organic spring wheat systems and, as such, that it is worth investigating further in order to discover what is causing this structure, and what functions this structure might perform.

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CHAPTER 4

THE EFFECTS OF WEED SPECIES DIVERSITY ON
SPRING WHEAT PERFORMANCEIntroduction

Competition is an important process that affects individual plants, plant populations, and plant communities (Harper, 1977). Plant competition can occur between or within species for a set of limiting resources such as light, water, and nutrients (Tilman, 1997). The degree to which a plant or plant species efficiently captures resources has a large influence on its fitness (Tilman, 1997; Watkinson, 1997). In general, organisms can be affected by competition on a variety of scales, and the range of scales at which the effects of competition can be observed depends on the particular species or set of organisms under consideration (Krohne, 1998). However, within plant communities competition for resources typically occurs on a local scale, between a plant and its nearest neighbors (Harper, 1977; Crawley, 1997).

Competition is of particular concern in agricultural settings. It has long been recognized that the presence of weeds in a crop field could result in yield reductions (O'Donovan and Sharma, 1983; Cousens, 1985; Bostrom et al., 2003; Eslami et al., 2006). Although knowledge of the competitive process between weeds and crops was an integral part of traditional weed control, the availability and widespread use of herbicides has supplanted this knowledge in favor of prescriptive management practices (Jordan, 1993). The prescriptive approach to weed management has had definite benefits in terms of decreased weed pressure and increased crop yields, but questions have arisen with

regard to its sustainability (Ng et al., 2005; Crane et al., 2006; Luke et al., 2006).

Therefore, there is an increasing interest in alternative methods of weed control as a result of an interest in sustainable agriculture.

A better understanding of the mechanisms of competition within agricultural systems could result in more effective use of agronomic practices to control weeds (Park et al., 2003). For example, crops bred to perform in high resource conditions can be manipulated through spatial arrangement and increased density to impose strong competitive effects on neighboring weed plants and thereby represent one of the best alternatives to herbicides for weed management (Jordan, 1993; Doll, 1997; Olsen et al., 2005; Olsen et al., 2006). Despite the increased knowledge of the importance and mechanisms of crop-weed interference, there are still aspects of competition within agricultural settings that are poorly understood. For example, little is known about the effect of weed community composition on weed/crop competition. Clements (1994) hypothesized that increased weed diversity, holding density constant, might lessen competition between weeds and crop via increased asymmetric and inter-specific competition within the weed community. However, it has also been suggested that increasing weed diversity would also increase the probability of a highly competitive weed species being introduced into the system (Fargione and Tillman, 2005).

Observations from organic small grain farmers in Montana loosely support the Clements (1994) hypothesis. Organic small grain fields were found to have significantly higher α and β diversity in their weed communities (Chapter 2) and higher percent cover of weeds (Chapter 3). Therefore, one would expect much lower yields in organic systems where

weeds are more abundant under the simplistic assumption that the competitive effects of different weed species are strictly additive. Although there is a lack of yield per weed density information for organic small grain farms in Montana, organic farmers generally report yields that are only slightly lower than their conventional counterparts. This suggests that there may be some positive link between weed diversity and spring wheat yield in organic cropping systems. Therefore, the primary goal of this study was to investigate the relationship between spring wheat yield and weed community diversity. Specifically, we tested the null hypothesis that, in addition to the effects of neighborhood density, increased neighborhood species richness would have no effect on spring wheat target plant performance via increased inter-specific competition (Figure 4.1).

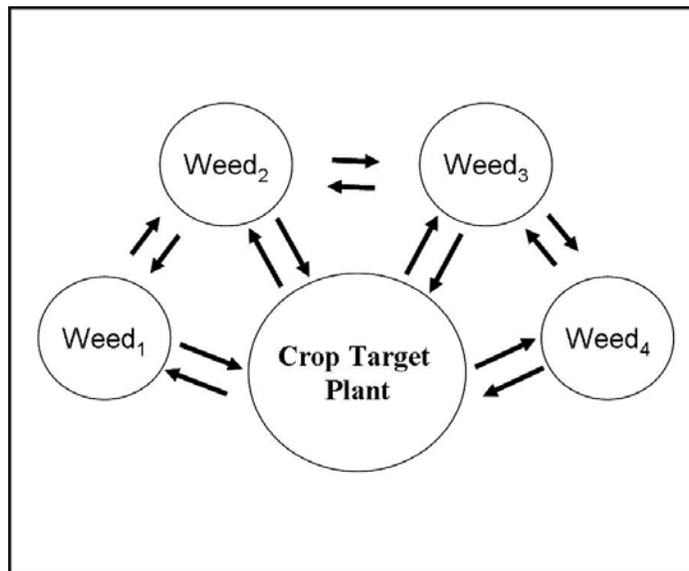


Figure 4.1. Diagram of null hypothesis, showing strictly additive competitive effects from weeds, with no modification of competitive effects by weed species composition (all arrows of equal weight).

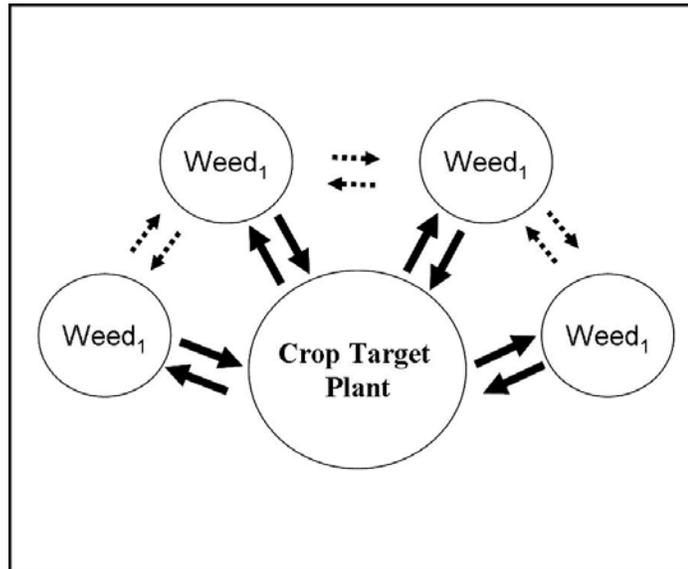


Figure 4.2. Diagram of alternative hypothesis, showing decreased competition within the weed community at low weed diversity and increased competitive effects on crop from weeds.

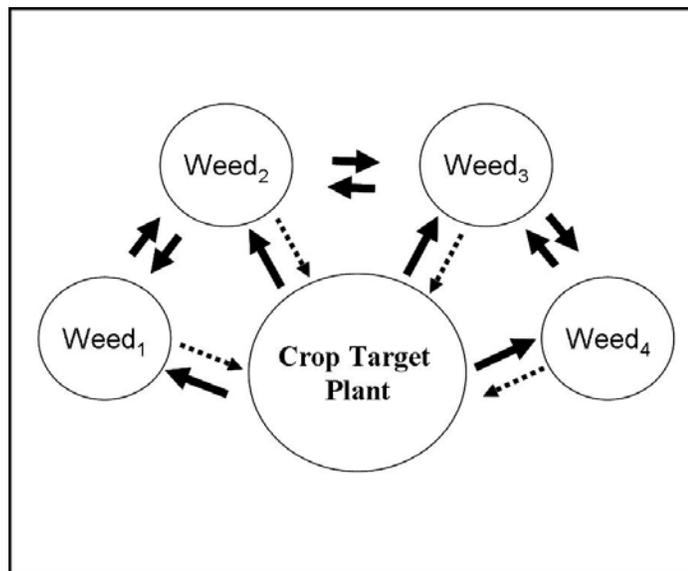


Figure 4.3. Diagram of alternative hypothesis, showing increased inter-specific competition within the weed community at high weed diversity resulting in less competitive effects on crop target from weed competition.

The alternative hypothesis would be that, at a given weed density level, increasing weed species richness would decrease the effects of competition from weeds on the target crop species due to increased inter-specific competition in the weed community (Figures 4.2 and 4.3).

The null hypothesis was tested with dependent variables measured on individual target plants surrounded by created neighborhoods. Data were analyzed within two contexts. The first, based on harvest data, served as a measure of absolute performance (total growth). The second, based on the relative growth rate (RGR), served as a measure of relative performance and competitive ability. Model selection based on a specifically parameterized global model was then employed in a more detailed examination of the data, following the idea that statistical models allow for both the testing of existing hypotheses and the generation of new ones (Sullivan and Joyce, 2005).

Materials and Methods

This study was conducted during two consecutive years at the Montana State University Arthur H. Post Agronomy Farm in Bozeman, MT, 45° 40'29" N, 111°09'14"W, 1423 m elevation. Mean annual precipitation for the last 5 yrs was 334 mm. Soil in the area is classified as an Amsterdam-Quagle Silt Loam (Brooker, 2002). This study was initiated in October 2004 at a 27.5 m by 35 m area in a field that had been fallow for 3 yrs prior to the start of this study. Using four weed species (green foxtail [*Setaria viridis* (L) Beauv.], wild oat [*Avena fatua* (L)], kochia [*Kochia scoparia* (L) Schrad.], and field pennycress [*Thlaspi arvense* (L)]), and spring wheat (*Triticum aestivum* L.), a completely randomized full factorial addition series experiment was set up

using combinations of one, two, three, four, and five species at four levels of density for a total of 124 one m² plots. The targeted plot densities were 49, 100, 169, and 361 plants per square meter. Weed species were chosen to represent a combination of species which naturally co-occur in spring wheat systems in Montana (Chapter 2). Green foxtail is an annual monocot native to Eurasia. Germination took place in early to mid-June at the study area, and seeds started to drop by mid-August. Wild oat is an annual monocot native to Europe. Emergence took place in late May to early June at the study area, and most seeds dropped by early August. Kochia is an annual dicot native to Asia. Emergence occurred in mid-May at the study area, although some plants germinated earlier and were killed by frost. Kochia plants had not begun to drop seed by the time plants were harvested in late August. Field pennycress is an annual dicot native to Europe. This species behaved as a winter annual at the study area, with some plants emerging in late October after planting. The remaining seed germinated by late April the following spring. Seedling mortality due to frost was observed to be very low. Field pennycress plants began to die back by mid-July, although seed was retained in pods for a much longer period of time.

Plots were placed with 1.5 m spacing, both within and between rows of plots. In the fall of 2005, the experimental area was shifted slightly to the East to minimize problems caused by weed seed contamination from the previous year. Plots were planted using 1 m² cardboard templates in which a hole had been drilled for each location of seed placement, each hole being color coded to facilitate planting of different species. Holes were evenly spaced in a grid pattern on each template at either 5 cm, 7.5 cm, 10 cm, or 15

cm intervals, based on the density level of the given template. In the early fall, the area was tilled and then chained in preparation for planting. Flags were then placed at the corners of each plot. Each plot was planted following the same basic protocol. The soil surface of the plot was raked to provide a more uniform and level planting surface. The appropriate template was then placed on the ground and two 30 cm lengths of PVC pipe were driven through two large holes at the corners of the template and into the ground. This stabilized the template during planting and facilitated the proper placement of the same template the following spring when spring wheat would be planted, as the pipe was left in the ground after the initial planting. A length of dowel was pressed through each hole in the template to create a hole in the ground for seed placement which was approximately 2 cm deep. At least three seeds of the proper species were dropped through each hole using a small metal funnel and covered with a small amount of soil. When planting was completed, the template was removed and the ground was closely inspected. At this point, any holes which had not been adequately filled with soil were filled.

The following spring, wheat was planted into each plot where it was a part of the species combination using the same template that had been used to plant weed species in the fall. The template was placed on the two PVC stakes and wheat was planted into the designated holes using the same process as in the fall. However, during the spring, plots were not raked in preparation of planting as this would disturb seed already present in the soil.

During the early part of the growing season, each plot was visited frequently and thinned by hand in order to ensure that there was only one individual plant growing from each planting location. Other unwanted plants were also removed by hand from the plots at this time. Throughout the growing season, the spaces between plots were mechanically kept weed free. No herbicides were used for weed control at any point during this experiment.

