Weeds and Ground Beetles (Coleoptera: Carabidae) as Influenced by Crop Rotation Type and Crop Input Management

BY

SHAUNA MARIE HUMBLE

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Plant Science
University of Manitoba
Winnipeg, Manitoba

0-612-62758-6

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
*****
COPYRIGHT PERMISSION

WEEDS AND GROUND BEETLES (COLEOPTERA: *CARABIDAE*) AS INFLUENCED BY CROP ROTATION TYPE AND CROP INPUT MANAGEMENT

BY

SHAUNA MARIE HUMBLE

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

of

MASTER OF SCIENCE

ACKNOWLEDGEMENTS

I would like to acknowledge the following, for without you this thesis could not have been completed:

Dr. Martin Entz whose enthusiasm for sustainable agriculture has challenged me to consider the big picture. I have learned and improved many skills because of the time you have invested in me. I will always be grateful for the practical knowledge I have acquired.

Dr. Rene Van Acker and Dr. Neil Holliday, my supervisory committee, for taking the time to share with me the wealth of knowledge they each possess.

Keith Bamford for the incredible time and effort you have put into the Glenlea long-term cropping system study. I also thank you for challenging me to learn the production and practical areas of agriculture, and for keeping me on track when that data was overwhelming.

John Bullied and Dr. Gary Crow for the hours you spent helping me with my univariate analysis

Dave, Darren, Carla, Joanne, Anthony, Stuart, Simon, Brock, Andrea, Roberta, Jeff, Kim, Quinn, Amy, Tamara, Yvonne, Matt, and Cropping Systems Students for your help in collecting, preserving, separating and identifying the insects and ground beetles.

Julie, Brock, Simon, Roberta, Joanne, Andrea, and Angus for identifying and counting the many, many, many weed seedlings.

The graduate students I have met and friends I have made while studying at University of Manitoba. I will always be able to look upon my time in Manitoba with favour because of the great times we have shared together. I especially wish to acknowledge Delaney Ross, Melanie Couture, Quinn Holtslag, Jeff Hoeppner, Michelle DuCroix-Sissons, Jennifer Jacobs and Rajesh Ramarathnam for being the best buddies a girl could ask for.

The people of Fort Richmond Assembly whose thoughts and prayers have sustained me through the highs and lows experienced while completing my thesis. Thank you to God who has made all things work together for good (Romans 8:28).

Janya and David, my sister and brother, for always having a listening ear and being able to make me laugh in all situations.

My Mom and Dad for always believing in me. Your love, patience, strength, protectiveness, prayers and encouragement have made me who I am. I am truly blessed to have you for parents.

My fiancee, Angus Mellish, for your unconditional love. Thank you for the sacrifices you have made, the patience you have had and for always being on my side. Knowing you were there, thick or thin, lightened the load and made all things seem possible.

TABLE OF CONTENTS

Page

LIST OF TABLES

TABLES IN APPENDICES

LIST OF FIGURES

ABSTRACT

Humble, Shauna Marie. M.Sc., The University of Manitoba, June, 2001. Weeds and Ground Beetles (Coleoptera: Carabidae) as Influenced by Crop Rotation Type and Crop Input Management. Major Professor; Martin H. Entz.

Weeds and ground beetles are bioindicators of cropping system sustainability. In 1992, a study was initiated near Winnipeg to determine how cropping system diversity and input use affect populations of weeds and ground beetles, and the association between weed and ground beetle populations. Three, four-year rotations (rotation1 = annual crops only; rotation 2 = annuals plus one green manure crop; rotation 3 = annuals plus two year alfalfa hay crop) were subdivided into four subplots based on fertilizer (f) and herbicide (h) use (all four combinations: f+h+, f+h-, f-h+, f-h- in each rotation type). A prairie grass system was included in each of three replicates. A common test crop (flax [*Linum usitatissimum* L.]) was seeded in all plots at the end of each rotation cycle (1995; 1999). Plant growth, crop yield, weed and ground beetle diversity, weed populations and ground beetle activity, were assessed each year and subjected to univariate analysis. Weed populations and ground beetle activity for 1995 to 1999 were analyzed using multivariate redundancy analysis (RDA).