One target plant of each species in each plot was identified with a plastic pot tag after plots had been thinned. Spring wheat target plants were located as close to the center of the plot as possible. Target plants of other species were located wherever space allowed. Throughout the growing season, each target plant represented the center of a circular neighborhood of 16.5 cm radius. This neighborhood size was selected based on the assumption that plants only compete strongly with their nearest neighbors (Crawley, 1997; Stoll and Weiner, 2000), the spacing between seed placements at the lowest density of planting (15 cm), and the fact that 16cm was shown to be an ideal neighborhood radius in a small grain system (Lindquist et al. 1994). Measurements for growth analysis were taken starting June 8, June 28, July 19 and Aug. 17 in 2005, and June 13, July 5, July 25, and Aug. 15 in 2006. Within each neighborhood, the largest width, width perpendicular to the largest width, and the height of each target plant were measured. In addition, the average height, maximum height, and percent cover of each neighbor species within the neighborhood were also recorded. Average and maximum height were measured and percent cover estimated for each species within the neighborhood boundaries, regardless of whether or not it was rooted in the neighborhood. To ensure consistency, one person

was responsible for all neighborhood measurements. At the end of the growing season in 2005 and throughout the growing season in 2006, several individual plants of each species located in separate plots were measured, harvested, dried, and then weighed to establish a relationship between plant volume and plant dry biomass so that RGR could be estimated non-destructively.

In late August of 2005 and 2006, selected neighborhoods from each plot were harvested. Target plants were harvested and bagged separately. Field pennycress target plants were harvested in mid July to reduce the risk of seed loss. This did not affect final biomass measurements, as field pennycress plants had died back by that time. Other individuals rooted in each neighborhood were harvested and bagged by species, noting the number of individuals for each species. Only plants rooted within the neighborhood were harvested. All harvested plant material was then dried in an oven for 1 week until constant weight was achieved and then weighed. Seed production was estimated for all individual target plants of each species except kochia, as seed production in kochia was incomplete at the time of harvest. Seed production for each species was estimated by establishing a relationship between seed weight and seed number using linear regression. Seeds from target plants were cleaned using a seed blower. Seeds were then weighed and number of seeds produced per target plant was estimated using the regression equation. The number of seeds for wild oat target plants had to be estimated at harvest by counting the number of glumes on each plant, as some of the seed had already dropped.

Data Analysis

Predictors of Target Plant Biomass, Seed Yield, and Tiller Number

The first step to test the null hypothesis that species richness, via inter-specific competition, does not account for any of the variation in the target plant dependent variables (Table 4.1) when neighborhood density was in the model, was to regress each dependent variable against neighborhood density, neighborhood species richness, and the interaction term between neighborhood density and neighborhood richness. This model was termed the combined neighbor species model (CNSM) because the independent neighborhood density variable did not take into account individual species contributions to neighborhood density and their individual effects on target plants. Dependent variables were transformed as necessary to deal with non-normality and non constant variance using the Box Cox routine in R 2.2.1 (CRAN, 2005). A *p*-value of 0.1 was used as the cutoff for statistical significance of parameters for inclusion in the model for the CNSM. If the CNSM model for spring wheat target plants included a positive regression coefficient for neighborhood species richness and a negative coefficient for neighborhood density, then one could conclude that diversity positively affected crop performance (Figure B.1).

Table 4.1. Dependent variables measured for target plants of each species.

	S W	F P	K	G F	W O
Seed Yield (g)	X				
Number of seeds produced		X		X	X
Plant Dry Biomass (g)	X	X	X	X	X
Number of Tillers ¹	X			X	X

SW= spring wheat, FP = Field Pennycress, K = Kochia, GF = Green Foxtail, WO = Wild Oat. 1 = variables not measured in 2005.

A similar conclusion could be drawn, but with more complicated stipulations, if a positive interaction term came into the model even if the coefficient for neighborhood species richness and density were both negative (Figure B.2). All other outcomes would be regarded as a basis to conclude that neighborhood species richness had no positive effect on spring wheat performance. In essence, this first regression was necessary to separate the effects of neighborhood density from neighborhood species richness. If a positive neighborhood species richness effect was detected, this could lead one towards rejecting the null hypothesis.

To completely test the null hypothesis it was necessary to look beyond the potential positive effects of species richness and into the factors contributing to any observed positive species richness effect by teasing apart neighborhood factors that influence inter-specific competition on target plant biomass or yield. In the second phase of the analysis, models containing the ratio of target plant biomass to neighbor biomass at the first growth analysis measurement (t_1 ratio, an indication of early season competitive environment), the biomass of each neighbor species, and all of the individual species biomass interaction terms were examined for influence on the dependent variable for each species. This model was termed the by neighbor species model (BNSM), because the effects of each neighbor species on the target plant were taken into account. Schwarzze's Bayesian Information Criterion (BIC) was used to select variables which had the most effect on the dependent variables (Burnham and Anderson, 2004). The resulting model was called the best BNSM. The BIC was chosen due to its tendency to reject

models that over-fit in favor of more simple models (Burnham and Anderson, 2004; Sullivan and Joyce, 2005).

The reasoning behind this two step approach was that the CNSM would separate the affects of species richness from density. The best BNSM would then give an indication of which species specific variables affected target plant performance. If any positive interaction terms between neighbor weed species variables came into the best BNSM for the target plant, this would indicate that inter-specific competition was occurring and decreasing the negative effects of competition on the target. Conversely, if negative interactions between neighbor species biomass variables were included in the best BNSM, this would indicate negative species richness affects on target plant performance, perhaps due to increasing use of a particular resource by a multi-species community. The regression analysis and model selection were all performed in R 2.2.1 (see example in Appendix D). Analyses were conducted on 2005 and 2006 data separately. However, data from 2006 are emphasized in the results and discussion due to potential problems arising from inconsistent emergence and plant symptoms indicating potential residual herbicide effects in 2005. Inconsistent emergence may have skewed any competitive interactions occurring in the experiment in ways that would not have occurred naturally, i.e. weed species emerging much later than normal or crop species suffering from frost damage due to early planting. In addition, areas of residual herbicide were identified around the experimental area in 2005 that could have affected plants within the area. In 2006, the experimental area was shifted to an area where no residual herbicide had been detected.

Predictors of Relative Growth Rate

Relative growth rate (RGR) was calculated for each target plant using the classical method where $RGR = \ln(\text{dry biomass } t_2) - \ln(\text{dry biomass } t_1) / (t_2 - t_1)$ and t was day of year. The period from the first to the third measurement was used to calculate the RGR of each target plant for spring wheat, kochia, green foxtail, and wild oat, as it coincides with the period of most active growth. The period from the first to the second measurement was used to calculate RGR for field pennycress, due to earlier senescence of this species. Plant dry biomass was estimated based on a biomass/volume relationship using species specific linear regressions. RGR was then used as the dependent variable in a series of regression analyses to identify neighborhood variables influencing target plant RGR to test the same hypotheses as described above where target plant biomass, yield or number of tillers were the dependent variables. The initial planting density was used as an estimator of neighborhood density because actual neighborhood density was not measured for all neighborhoods during the period of growth rate data collection in this study. In addition to this regression analysis, an ANOVA with Tukey-Kramer procedure was applied to the RGR data to examine differences in mean RGR between species within each level of neighborhood species richness. Regression analyses, model selection, and ANOVA were all performed in R 2.2.1 (see code in Appendix D). The RGR analysis was only carried out for the 2006 data.

Results

Predictors of Target Plant Biomass, Seed Yield, and Tiller Number

Spring Wheat. In 2006, spring wheat dry biomass and seed yield were both negatively affected by increasing neighborhood density, and no significant effects of neighborhood species richness were observed (Tables 4.2 and 4.3). The number of tillers per target plant was also only affected by neighborhood density (Table 4.4). There were no significant interactions between neighborhood density and richness for any of the dependent variables. This indicated that species richness had no effect on spring wheat performance.

Table 4.2. Combined Neighbor Species Model for spring wheat transformed dry biomass (2006).

	Estimate	P-value
Intercept	2.8	<0.001
Neighborhood Species Richness	-0.11	0.28
Neighborhood Density	-0.07	0.003
Richness * Density	0.01	0.36

Residual standard error: 0.4275 on 71 degrees of freedom
 Multiple R-Squared: 0.3228, adjusted R-squared: 0.29
 F-statistic: 11.28 on 3 and 71 DF, *p*-value: 3.887e-06,
 transformed dry biomass = dry biomass^{0.3}

Table 4.3. Combined Neighbor Species Model for spring wheat transformed seed yield (2006).

	Estimate	P-value
Intercept	2.7	<0.001
Neighborhood Species Richness	-0.16	0.26
Neighborhood Density	-0.08	0.02
Richness * Density	0.01	0.44

Residual standard error: 0.6137 on 71 degrees of freedom
 Multiple R-Squared: 0.2462, adjusted R-squared: 0.2143
 F-statistic: 7.73 on 3 and 71 DF, *p*-value: 0.0002 transformed
 seed yield = seed yield^{0.4}

Table 4.4. Combined Neighbor Species Model for spring wheat number of tillers per target plant (2006).

	Estimate	<i>P</i> -value
Intercept	11.17	<0.001
Neighborhood Species Richness	-0.45	0.55
Neighborhood Density	-0.53	0.002
Richness * Density	0.05	0.47

Residual standard error: 3.118 on 71 degrees of freedom

Multiple R-Squared: 0.3722, adjusted R-squared: 0.3457

F-statistic: 14.03 on 3 and 71 DF, *p*-value: 2.818e-07

Thus, the likelihood of rejecting the null hypothesis at this point was extremely low.

However, knowledge of what specific neighborhood factors were affecting spring wheat performance was still desired in order to direct further research. Therefore, the next step was to look at the neighborhood species specific factors responsible for the variation in spring wheat performance and thereby determine which, if any, were having an effect on spring wheat performance.

The best BNSM for spring wheat target plant dry biomass included the t_1 ratio, spring wheat neighbor biomass, and field pennycress neighbor biomass as independent variables and accounted for 22% of the variation (Table 4.5). The best BNSM for spring wheat yield included only the t_1 ratio, and accounted for 11% of the variation in yield (Table 4.6). The best BNSM for number of tillers per target plant was identical to the first model in terms of the independent variables selected, and accounted for 33% of the variation (Table 4.7). None of the best BNSMs included any neighbor species biomass interactions, suggesting that no specific species interactions were playing a role in final wheat target biomass, yield, or tiller production. The inclusion of spring wheat, and field pennycress neighbor biomass terms in the best BNSMs for dry biomass and number of

tillers suggests that early season competition has the most effect on spring wheat performance, as both spring wheat neighbors and field pennycress neighbors were present at the time of target emergence. The inclusion of the t_1 ratio also indicates that the early season competitive environment has important effects on spring wheat performance. Thus, the original null hypothesis could not be rejected, as no species interaction terms were incorporated into the best BNSM. For the 2005 data, neither neighborhood species richness nor density had any affect on spring wheat target plant dry biomass or yield.

Table 4.5. Best Between Neighbor Species Model for spring wheat transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	2.43	<0.001
Neighborhood		
t_1 Ratio	0.001	0.04
Spring wheat biomass	-0.005	0.003
Field pennycress biomass	-0.029	0.02
Residual standard error: 0.4394 on 70 degrees of freedom		
Multiple R-Squared: 0.2557, adjusted R-squared: 0.2238		
F-statistic: 8.015 on 3 and 70 DF, <i>p</i> -value: 0.0001,		
transformed dry biomass = dry biomass ^{0.3}		

Table 4.6. Best Between Neighbor Species Model for spring wheat transformed seed yield (2006).

	Estimate	<i>P</i> -value
Intercept	1.88	<0.001
Neighborhood		
t_1 Ratio	0.001	0.003
Residual standard error: 0.6363 on 72 degrees of freedom		
Multiple R-Squared: 0.119, adjusted R-squared: 0.1068		
F-statistic: 9.725 on 1 and 72 DF, <i>p</i> -value: 0.003,		
transformed yield = yield ^{0.4}		

Table 4.7. Best Between Neighbor Species Model for spring wheat tillers per plant (2006).

	Estimate	<i>P</i> -value
Intercept	8.83	<0.001
Neighborhood		
t_1 Ratio	0.01	<0.001
Spring wheat biomass	-0.04	<0.001
Field pennycress biomass	-0.2	0.03
Residual standard error: 3.123 on 70 degrees of freedom		
Multiple R-Squared: 0.3621, adjusted R-squared: 0.3348		
F-statistic: 13.25 on 3 and 70 DF, <i>p</i> -value: 6.09e-07		

Weed Species. Field pennycress target plant dry biomass was negatively affected by increasing levels of neighborhood density (Table C.1). However, the number of seeds produced per target plant was not explained by either neighborhood density or species richness (Table C.2). The best BNSM for field pennycress dry biomass contained the t_1 ratio, spring wheat, field pennycress, kochia, and green foxtail biomass, as well as the interaction terms for spring wheat x kochia biomass and kochia x green foxtail biomass (Table C.3). This model accounted for 65% of the variation in field pennycress dry biomass. The best BNSM for field pennycress target plant seed production included the same variables, along with the addition of wild oat biomass and interaction terms for field pennycress x wild oat biomass and green foxtail x wild oat biomass (Table C.4). This model accounted for 55% of the variation in transformed number of seeds produced. For field pennycress, the most important factor effecting target plant performance appeared to be early establishment, as indicated by the presence of t_1 ratio in the final model for dry biomass and seed production. Field pennycress is a winter annual and has thus become adapted to emerge prior to other commonly associated species and thus takes advantage

of resources before other plants emerge. Significant negative interaction terms further suggest that field pennycress can be negatively affected by the increased resource use presented by multiple species. Green foxtail appeared to have the largest negative effect on field pennycress performance, but the reasons for this are not clear. There were also some positive interactions, suggesting that when certain species were present in addition to green foxtail, the effects of green foxtail on field pennycress targets was reduced. In 2005, neighborhood density affected both target dry biomass and seed production negatively and neighborhood species richness was not a factor.

Kochia target plant dry biomass was not affected by either neighborhood density or species richness (Table C.6). The best BNSM for kochia dry biomass included spring wheat, kochia, and wild oat biomass as well as the interaction term for kochia x wild oat biomass (Table C.7). This model accounted for 25% of the variation in kochia dry biomass. Similarly, in 2005 neither neighborhood species richness nor density explained any of the variation in kochia dry biomass. Target plant performance in kochia was most affected by spring wheat neighbor biomass. This is probably a sampling effect and evidence that spring wheat grew better in plots where there was less kochia. The fact that field pennycress biomass did not enter the best BNSM for kochia suggests that, among the dicot species in this study, kochia was the superior competitor, in spite of the early emergence of field pennycress. The inclusion of the negative interaction term for kochia x wild oat biomass suggests competition for a common resource between kochia and wild oat.

For green foxtail target plants, neighborhood species richness and neighborhood density did not explain the variation in target plant dry biomass, seed production, or the number of tillers produced per target plant, and p -values for the regression models were not significant (Tables C.8-C.10). The best BNSMs for green foxtail dependent variables as selected by the BIC contained a large number of dependent variables and were based on a data set with a small number of points (Tables C.11 – C.12). Thus, they should be treated with caution. There are some interesting trends to note between the models, however.

The negative affects of the biomass of other grass species on green foxtail target dry biomass suggest that it is a weak competitor with other grass species. The late emergence time of green foxtail in this particular study area is most likely responsible for these results as it allowed spring wheat to establish before green foxtail had begun to emerge and capture resources. The positive effects of green foxtail biomass on all measures of green foxtail target performance suggest that inter-specific competition is not an issue for this species. The t_1 ratio negatively impacted all of the dependent variables for green foxtail target plants. This probably indicates that green foxtail plants which emerged early (increasing the t_1 ratio) suffered increased mortality due to exposure to cold temperatures early in the growing season. The majority of species interaction coefficients in these models were positive and include field pennycress, suggesting that green foxtail performs better in multi species communities where field pennycress can be suppressed. In 2005, both the dry biomass and seed production of green foxtail were negatively affected by neighborhood species richness.

The variation in wild oat target plant dry biomass, seeds produced, and number of tillers was not explained by neighborhood species richness or density (Tables C.13 - C.15). The best BNSM for wild oat dry biomass included the t_1 ratio, all individual neighbor species biomass variables, and the interaction terms for spring wheat x green foxtail biomass, spring wheat x wild oat biomass, field pennycress x kochia biomass, and kochia x green foxtail biomass (Table C.16). This model accounted for 80% of the variation in wild oat target plant dry biomass. The best BNSM for wild oat target plant seed production included the t_1 ratio, all of the individual neighbor species biomass variables, and the interaction terms for spring wheat x wild oat biomass, field pennycress x kochia biomass and kochia x wild oat biomass (Table C.17). This model accounted for 68% of the variation in wild oat target plant seed production. The best BNSM for wild oat number of tillers for target plant included the t_1 ratio, all of the neighbor species biomass variables, and the interaction terms for field pennycress x kochia biomass, field pennycress x green foxtail biomass, kochia x green foxtail biomass, and green foxtail x wild oat biomass. As with green foxtail, all of the best BNSMs for wild oat dependent variables were very highly parameterized given the size of the data set. However, there were noticeable trends between models.

For wild oat biomass, the inclusion of the t_1 ratio in the best BNSM suggests that early conditions are important in wild oat growth. As with green foxtail, the coefficients for this effect were negative, suggesting increased mortality due to early emergence. Spring wheat biomass and wild oat biomass both had a negative affect on wild oat target biomass, suggesting that intra-specific competition and competition with wheat both

negatively affect wild oat performance. The majority of the species interaction were negative, suggesting that wild oat performance is affected negatively in multi-species communities. In 2005, neighborhood species richness explained some of the variation in wild oat target plant dry biomass while neighborhood density explained some of the variation in wild oat target plant seed production.

Predictors of Relative Growth Rate

The relationship between plant volume and dry biomass was successfully established for all species. Plant volume accounted for 95% ($p = <2e-16$), 74% ($p = 6.334e-09$), 83% ($p=1.202e-12$), 44% ($p = 0.0002$) and 85% ($p = 2.804e-12$) of the variation in plant dry biomass for field pennycress, green foxtail, kochia, spring wheat, and wild oat respectively.

Spring Wheat. For spring wheat, neighborhood species richness and neighborhood density did not explain a significant portion of the variation in RGR (Table 4.8). The best BNSM explaining the variation in spring wheat target plant RGR included only spring wheat neighbor biomass (Table 4.9). This model accounted for 10% of the variation in spring wheat RGR. This suggests that intra-specific competition has the greatest effect on spring wheat RGR, and that neighboring weed species were having no influence on spring wheat during the period of most active growth.

Table 4.8. Combined Neighbor Species Model for spring wheat target RGR (g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.01	0.02
Neighborhood Species Richness	0.002	0.44
Neighborhood Density	-2.2e-04	0.40
Richness * Density	4.03e-05	0.67
Residual standard error: 0.0108 on 71 degrees of freedom		
Multiple R-Squared: 0.06641, adjusted R-squared: 0.02696		
F-statistic: 1.684 on 3 and 71 DF, <i>p</i> -value: 0.1783		

Table 4.9. Best Between Neighbor Species Model for spring wheat target plant RGR(g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.02	<0.001
Neighborhood Spring Wheat Biomass	-0.001	0.003
Residual standard error: 0.01038 on 73 degrees of freedom		
Multiple R-Squared: 0.1135, adjusted R-squared: 0.1014		
F-statistic: 9.346 on 1 and 73 DF, <i>p</i> -value: 0.003121		

Weed Species. Neighborhood density had a negative effect on field pennycress target plant RGR (Table C.19). Neighborhood species richness did not account for a significant portion of the variation in field pennycress RGR, but there was a negative interaction between RGR and neighborhood density. When the model selection procedure was applied, none of the variables included in the global model explained the variation in RGR sufficiently. Hence, a best BNSM was not selected for field pennycress. This suggests that neighborhood conditions had very little effect on field pennycress growth rate, and that the amount of biomass accumulated early in the season

(before full neighborhood establishment) was probably responsible for each individual plants' final biomass.

For kochia, neighborhood density had a negative effect on target plant RGR (Table C.20). The best BNSM for kochia RGR included spring wheat, field pennycress, kochia, and green foxtail biomass, as well as the interaction terms for spring wheat x field pennycress biomass and field pennycress x green foxtail biomass (Table C.21). This model accounted for 20% of the variation in kochia RGR. The only significant effects were for kochia biomass and the two interaction terms. This suggests that kochia RGR is affected by increased resource consumption due to multiple species rather than just one species, even at high densities of neighbors

Neighborhood species richness negatively affected green foxtail RGR (Table C.22). The best BNSM for green foxtail RGR included spring wheat, field pennycress, and wild oat biomass, and the interaction term for field pennycress x wild oat biomass. This model accounted for 57% of the variation in green foxtail RGR (Table C.23). The negative effects of other grass species on green foxtail RGR suggest that it is a poor competitor with other grass species. The negative interaction term for field pennycress x wild oat biomass could indicate that the negative effects of field pennycress on green foxtail targets are exacerbated when there wild oat plants in the neighborhood, perhaps due to use of a common resource.

The variation in wild oat RGR was not explained by neighborhood species richness or neighborhood density (Table C.24). The best BNSM for wild oat RGR contained spring wheat and green foxtail biomass, and accounted for 12% of the variation

in wild oat RGR (Table C.25). This suggests that the growth of wild oat throughout the season is effected by competition with other grass species.

The ANOVA with Tukey-Kramer procedure indicated that there were several differences between species within richness levels (Table 4.10). Kochia and wild oat generally had the highest RGR across levels of species richness, suggesting that Kochia and wild oat are superior competitors. However, as species richness increased, the competitive abilities of all species in the neighborhoods became more similar. As with the regression models, the comparison of RGR within species across richness levels indicated that neighborhood species richness had very little effect on individual species RGR.

Table 4.10. Within species and within richness level differences in RGR values (g/g/day) for target plants.

Species	Neighborhood Species Richness			
	1	2	3	4
Spring Wheat	0.01 A – a	0.02 A – a	0.02 A – a	0.02 A – a
Field Pennycress	0.09 A – ab	0.02 B – a	0.02 B – a	0.03 AB – ab
Kochia	0.06 A – ab	0.07 A – b	0.06 A – b	0.07 A – b
Green Foxtail	0.09 A – ab	0.04 B – ac	0.03 B – a	0.03 B – a
Wild Oat	0.13 A - b	0.09 A - d	0.06 A - b	0.06 A - ab

Capital letters indicate differences in the within species between richness level comparison, lower case letters indicate differences in the between species within richness level comparison. Differences based on Tukey-Kramer procedure with 95% confidence interval.

Discussion

Effects of Diversity on Spring Wheat

The primary goal of this study was to examine the effects of neighborhood species richness on spring wheat performance, holding density constant, via inter-specific

competition. The null hypothesis that neighborhood species richness has no effect on spring wheat performance via inter-specific competition could not be rejected. The data suggested that neighborhood species richness had no effect spring wheat target biomass or yield. Furthermore, the absence of any neighbor species biomass interactions in the best BNSM suggested that inter-specific weed competition did not play an alleviating role in the competition between the neighbor weeds and spring wheat target plants.

The best BNSM suggested that the t_1 ratio, spring wheat neighbor biomass and field pennycress neighbor biomass were the only variables that affected spring wheat target plant dry biomass and tiller production, and that yield was only affected by the t_1 ratio. This indicates that early season conditions had the largest effect on spring wheat performance. These results are in accordance with previous observations that the effects of competition are most pronounced early in the growing season (Zimdahl, 1988). Thus, any further studies of this kind should also take early season competition into account. It is quite possible that the negative neighborhood density effect was inflated by an increased number of field pennycress being present in a given neighborhood as neighborhood density increased. Similar sampling effects, where diversity affected dependent variables via an increased probability of contact with a dominant species, have been discussed in previous works (Huston, 1997; Fargione and Tilman, 2005).

The null hypothesis could not be rejected based on spring wheat target plant RGR analysis, as neighborhood species richness had no effect on spring wheat target plant RGR. The best model selected to explain the variation in target plant RGR included only

spring wheat neighbor biomass. This suggests that intra-specific competition plays a bigger part in the growth of spring wheat than does inter-specific competition.