In 1995, crop and total dry matter (DM) were significantly greatest in the f+h+ subplots. Weed DM was significantly affected by rotation, and crop input, and there was a rotation X treatment interaction. Weed DM was highest in f+h- treatments and lowest in f-h+ for all rotations, with greatest overall weed DM occurring in the f+h- subplot of rotation 1. Grain yield was significantly greater in f+h+ system than other crop input systems. Total weed population density was significantly different between rotations, with the highest densities occurring in rotations 1 and 2. Total ground beetle capture was greatest in the f+h- and f-h-

crop input systems. Weed and ground beetle diversity and evenness were not significantly affected by rotation type or crop inputs. In 1999, crop input system significantly affected crop, weed and total DM. Crop DM was greatest in f+h+ subplots, weed DM was greatest in the f+h- subplots and total DM was greatest in both the f+h+ and f+h- subplots. Crop yield was significantly influenced by herbicide use, as the highest yields occurred in f+h+ and f-h+ subplots. Weed diversity and density were assessed 3 times over the 1999 cropping season; pre-seeding, pre in-crop spraying and pre-harvest. Weed total population was significantly influenced by crop inputs at all 3 populations assessments, but influenced by rotation only at the pre in-crop spraying assessment with the highest weed densities occurring in annual crops rotation. Greatest weed densities occurred in the f+h- subplots at each weed population assessment. Shannon-Weiner and Simpson diversity indices for weeds were significantly influenced by crop rotation at the pre-seeding and pre in-crop spraying assessments with greatest diversity occurring in rotations 1 and 3, and rotation 2 and 3, respectively. Shannon's and Simpson's indices were significantly influenced by crop inputs at the pre-harvest assessment with greatest diversity in f-h- and f+h- systems. Ground beetle capture was greatest in rotation1 > rotation 2 > rotation 3. For crop input systems, ground beetle capture from greatest to least was f+h- > f-h- > f+h+ and f-h+. Ground beetle diversity was not significantly affected by rotations or crop inputs.

The RDA's for the weed population indicated rotation 1 was associated with green foxtail, rotation 2 was associated with stinkweed and Canada thistle and rotation 3 was associated with dandelion. Wild buckwheat, lady's thumb, redroot pigweed, green foxtail, wild mustard, lamb's quarters and Canada thistle were associated with either the h- or the combined h- and f+ environmental variables. The RDA's for the ground beetle activity indicated that although ground beetle community composition was influenced by crop rotation, the effect of rotation on ground beetle species community composition was not consistent. The majority of beetle species were associated with the f+ and h- systems.

The datasets for weeds and ground beetles were combined to assess associations between weeds and ground beetles. All weed and ground beetle vectors fell between rotations 1 and 3 on the ordination biplot, somewhat associating with f+ and h-. Four consistent associations existed between weed and beetle species in 1995 and 1999. These included *H. pensylvanicus* and redroot pigweed; *A. carinata* and stinkweed; *A. placidum* and *C. calidum*, and wild mustard.

It was concluded that cropping systems diversity is key to stabilizing yields, reducing use of, and thereby expenses for, external inputs, and managing populations of weeds and ground beetles.

1.0 INTRODUCTION

Agricultural cropping systems have often limited biological and system diversity through the replacement of natural diversity with a small number of cultivated plants (Altieri, 1994) produced using similar farming practices for successive years. As a result, cropping systems become fragile, requiring external inputs, such as herbicide and fertilizer, to maintain stability and to produce a satisfactory yield. However, the continuous use of external inputs can result in reduced profit and undesirable ecological effects.

One of the goals of a sustainable cropping system is to utilize natural physical, biological and ecological processes (Paoletti et al., 1989), such as weed suppression through crop canopy closure or pest management by beneficial insects. If the concept of sustainable agriculture is to be applied, it must be put into practical alternative systems which meet the needs of farmers (Altieri, 1994). Thus, there is a need to assess the biological performance of various practical cropping systems and to study the effects of external fertilizer and herbicide inputs on cropping system sustainability.

The study of whole cropping systems, rather than the individual components of cropping systems, is required to better understand long-term cropping system sustainability and how the interactions of cropping system components affect connected communities, such as weeds and ground beetles (Coleoptera: Carabidae).

In addition to looking at the whole cropping system, it is often necessary to conduct studies over the long-term. The short term dynamics of a plant community following disturbance differ greatly from the long-term dynamics following disturbance, and are also different in the short and long term equilibrium effects of the same disturbance (Tilman, 1986). Descriptive data obtained in various years of field research should reflect the various processes and interactions that take place in the real world (Fernandez-Quintanilla, 1988). For example, long-term cropping system studies allow for the assessment of developing residual weed populations under various crop management techniques (Legéré et al., 1996). Another example is that changes in ground beetle abundance and community structure may manifest themselves slowly over many years (Clark et al., 1997). Contradictory results which exist in the literature concerning ground beetle populations may be a result of short term effects after the establishment of an experimental treatment or system differing from long-term effects after the ground beetle populations have reached an equilibrium. The disadvantage of long-term studies is that they require many years of field work, and the effect of specific factors cannot be isolated thereby resulting in low predictive value (Fernandez-Quintanilla, 1988).