The Effects of Diversity on Weed Species

Measures of plant performance (dry biomass, seed yield, and number of tillers, RGR) were also made for target plants of weed species throughout the course of this study. In summary, neighborhood species richness had very few significant effects. Green foxtail RGR was the only weed species variable measured upon which neighborhood species richness had any significant effect, and this was a negative effect. Neighborhood density negatively affected field pennycress dry biomass and RGR. Neither neighborhood density nor neighborhood species richness had any other significant effects on weed species performance.

In general, our results indicated that specific aspects of the weed community, such as composition and life history strategies of certain species, played a larger role in determining weed target plant performance than did the species richness of the weed community. For example, neighbor monocot species seemed to negatively affect green foxtail and, to some extent, wild oat performance. Early establishment also seemed to be an important determinant in the success of field pennycress, green foxtail, and wild oat. Interestingly, despite the lack of a negative relationship between species richness and weed performance in general, a number of the best BNSMs included negative species biomass interaction terms. This suggests that the presence of multiple species does have a negative impact on weed target plant performance, perhaps through increased resource competition. However, the lack of a general negative relationship between species

richness and weed target performance suggested that the identity of the species was more important than the number of species.

Relative Growth Rates Within the Pant Community

The quantified effects of neighborhood conditions on target plant performance allowed for some speculation about the relative competitive abilities of the species under different neighborhood density and species richness conditions. RGR was proposed as a good analog of the relative competitive ability of a species in relation to other species (Holt and Orcutt, 1991; Hegazy et al., 2005; Wang et al., 2006). The regression analysis and ANOVA suggested that, within species, RGR generally was not altered significantly by neighborhood species richness. However, within levels of neighborhood species richness, there were several differences between individual species RGRs within levels of neighborhood species richness.

Wild oat and kochia generally had the two highest RGRs across richness levels and could thus be considered dominant competitors if RGR is used as an analog of competitive ability. However, an interesting trend developed as the level of richness increased. Examination of the differences in RGR between species revealed that, as neighborhood species richness increased, the number of these between species differences in RGR increased from 1 to 7 between species richness levels 1 and 2. Moving from richness level 2 to 4, the number of differences dropped from 7 to 2. This result suggested that, as neighborhood species richness increased, the RGR and thus competitive ability of the neighborhood species were becoming more similar. The between species differences in RGR at species richness level 4 also revealed that wild oat

and kochia may be losing their spots at the top of the competitive hierarchy, no longer being significantly different from all of the other three species. This suggests that competitive dominance of certain weedy species might be overcome by increasing species richness.

When analyzing the species richness data, we were confronted with the problem of how exactly to characterize the conditions of the neighborhood using species richness. The first option was to consider neighborhood species richness independent of the target plant identity i.e. the target plant would not contribute to neighborhood species richness. Effects of the number of species represented by neighboring plants on the target plant could then be tested. This presented a problem when relating species richness to competition, in that the target plant is also competing with its neighbors. In this case, a species richness of 1 indicated a monoculture surrounding the target plant. The entire neighborhood could either be a monoculture (if the target and neighbors were the same species) or a bi-culture (if the target plant species was different from the neighboring plants). This essentially confounded inter and intra-specific competition at this richness level. The other alternative was to include the target plant in the measure of neighborhood species richness. In this case, a richness level of one represented a true monoculture (target and neighbor species having the same identity). This dealt with the fact that the target plant was also a competing individual, but gave rise to another potential problem. Including the target plant in the neighborhood species richness level had the effect of combining two potentially different neighbor plant community conditions into a single richness level. For example, a neighborhood species richness of

two could represent a situation in which there were two species (the target species and another) surrounding the target plant in equal proportion. Alternatively it could represent a situation in which the target plant is surrounded by a monoculture of a different species. Additional care in experimental design, whereby the effects of inter and intra-specific competition could have been separated cleanly for each species, could have potentially dealt with this problem. However, the full factorial addition series design could not accommodate a remedy for this problem. Therefore, a more precise measure accounting for the number of inter and intra-specific interaction, or the ratio of inter to intra-specific interactions might be a better alternative in this type of analysis as compared to the simple measure of neighborhood species richness that we employed.

Conclusions

This study set out to examine the effects of weed species richness on spring wheat performance, simultaneously accounting for density. Results indicated that neighborhood species richness has no obvious direct effect on spring wheat performance via inter-specific competition. We were able to conclude that species richness no effect on spring wheat dependent variables. However, we did identify some potential problems with using species richness as an approximation of the levels of inter and intra-specific competition, and suggest that more precise measures be employed in the future. Thus, the hypothesis proposed by Clements *et al.* (1994) that weed species richness might have a positive effect on crop yield at a constant weed density has not been completely rejected. This study has simply presented evidence that inter-specific competition is not the mechanism whereby species richness positively affects crop yield. However, a more

detailed examination of the effects of the number of inter-specific interactions might yield different results than this study. Clements *et al.* (1994) suggested that the number of interactions would increase as weed diversity increased, thereby limiting the effects of weeds on crop plants, but did not specify the whole suite of interactions that might have effects on crop yield. Therefore, even if inter-specific competition is not the mechanism whereby species richness positively affects spring wheat performance, other possible mechanisms remain, such as a soil microbial feedbacks. Thus, the question still exists, but we have presented evidence favoring the rejection of one possible answer.

This study has illustrated some of the aspects of competition that may be occurring within cropping systems with variable weed species richness. It has shown that the specific traits of each species, such as growth habit, emergence time, and relative competitive ability, must all be considered when attempting to determine the outcome of competition in a multi-species setting. Furthermore, it has hinted that the competitive dominance of a species may be reduced at higher levels of species richness. This may be why weed communities in organic systems are perceived as being less troublesome by organic farmers. It may be that the weed communities of organic systems are more self regulating by virtue of the relative suppression of species which are dominant in lower diversity settings. Therefore, there may be avenues by which the composition of the weed community can be used as a tool to limit the effects of weeds on crop species. Whether or not increasing species richness could subdue a dominant weed has yet to be determined, but it is certainly worth investigating in the pursuit of a more integrated and sustainable agricultural weed management approach.

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CHAPTER 5

SUMMARY OF FINDINGS / FUTURE RESEARCH

This study has highlighted fundamental differences between the weed communities of conventional no-tillage and organic dry-land spring wheat systems. First, this study has confirmed previous observations that species richness is higher in organic systems than in conventional ones. This study has also shown that both α and β diversity are higher within organic spring wheat systems, which differs from expectation based on predictions where levels of β diversity are determined by the level of dispersal. We had expected to find higher β diversity in the conventional no-tillage systems, where dispersal was limited in comparison to the tillage intensive organic system. In addition, these findings were generated using species-area curves, a method which has seen limited use in agricultural settings. Using this method allowed us to 1) compare the mean species richness of conventional and organic spring wheat systems at multiple spatial scales 2) compare the levels of relative α and β diversity of these two systems and 3) confirm that we had sampled areas large enough to adequately describe the diversity present within each system (data not shown). Furthermore, we took three observations per year, as opposed to most other studies where diversity was only measured at one point in the growing season. This allowed us to look at species richness over time as well, and the data indicated that there were significant decreases in species richness from early to late in the growing season for both organic and conventional systems.

Second, this study has shown that the weed communities of organic spring wheat systems display spatial patterns other than random, and that these patterns tend to be

aggregated. The weed communities of the conventional no-tillage systems also displayed an aggregated pattern, as has been shown in previous studies. Further testing showed that there was no difference between the levels of aggregation in each system. However, using a combination of percent cover plots and three-term local quadrat variance plots, we were able to show that the aggregation manifested differently in organic and conventional no-tillage systems. We also found that the differences in weed species richness and percent cover were consistent between the study area scale and at the weed patch scale.

Lastly, this study presented evidence that weed species richness does not directly affect individual spring wheat plant biomass, yield or RGR when accounting for weed density. Furthermore, weed species richness had very few effects on individual weed species performance. However, this study indicated that as species richness increased, the relative growth rates of all species became more similar. Furthermore, as the level of richness increased, the RGR of spring wheat was not affected. This suggests that as weed species richness increases, the competitive ability of species becomes more similar, and that perhaps higher levels of weed species richness might suppress dominant weed species in favor of spring wheat.

In light of the findings of this study, the potential for future research in this area is very large. Specifically, further research should be directed at whether or not the differences in α and β diversity between conventional no-tillage and organic spring wheat systems are consistent in other types of crops. If that is the case, then it would certainly be worth investigating what the drivers of these differences in α and β diversity are, and if

there are any consequences of varying levels of each in regards to both crop and weed growth and other processes such as nutrient cycling.

Similarly, the spatial pattern of weed communities in organic systems should be investigated more fully. This study has shown that weed communities in an organic dry-land spring wheat production system display a unique pattern of weed percent cover. Further studies should examine the patterns of weed communities in other types of organic cropping systems to see if the phenomenon can be generalized across organic cropping systems. Furthermore, the spatial patterns present in the weed communities of organic dry-land spring wheat production systems should be examined in greater detail, introducing both species identity and temporal aspects. Such investigations would provide valuable evidence as to whether or not the weed communities of organic spring wheat systems are more stable than their conventional counterparts i.e. less prone to large spatially explicit fluctuations in weed density of a given species over time. If this is the case, it is possible that yield stability would be greater in organic systems over time.

Finally, the role of weed species richness in agricultural systems deserves further investigation. Experiments that more closely resemble actual agricultural field conditions should be pursued to investigate the effects of weed diversity on crop yield, especially under high weed density conditions. Furthermore, the RGR of weed species should be examined under a broader array of weed density and weed diversity conditions to determine if the trend indicated by the data in this study represents an actual response of weed RGR to overall weed diversity.

This study represents a small piece of the larger puzzle that the scientific community needs to complete in order to move towards a system sustainable agriculture. Overall, the findings of this study have demonstrated the potential of species diversity and spatial patterns of weed communities to be used in the development of more integrated weed management strategies. Although the species richness and spatial structure of weed communities need to be investigated more fully in order to develop this potential into actual management recommendations, this study has, at the least, demonstrated the validity of following this particular course of research to whatever end.

APPENDICES

APPENDIX A:

SUPPLEMENTAL THREE TERM LOCAL QUADRAT VARIANCE

AND

PERCENT COVER GRAPHS

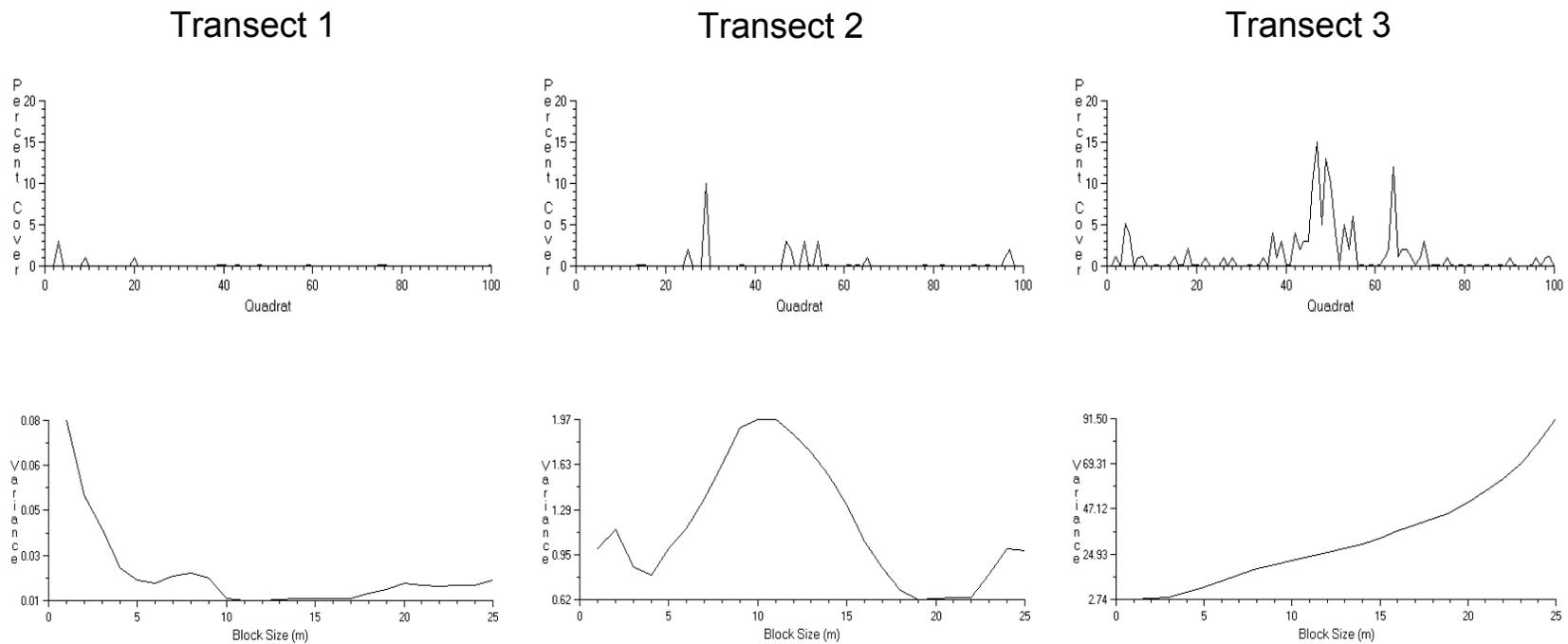


Figure A.1. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Conventional No-Till Field 2, 2005. 3TLQV calculated based on 25m maximum block size.

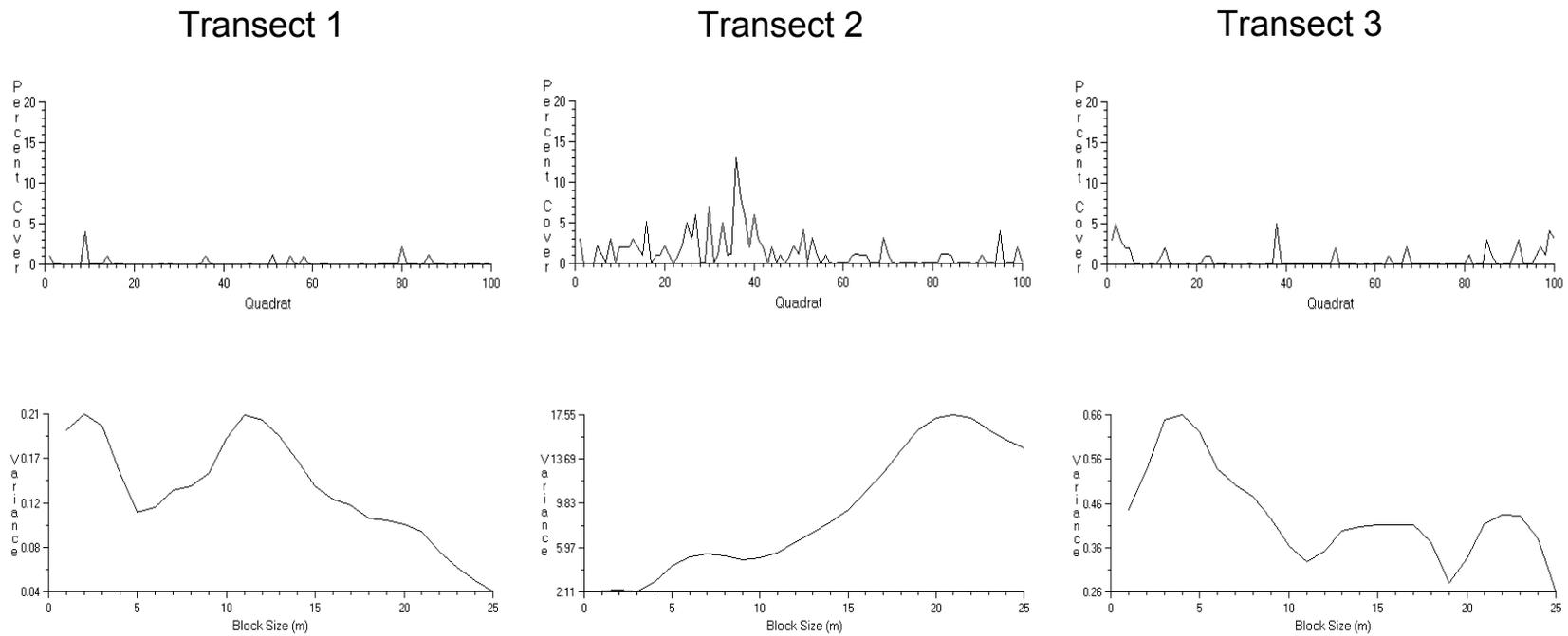


Figure A.2. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Conventional No-Till Field 3, 2005. 3TLQV calculated based on 25m maximum block size.

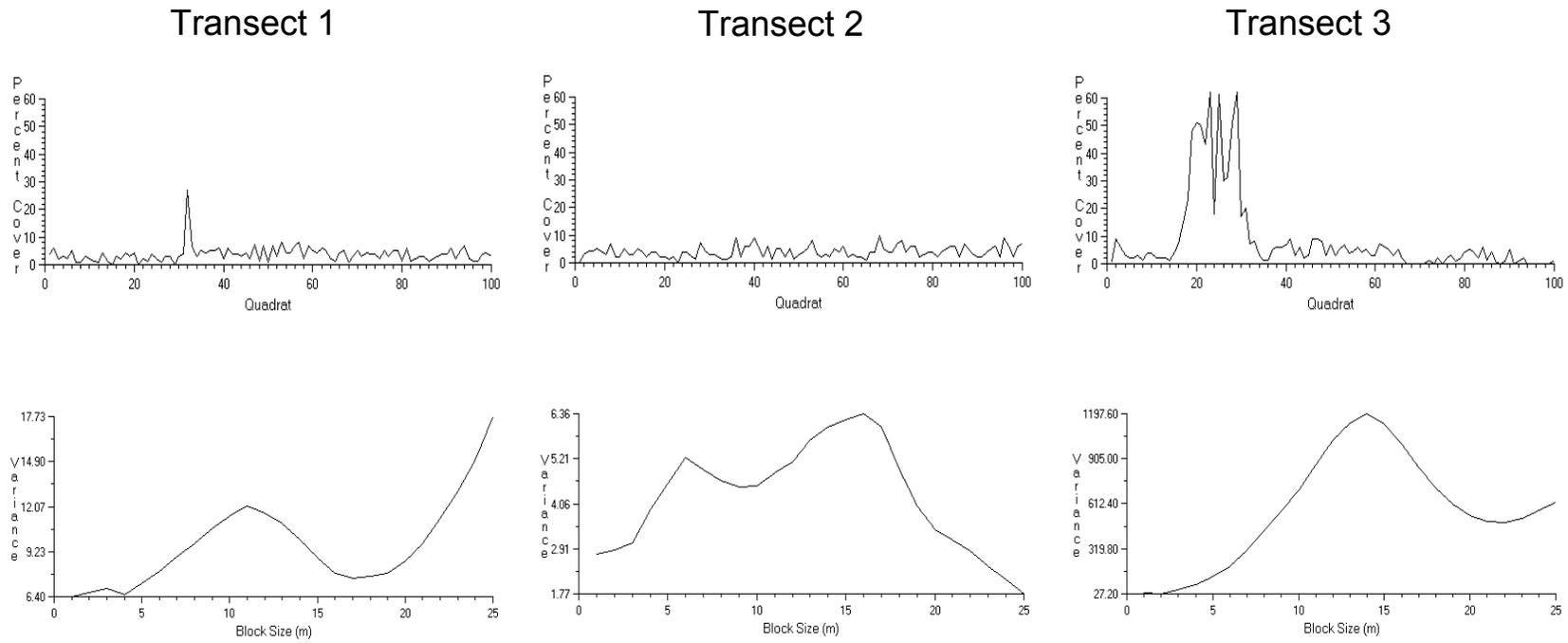
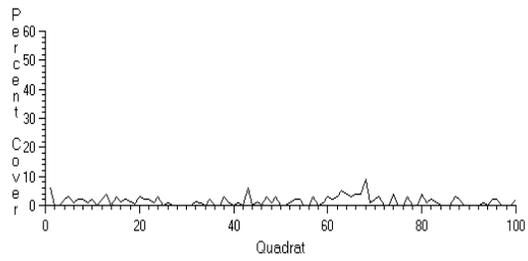
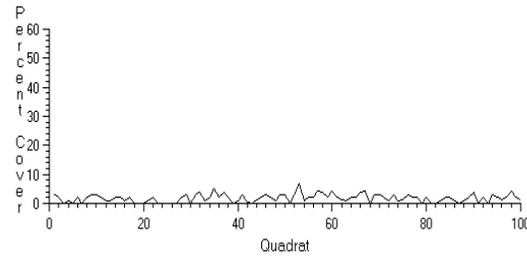


Figure A.3. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Organic Field 2, 2005. 3TLQV calculated based on 25m maximum block size.

Transect 1



Transect 2



Transect 3

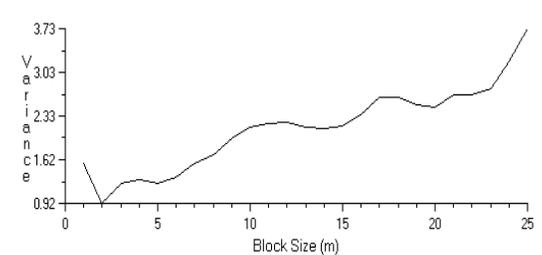
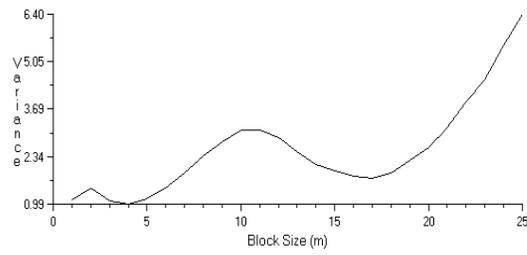
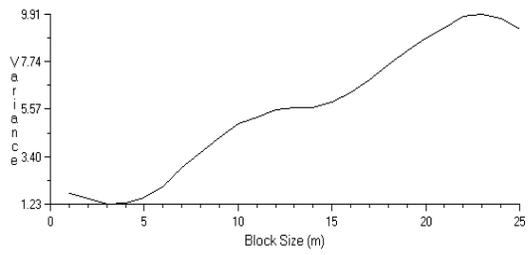
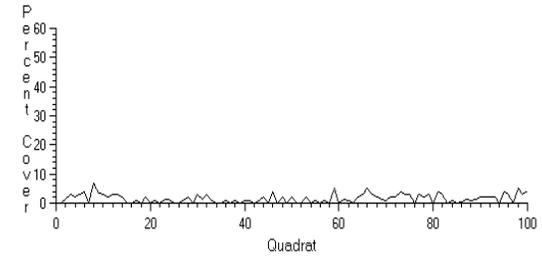


Figure A.4. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Organic Field 3, 2005. 3TLQV calculated based on 25m maximum block size.