The Glenlea rotation study is the longest running cropping systems study in Manitoba and is unique in Canada since it was established to determine the effects of both fertilizer and pesticide on cropping system sustainability. In the present study, the Glenlea long-term cropping systems study was used to address the following objectives:

1. To determine the effect of rotation and crop inputs on crop productivity and yield

2. To determine the influence of three different crop rotations and, external fertilizer and herbicide inputs on weeds

3. To determine the influence of three different crop rotations, and external fertilizer and herbicide inputs on ground beetles

4. To identify associations between the ground beetle and weed communities.

2.0 LITERATURE REVIEW

2.1 Cropping Systems

2.1.1 Progression of Weeds and Cropping Systems

In comparison to evolutionary and geological time scales, the period of agriculture is short, having existed for a maximum of 10,000 years (Young and Evans, 1976). As agriculture has become more technologically dependent, increased energy from inputs such as pesticides, fertilizer and mechanical energy, have been required to support increased productivity (Swanton and Murphy, 1996). Weeds are secondary successional plant species whose pressure increased in response to the manipulations in the physical environment necessary for crop production (Dekker, 1997; Young and Evans, 1976).

Prior to World War II, weeds were controlled through crop rotation and mechanical cultivation (Edwards and Regnier, 1989). In 1947, the first modern weed killer, 2,4-D, became commercially available for control of broadleaved weeds in monocotyledonous crops (Hay, 1968). By 1967, 70% of the prairie cereal crops were sprayed with 2,4-D or MCPA. Species shifts as a result of herbicide use have occurred and some weeds appeared to be more numerous than prior to the use of herbicide control measures.

The increased use of nitrogen (N) fertilizer in the last 50 years has been cited as the reason for decreased diversity of weeds observed in farm fields (Jornsgard et al., 1996). Tilman (1987) found plant species richness to decrease along an increasing N nutrient gradient in Minnesota. Dominant species within the high-N treatments were less abundant in low-N treatments. For example, the absolute abundance of quackgrass (*Agropyron repens* (L.) Beauv.) increased with nitrogen. By the final year of the study, quackgrass contributed 90% of the total biomass across treatments.

In previous decades, it was viewed that weed populations, even at light infestation, should be treated with herbicides "on a regular basis to prevent build up of weed populations" (Hay, 1968). Use of the same herbicide or herbicides with similar modes of action applied in successive years will impose selective pressure for increased tolerant and resistant weed species (Altieri and Liebman, 1988; Chancellor, 1979; Coble, 1996; Hallgren, 1996; Sibuga and Bandeen, 1980). To combat a buildup of resistant weed species, a new supply of chemicals would be made available (Hay, 1968). Although new herbicide products continue to be marketed, the majority of these represent a small number of modes of action, with few novel modes of action being introduced (Coble, 1996; Powles et al., 1997). Exclusive reliance on a single, highly efficient control method, chemical or nonchemical, fails to recognize the evolutionary process which has lead to resistant weed populations. Using combinations of crop rotation, seeding date, non-selective herbicides, high crop seeding rates, vigorous crop growth and capture of weed seed in the harvest operation have been effective in controlling herbicide-resistant weeds (Powles et al., 1997).

2.1.2 The Shift to Integrated Cropping Systems

In 1986, Chancellor and Froud-Williams predicted that a reduced profit margin would lead to reductions in crop inputs in the United Kingdom. In 2001, Manitoba grain producers will pay an average of $67/ha for fertilizer plus $50/ha for pesticides (Manitoba Agriculture, 2001). With costs greater than returns, conventional farming is often uneconomical, therefore economics were forcing farmers to consider fewer chemical inputs (Dietz, 1993). Increasing environmental awareness, within the rural and urban communities and among farm managers, is a second factor that has stirred interest in decreasing herbicide use and implementing alternative forms of agriculture (Forcella et al., 1993). The challenge in modern agriculture is to produce an economical crop yield while preserving local, regional and global sustainability (Altieri,1994).

The focus of sustainable agriculture is on understanding how factors within the cropping system interact and respond. The objective is to optimize, not maximize the system as a whole (Altieri, 1994; Swanton and Murphy, 1996). The concept of sustainable agriculture utilizes natural physical, biological and ecological processes to provide long-term yields (Altieri, 1994; Paoletti et al., 1989) thus decisions are made based on ecological processes rather than strictly on economics (Vandermeer, 1995). Themes surrounding sustainable agriculture include environmental quality, renewing resources, food safety, technology assessment, economic feasibility, and the enhancement of life in rural and urban communities (Swanton and Weise, 1991). It must be recognized that no factor within the system exists in isolation (Swanton and Murphy, 1996). Agricultural research must shift from the goals of short term productivity and efficiency, and move toward food production as a social process (Swanton and Weise, 1991).