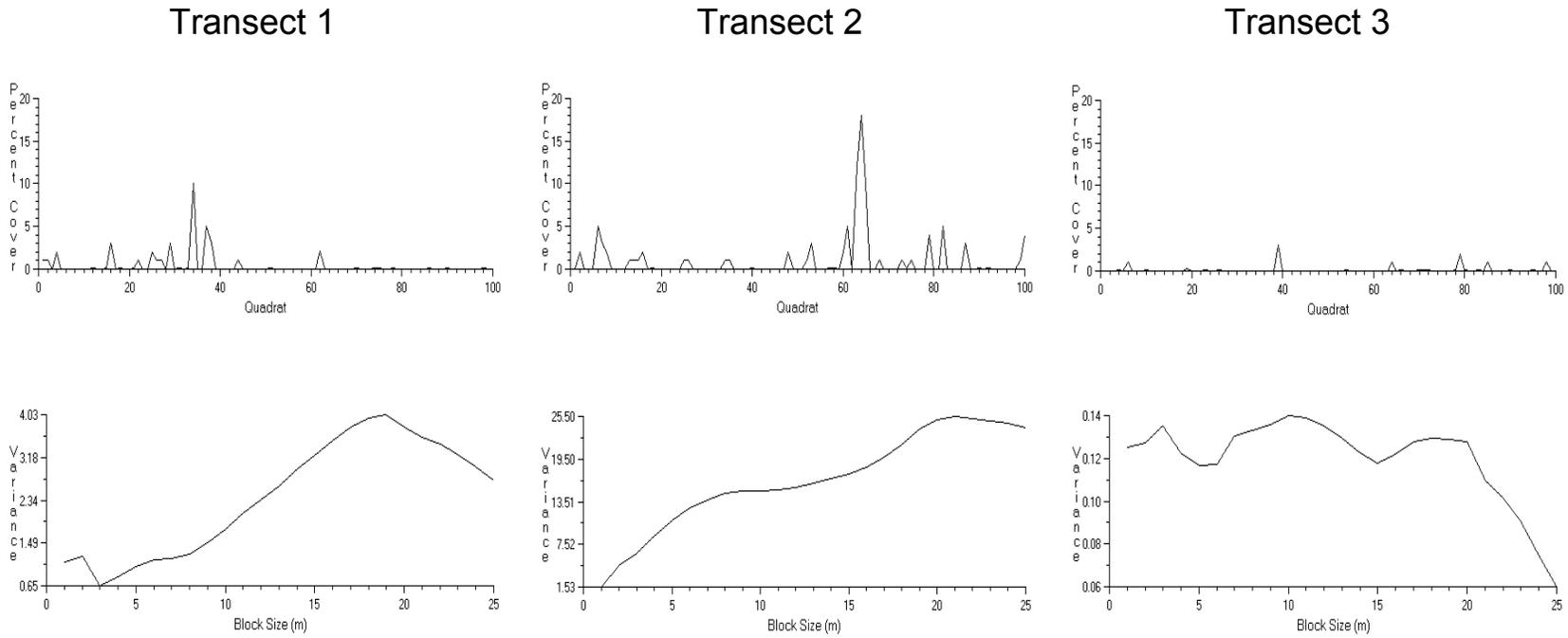


Figure A.5. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Conventional No-Till Field 2, 2006. 3TLQV calculated based on 25m maximum block size.

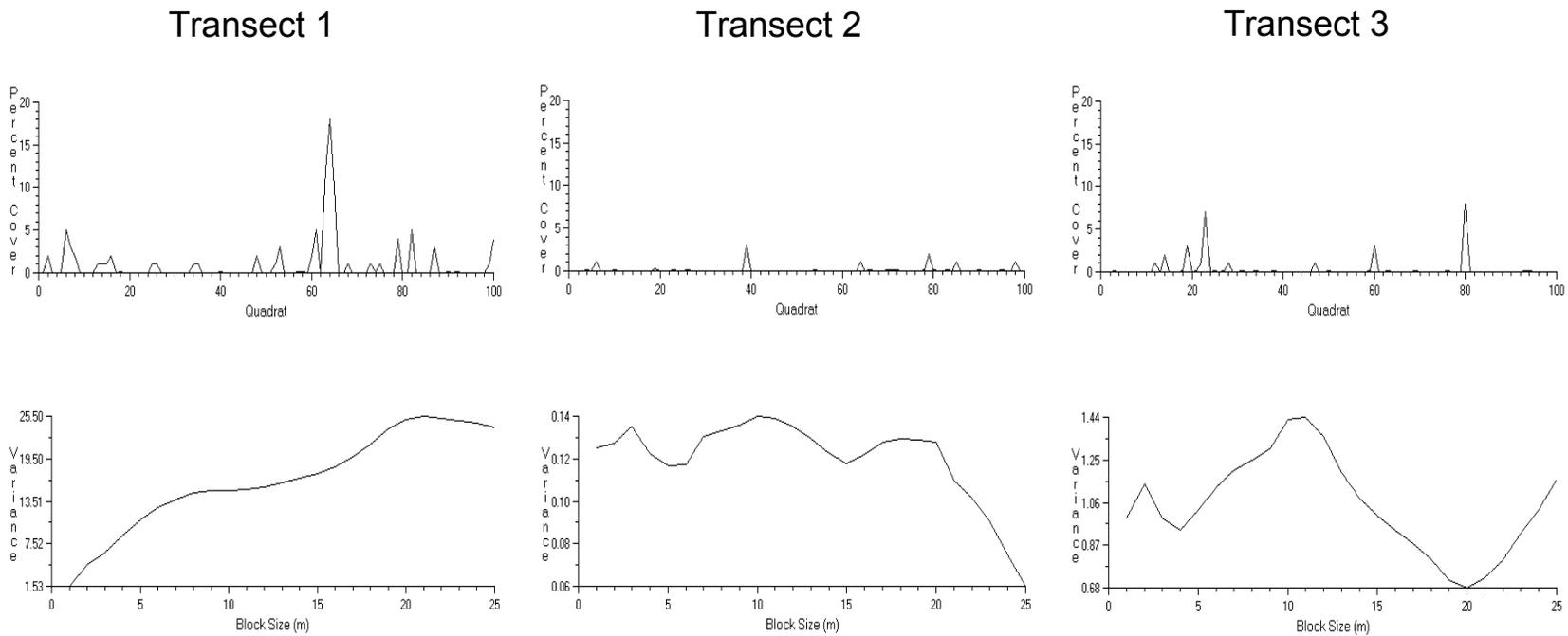
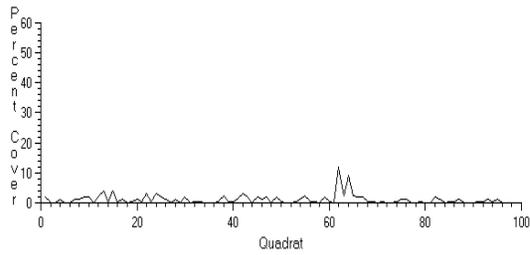
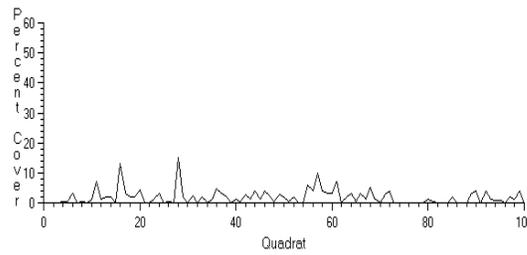


Figure A.6. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Conventional No-Till Field 3, 2006. 3TLQV calculated based on 25m maximum block size.

Transect 1



Transect 2



Transect 3

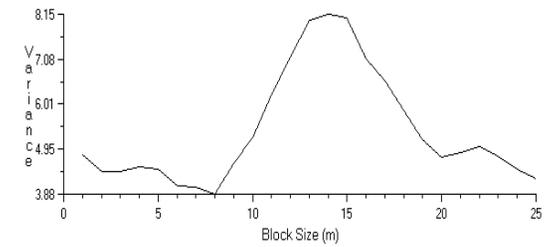
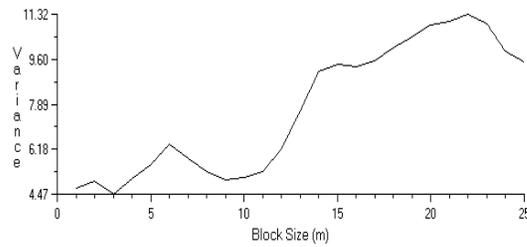
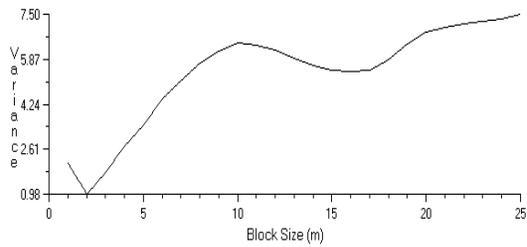
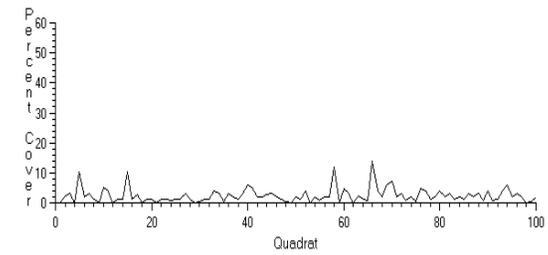


Figure A.7. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Organic Field 2, 2006. 3TLQV calculated based on 25m maximum block size.

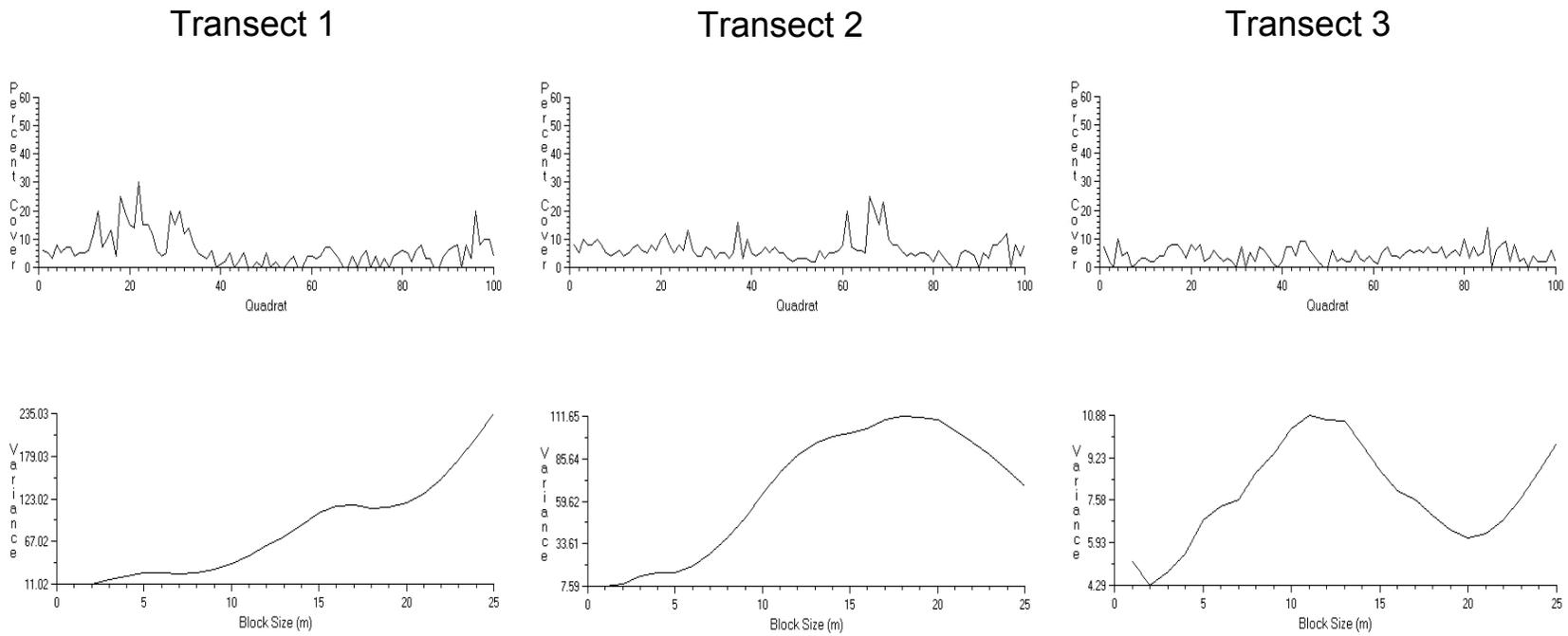


Figure A.8. Percent cover and three term local quadrat variance (3TLQV) plot for each transect in Organic Field 3, 2006. 3TLQV calculated based on 25m maximum block size.

APPENDIX B:

EXAMPLES OF REGRESSION SURFACES

UNDER DIFFERENT MODEL SITUATIONS

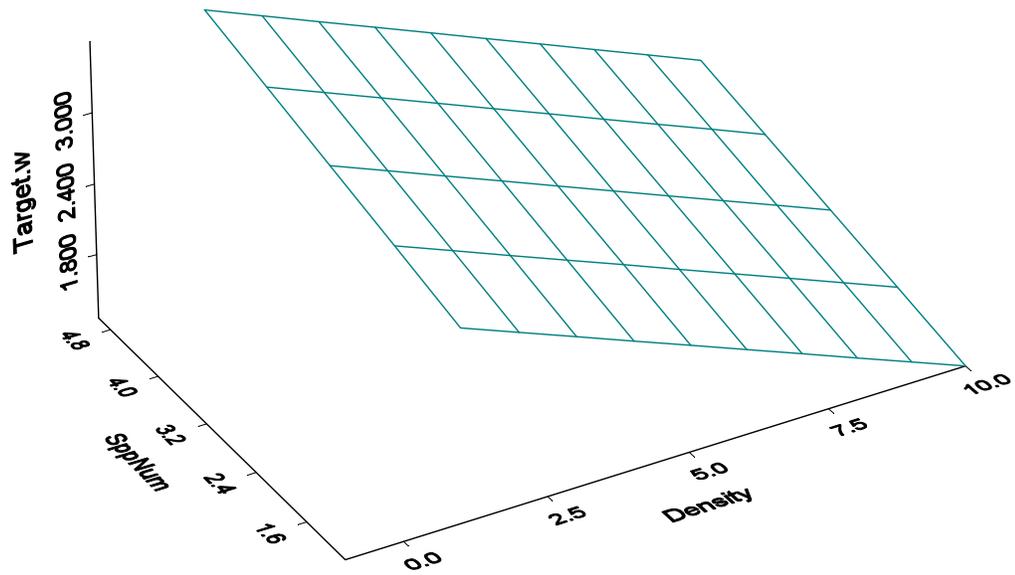


Figure B.1. Regression surface depicting positive effects of neighborhood species richness (spp. num) on target performance (Target. W) at all levels of neighborhood density, and the negative effects of increased density at all levels of neighborhood species richness. Such a surface would be generated if the regression coefficient for neighborhood density was negative and the coefficient for neighborhood species richness was positive.

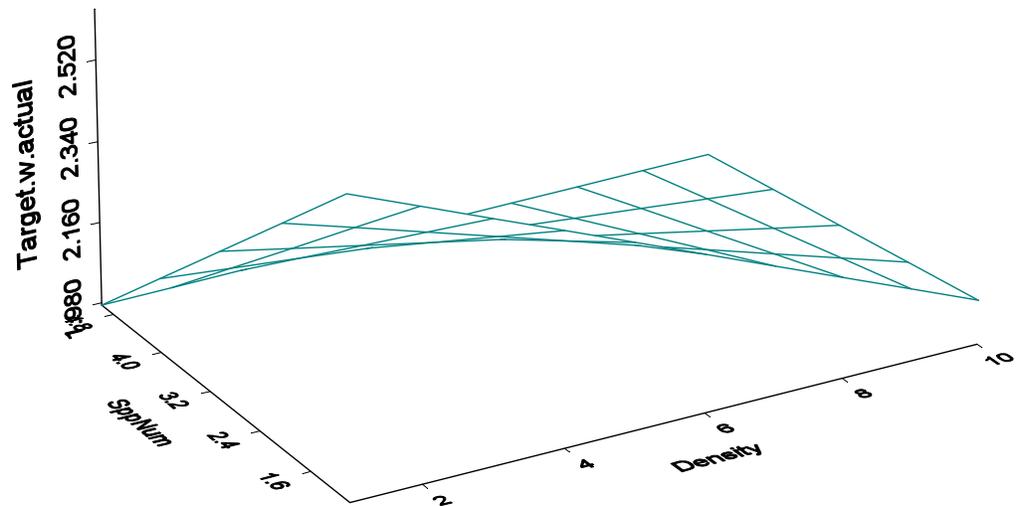


Figure B.2. Regression surface depicting negative effects of neighborhood species richness (spp. num) on target performance (Target. W) at low levels of neighborhood density, and the positive effects of neighborhood species richness at higher densities. This graph also depicts negative affects of neighborhood density on target plant performance at low species richness, and positive effects at high species richness. Such a surface would be generated if the regression coefficients for both neighborhood density and species richness were negative, but there was a positive interaction term. The magnitude of effect shifts (from negative to positive) would then depend on the magnitude of the interaction coefficient.

APPENDIX C:

COMBINED NEIGHBOR SPECIES MODELS

AND

BETWEEN NEIGHBOR SPECIES MODELS

FOR WEED TARGET PLANT SPECIES

Table C.1. Combined Neighbor Species Model for field pennycress transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	1.45	<0.001
Neighborhood Species Richness	-0.06	0.54
Neighborhood Density	-0.06	0.02
Richness * Density	0.02	0.14

Residual standard error: 0.2352 on 30 degrees of freedom
 Multiple R-Squared: 0.218, adjusted R-squared: 0.1154
 F-statistic: 2.434 on 3 and 30 DF, *p*-value: 0.1398,
 transformed dry biomass = dry biomass^{0.2}

Table C.2. Combined Neighbor Species Model for field pennycress transformed number of seeds produced per target plant (2006).

	Estimate	<i>P</i> -value
Intercept	8.92	<0.001
Neighborhood Species Richness	-0.02	0.98
Neighborhood Density	-0.41	0.12
Richness * Density	0.12	0.33

Residual standard error: 2.63 on 30 degrees of freedom
 Multiple R-Squared: 0.1371, adjusted R-squared: 0.051
 F-statistic: 1.589 on 3 and 30 DF, *p*-value: 0.2125,
 transformed seeds produced = seeds produced^{0.3}

Table C.3. Best Between Neighbor Species Model for field pennycress transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	8.38e-01	<0.001
Neighborhood		
t ₁ Ratio	3.57e-02	<0.001
Spring wheat biomass	3.65e-03	0.008
Field pennycress biomass	02.16e-02	<0.001
Kochia biomass	2.36e-04	0.32
Green foxtail biomass	-1.35e-01	0.06
S. wheat bio. : Kochia bio.	-2.79e-04	0.002
Kochia bio. : G. foxtail bio.	3.38e-03	0.001

Residual standard error: 0.1496 on 26 degrees of freedom
 Multiple R-Squared: 0.7258, adjusted R-squared: 0.652
 F-statistic: 9.833 on 7 and 26 DF, *p*-value: 5.959e-06
 transformed dry biomass = dry biomass^{0.2}

Table C.4. Best Between Neighbor Species Model for field pennycress transformed seeds produced (2006).

	Estimate	<i>P</i> -value
Intercept	4.25	<0.001
Neighborhood		
t_1 Ratio	0.34	<0.001
Spring wheat biomass	0.04	0.03
Field pennycress biomass	0.22	0.01
Kochia biomass	0.002	0.47
Green foxtail biomass	-1.27	0.15
Wild Oat biomass	0.02	0.62
S. wheat bio. : Kochia bio.	-0.003	0.02
F. pennycress bio : W. Oat bio.	-0.02	0.09
Kochia bio. : G. foxtail bio.	0.02	0.02
G. Foxtail bio. : W. Oat bio.	1.25	0.09

Residual standard error: 1.819 on 23 degrees of freedom
Multiple R-Squared: 0.6842, adjusted R-squared: 0.5469
F-statistic: 4.984 on 10 and 23 DF, *p*-value: 0.0007, seeds transformed = seeds^{0.3}

Table C.5. Combined Neighbor Species Model for kochia transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	2.39	0.04
Neighborhood Species Richness	0.54	0.33
Neighborhood Density	0.04	0.82
Richness * Density	0.09	0.33

Residual standard error: 0.9379 on 21 degrees of freedom
Multiple R-Squared: 0.2692, adjusted R-squared: 0.1648
F-statistic: 2.579 on 3 and 21 DF, *p*-value: 0.081,
transformed dry biomass = dry biomass^{0.2}

Table C.6. Best Between Neighbor Species Model for kochia transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	3.13	<0.001
Neighborhood		
Spring wheat biomass	-0.03	0.01
Kochia biomass	0.0001	0.75
Wild oat biomass	0.031	0.36
Kochia bio. : W. oat bio.	-0.002	0.04

Residual standard error: 0.8916 on 20 degrees of freedom
Multiple R-Squared: 0.371, adjusted R-squared: 0.2452
F-statistic: 2.949 on 4 and 20 DF, *p*-value: 0.046,
transformed dry biomass = dry biomass^{0.2}

Table C.7. Combined Neighbor Species Model for green foxtail transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	1.41	<0.001
Neighborhood Species Richness	-0.13	0.16
Neighborhood Density	-0.03	0.35
Richness * Density	0.01	0.447

Residual standard error: 0.1508 on 15 degrees of freedom
Multiple R-Squared: 0.282, adjusted R-squared: 0.1384
F-statistic: 1.964 on 3 and 15 DF, *p*-value: 0.1628,
transformed dry biomass = dry biomass^{0.1}

Table C.8. Combined Neighbor Species Model for green foxtail number of seeds produced per target plant (2006).

	Estimate	<i>P</i> -value
Intercept	9656	0.14
Neighborhood Species Richness	-3638	0.25
Neighborhood Density	-391	0.74
Richness * Density	193	0.68

Residual standard error: 4754 on 12 degrees of freedom
Multiple R-Squared: 0.2183, adjusted R-squared: 0.0228
F-statistic: 1.117 on 3 and 12 DF, *p*-value: 0.3807

Table C.9. Combined Neighbor Species Model for green foxtail number of tillers per target plant (2006).

	Estimate	<i>P</i> -value
Intercept	38	0.06
Neighborhood Species Richness	-12	0.19
Neighborhood Density	-2	0.50
Richness * Density	0.8	0.55

Residual standard error: 15.43 on 15 degrees of freedom

Multiple R-Squared: 0.2213, adjusted R-squared: 0.066

F-statistic: 1.421 on 3 and 15 DF, *p*-value: 0.2758

Table C.10. Best Between Neighbor Species Model for green foxtail transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	1.09	<0.001
Neighborhood		
t ₁ Ratio	-3.26e-04	0.1
Spring wheat biomass	-2.51e-03	0.01
Field Pennycress biomass	1.67e-02	0.06
Kochia Biomass	1.24e-05	0.8
Green foxtail biomass	5.91e-03	0.001
Wild Oat Biomass	-2.87e-03	0.38
S. Wheat bio. : F. Pennycress bio.	5.83e-04	0.01
F. Pennycress bio. : Kochia bio.	-1.90e-04	0.11
F. Pennycress bio. : G. Foxtail bio.	6.91e-03	0.04
F. Pennycress bio. : W. Oat bio.	6.83e-03	0.04

Residual standard error: 0.07 on 8 degrees of freedom

Multiple R-Squared: 0.908, adjusted R-squared: 0.7929

F-statistic: 7.891 on 10 and 8 DF, *p*-value: 0.004,

transformed dry biomass = dry biomass^{0.1}

Table C.11. Best Between Neighbor Species Model for green foxtail number of seeds produced per target plant (2006).

	Estimate	P-value
Intercept	-813	0.37
Neighborhood		
t ₁ Ratio	-23	0.01
Spring wheat biomass	115	0.13
Field Pennycress biomass	-417	0.11
Kochia Biomass	8	0.29
Green foxtail biomass	290	0.004
Wild Oat Biomass	37	0.49
S. Wheat bio. : F. Pennycress bio.	42	0.14
S. Wheat bio. : Kochia bio.	-0.5	0.23
S. Wheat bio. : G. Foxtail bio.	888	0.29
F. Pennycress bio. : Kochia bio.	94	0.12
F. Pennycress bio. : G. Foxtail bio.	190	0.08
F. Pennycress bio. : W. Oat bio.	72	0.19
Kochia bio. : G. Foxtail bio.	-5	0.3

Residual standard error: 994.3 on 2 degrees of freedom

Multiple R-Squared: 0.9949, adjusted R-squared: 0.9614

F-statistic: 29.77 on 13 and 2 DF, *p*-value: 0.03295

Table C.12. Best Between Neighbor Species Model for green foxtail number of tillers per plant (2006).

	Estimate	P-value
Intercept	5	0.004
Neighborhood		
t ₁ Ratio	-0.08	<0.001
Spring Wheat biomass	-0.06	0.1
Field Pennycress biomass	-1	0.02
Green foxtail biomass	1	<0.001
Wild Oat biomass	-0.16	0.29
S. Wheat bio. : F. Pennycress bio.	0.02	0.04
F. Pennycress bio. : G. Foxtail bio.	0.43	0.01
F. Pennycress bio. : W. Oat bio.	0.79	<0.001

Residual standard error: 3.729 on 10 degrees of freedom

Multiple R-Squared: 0.9697, adjusted R-squared: 0.9454

F-statistic: 39.98 on 8 and 10 DF, *p*-value: 1.328e-06

Table C.13. Combined Neighbor Species Model for wild oat transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	2.48	<0.001
Neighborhood Species Richness	-0.26	0.31
Neighborhood Density	-0.07	0.55
Richness * Density	0.01	0.78

Residual standard error: 0.3219 on 18 degrees of freedom
Multiple R-Squared: 0.4297, adjusted R-squared: 0.3347
F-statistic: 4.521 on 3 and 18 DF, *p*-value: 0.01566,
transformed dry biomass = dry biomass^{0.2}

Table C.14. Combined Neighbor Species Model for wild oat transformed number of seeds produced per target plant (2006).

	Estimate	<i>P</i> -value
Intercept	2.07	<0.001
Neighborhood Species Richness	-0.14	0.38
Neighborhood Density	-0.01	0.84
Richness * Density	0.6e-04	0.97

Residual standard error: 0.196 on 18 degrees of freedom
Multiple R-Squared: 0.3251, adjusted R-squared: 0.2127
F-statistic: 2.891 on 3 and 18 DF, *p*-value: 0.06393,
transformed seeds produced = seeds produced^{0.3}

Table C.15. Combined Neighbor Species Model for wild oat number of tillers per plant (2006)

	Estimate	<i>P</i> -value
Intercept	19	0.06
Neighborhood Species Richness	-4	0.37
Neighborhood Density	-2	0.35
Richness * Density	0.5	0.5

Residual standard error: 5.264 on 18 degrees of freedom
Multiple R-Squared: 0.2717, adjusted R-squared: 0.1503
F-statistic: 2.239 on 3 and 18 DF, *p*-value: 0.1187

Table C.16. Best Between Neighbor Species Model for wild oat transformed dry biomass (2006).

	Estimate	<i>P</i> -value
Intercept	1.9	<0.001
Neighborhood		
t ₁ Ratio	-1.58e-04	0.15
Spring wheat biomass	-7.93e-03	<0.001
Field pennycress biomass	1.06e-02	0.04
Kochia biomass	-4.42e-05	0.76
Green foxtail biomass	2.73e-02	0.26
Wild oat biomass	-1.38e-02	0.003
S. Wheat bio. : G. Foxtail bio.	-4.04	0.18
S. Wheat bio. : W. Oat bio.	1.65e-01	0.15
F. pennycress bio. : Kochia bio.	-2.79e-04	<0.001
Kochia bio. : G. foxtail bio.	-1.38e-03	0.005
Residual standard error: 0.1749 on 11 degrees of freedom		
Multiple R-Squared: 0.8971, adjusted R-squared: 0.8036		
F-statistic: 9.594 on 10 and 11 DF, <i>p</i> -value: 0.0004,		
transformed dry biomass = dry biomass ^{0.2}		

Table C.17. Best Between Neighbor Species Model for wild oat transformed number of seeds produced per target plant (2006).

	Estimate	<i>P</i> -value
Intercept	1.8	<0.001
Neighborhood		
t ₁ Ratio	-7.98e-06	0.1
Spring wheat biomass	-3.9e-03	0.002
Field pennycress biomass	5.23e-03	0.13
Kochia biomass	3.18e-05	0.75
Green foxtail biomass	7.6e-03	0.65
Wild oat biomass	-5.01e-03	0.07
S. Wheat bio. : W. Oat bio.	7.81e-03	0.12
F. pennycress bio. : Kochia bio.	-1.83e-04	<0.001
Kochia bio. : W. Oat bio.	-6.18e-04	0.05
Residual standard error: 0.1247 on 12 degrees of freedom		
Multiple R-Squared: 0.8178, adjusted R-squared: 0.6812		
F-statistic: 5.986 on 9 and 12 DF, <i>p</i> -value: 0.0027,		
transformed seeds produced = seeds produced ^{0.3}		

Table C.18. Best Between Neighbor Species Model for wild oat number of tillers per target plant (2006)

	Estimate	<i>P</i> -value
Intercept	7.62	<0.001
Neighborhood		
t ₁ Ratio	-2.58e-05	0.19
Spring wheat biomass	-3.31e-02	0.15
Field pennycress biomass	4.05e-01	0.001
Kochia biomass	-1.26e-03	0.68
Green Foxtail Biomass	7.99	0.14
Wild Oat Biomass	-1.16e-01	0.29
F. Pennycress bio. : Kochia bio.	-2.33e-03	0.06
F. Pennycress bio. : G. Foxtail bio.	9.25e-01	0.14
Kochia bio. : G. Foxtail bio.	-6.03e-02	0.06
G. Foxtail bio. : W. Oat bio.	-5.74e-01	0.11
Residual standard error: 3.569 on 11 degrees of freedom		
Multiple R-Squared: 0.7954, adjusted R-squared: 0.6094		
F-statistic: 4.276 on 10 11 DF, <i>p</i> -value: 0.01252		

Table C.19. Combined Neighbor Species Model for field pennycress target RGR (g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	-0.03	0.45
Neighborhood Species Richness	0.02	0.13
Neighborhood Density	0.01	0.004
Richness * Density	-0.001	0.004
Residual standard error: 0.04875 on 60 degrees of freedom		
Multiple R-Squared: 0.1519, adjusted R-squared: 0.1095		
F-statistic: 3.581 on 3 and 60 DF, <i>p</i> -value: 0.01887		

Table C.20. Combined Neighbor Species Model for kochia target RGR (g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.09	<0.001
Neighborhood Species Richness	-0.002	0.71
Neighborhood Density	-0.001	0.12
Richness * Density	-0.0001	0.54
Residual standard error: 0.02822 on 60 degrees of freedom		
Multiple R-Squared: 0.1314, adjusted R-squared: 0.08801		
F-statistic: 3.027 on 3 and 60 DF, <i>p</i> -value: 0.03633		

Table C.21. Best Between Neighbor Species Model for kochia target plant RGR(g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.09	<0.001
Neighborhood		
Spring Wheat Biomass	0.001	0.49
Field pennycress biomass	0.01	0.34
Kochia biomass	-0.005	0.01
Green foxtail biomass	0.04	0.26
S. wheat bio. : F. pennycress bio.	-0.01	0.04
F. pennycress bio. : G. foxtail bio.	-0.18	0.03

Residual standard error: 0.02675 on 57 degrees of freedom

Multiple R-Squared: 0.2587, adjusted R-squared: 0.1801

F-statistic: 3.307 on 6 and 57 DF, *p*-value: 0.007

Table C.22. Combined Neighbor Species Model for green foxtail target RGR (g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.1	<0.001
Neighborhood Species Richness	-0.02	0.01
Neighborhood Density	-0.001	0.24
Richness * Density	0.0002	0.50

Residual standard error: 0.03103 on 46 degrees of freedom

Multiple R-Squared: 0.2456, adjusted R-squared: 0.206

F-statistic: 5.237 on 3 and 46 DF, *p*-value: 0.003

Table C.23. Best Between Neighbor Species Model for green foxtail target plant RGR(g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.07	<0.001
Neighborhood		
Spring Wheat Biomass	-0.01	<0.001
Field pennycress biomass	-0.03	0.001
Wild oat biomass	-0.08	<0.001
F. pennycress bio. : W. Oat bio.	-0.11	0.04

Residual standard error: 0.02288 on 45 degrees of freedom

Multiple R-Squared: 0.6037, adjusted R-squared: 0.5685

F-statistic: 17.14 on 4 and 45 DF, *p*-value: 1.31e-08

Table C.24. Combined Neighbor Species Model for wild oat target RGR (g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	1.39e-01	<0.001
Neighborhood Species Richness	-1.89e-02	0.12
Neighborhood Density	6.68e-06	0.99
Richness * Density	-2.47e-04	0.66

Residual standard error: 0.04005 on 49 degrees of freedom
 Multiple R-Squared: 0.247, adjusted R-squared: 0.2008
 F-statistic: 5.356 on 3 and 49 DF, *p*-value: 0.002858

Table C.25. Best Between Neighbor Species Model for Wild oat target plant RGR(g/g/day) (2006).

	Estimate	<i>P</i> -value
Intercept	0.09	<0.001
Neighborhood		
Spring Wheat biomass	-0.004	0.02
Green Foxtail biomass	-0.07	0.05

Residual standard error: 0.04202 on 50 degrees of freedom
 Multiple R-Squared: 0.1544, adjusted R-squared: 0.1206
 F-statistic: 5.566 on 2 and 50 DF, *p*-value: 0.01509

APPENDIX D:

R- CODE FOR CHAPTER 4 DATA ANALYSIS

2-Step Regression Analysis

The following code is an example using spring wheat as the target species.

Identical regressions were performed for each species. Ratio = t_1 ratio, neighwt = total neighbor biomass, swwt = weight of spring wheat neighbors, fpwt = weight of field pennycress neighbors, kwt = weight of kochia neighbors, gfw = weight of green foxtail neighbors, wowl = weight of wild oat neighbors.

Step 1:

```
lm1=lm(weight~richness+neighbors+richness*neighbors)
summary(lm1)
```

```
lm2=lm(seedweight~richness+neighbors+richness*neighbors)
summary(lm2)
```

```
lm3=lm(tillers~richness+neighbors+richness*neighbors)
summary(lm3)
```

Step 2, BIC Model Selection:

```
lm4=lm(weight~ratio+neighwt+swwt+fpwt+kwt+gfw+wowl+swwt*fpwt+swwt*kwt+swwt*gfw+swwt*wowl+fpwt*kwt+fpwt*gfw+fpwt*wowl+kwt*gfw+kwt*wowl+gfw*wowl)
```

```
step(lm4,k=log ###insert number of observations here### )
```

```
lm5=lm(seedweight~ratio+neighwt+swwt+fpwt+kwt+gfw+wowl+swwt*fpwt+swwt*kwt+swwt*gfw+swwt*wowl+fpwt*kwt+fpwt*gfw+fpwt*wowl+kwt*gfw+kwt*wowl+gfw*wowl)
```

```
step(lm5,k=log ###insert number of observations here###)
```

```
lm6=lm(tillers~ratio+neighwt+swwt+fpwt+kwt+gfw+wowl+swwt*fpwt+swwt*kwt+swwt*gfw+swwt*wowl+fpwt*kwt+fpwt*gfw+fpwt*wowl+kwt*gfw+kwt*wowl+gfw*wowl)
```

```
step(lm6,k=log ###insert number of observations here###)
```

ANOVA With Tukey-Kramer ProcedureSubsetting Richness Levels

```
rich1=subset( ## insert data frame here## ,rich=="1")
rich2=subset(## insert data frame here## ,rich=="2")
rich3=subset(## insert data frame here## ,rich=="3")
rich4=subset(## insert data frame here## ,rich=="4")
```

ANOVA of RGR by Species Within Richness Levels

```
aov1=aov(RGR~species,rich1)
summary(aov1)
aov2=aov(RGR~species,rich2)
summary(aov2)
aov3=aov(RGR~species,rich3)
summary(aov3)
aov4=aov(RGR~species,rich4)
summary(aov4)
```

Tukey-Kramer Procedure

```
### This function in R 2.2.1 corrects for unbalanced designs #####
```

```
TukeyHSD(aov1,which="species",conf.level=0.95)
TukeyHSD(aov2,which="species",conf.level=0.95)
TukeyHSD(aov3,which="species",conf.level=0.95)
TukeyHSD(aov4,which="species",conf.level=0.95)
```

APPENDIX E:

BIG SANDY MANAGEMENT INFORMATION

Table E.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	Frigstat with Honeybee rod	Frigstat 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"	3/4"	3/4"
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.