In the last two decades, various sustainable system approaches to cropping have been developed, including reduced herbicide use, integrated pest/weed management (IPM and IWM, respectively), pesticide free production (PFP) (Van Acker at al., 2001), and organic farming. For example, in an attempt to reduce and optimize herbicide use in Greece, Skorda et al. (1995) determined the effect of herbicide application in wheat (*Triticum aestivum* L.) in four subsequent wheat crops. Yields tended to increase in the year following application. In subsequent years yields declined but remained greater than those in untreated plots. A dramatic decline in wild oat (*Avena fatua* L.) numbers took place over the last three years of the study. Applying herbicides once in five years was both more cost effective and environmentally friendly than annual application.

Vandermeer (1995) indicated that the principle foundation of IPM was not to use pesticides unless necessary and to manage the ecosystem in such a way that pesticide use does not become necessary. IWM is used as part of this strategy (Shaw, 1982). IWM methods utilize plant breeding, fertilization, rotation, competition, successional management, and soil management methods (Swanton and Murphy, 1996; Swanton and Weise, 1991) but was developed from a relatively specific emphasis on chemical and mechanical weed control into a method for reducing weed interference while maintaining acceptable crop yields (Van Acker et al., 2001). IWM has been supported by research but has had poor adoption by producers (Norris, 1992).

The development of diverse and biologically robust cropping systems less susceptible to weed invasion, proliferation and interference may be the best approach to IWM (Van Acker et al., 2001). Low chemical use cropping systems require a much better understanding of an agroecological system, particularly since biological inputs must displace inorganic chemicals (Edwards and Regnier, 1989). Pesticide Free Production is a producer focussed IPM approach to cropping which was developed in Manitoba. Van Acker et al. (2001) estimated a net gain of $100 million per year from Manitoban farms if 20% of their acreage was PFP, assuming increased returns of $50/ha and reduced input costs by $50/ha.

Organic farming is a systems approach which does not use synthetic inputs to control pests or augment production. During the transition from conventional to organic cropping, many farmers find weeds the biggest concern (Macey, 1992). The farmer does not expect entirely clean fields, but sees the farm as an ecological system that has a diversity of plants with the crop as the dominant species Weeds are only considered a problem if they reduce yields or cause difficulty in harvesting.

2.1.3 Cropping Systems and Ecological Theory

Determining the response of ecological communities to disturbances can help predict the likely response of the community to future perturbations (Tilman and Downing, 1994). There are three aspects of stability that can be studied: 1) resilience and resistance, 2) local and global stability, and 3) fragility and robustness (Begon, 1990; Tilman and Downing, 1994). The resilience of a community is the speed at which it is able to recover from a disturbance, whereas resistance is the ability of the community to withstand disturbance. Local stability describes the communitiy's ability to return to the original state after undergoing a small disturbance, whereas global stability describes the communitiy's ability to return to the original state following a large disturbance (Begon, 1990; Kenkel, 1999, Personal Communication). Stability depends on the environment in which the community exists, and the density and characteristics of component species. A community is considered fragile when it can only exist under a narrow range of environmental conditions or for only a limited range of species. A robust community is one that can exist under a wide range of characteristics and conditions. For example, in a robust cropping system the variance of crop productivity, grain yield, weed populations and beneficial insect activity between systems which utilized or did not utilize external crop inputs, such as herbicide and fertilizer, would be minimal. However, in a fragile cropping system the crop productivity, grain yield and beneficial insect activity would be significantly reduced in the absence of external crop inputs, while weed populations significantly increased. As a result, cropping system stability in a fragile system would be dependent on external crop inputs.

A persistent idea among agroecological researchers is that the cropping system should mimic the functioning of non-managed ecosystems, with tight nutrient cycling, vertical structure and the preservation of biodiversity (Vandermeer, 1995). Biodiversity is often limited in agriculture because domesticated plant and animal species found in agriculture represent only a small fraction of the diversity found in a natural ecosystem, placing agriculture outside the governing rules of natural ecosystems (Cussans, 1996; Young and Evans, 1976). With massive disruptions, agriculture can be regarded as unstable, constantly representing a pioneer stage of community development (Cussans, 1996).

Intensification of crop production and use of herbicides has led to a rapid reduction in weed diversity on cultivated land (Bischoff and Mahn, 2000; Chancellor and Froud-Williams, 1986; Johnson and Coble, 1986). The surviving species are, however, present in greater numbers. For example, between 1961 and 1991 in Argentina, only a few economically important weed species increased in constancy, composing 20 and 50% of the community in 1961, to more than 50% in 1991 (Ghersa et al., 1996). By contrast, Ogilvy et al. (1996) found that the number of weed species increased as chemical inputs were reduced.

There are two well-debated theories on the influence of diversity on stability of an ecological community. The first, the species-redundancy hypothesis, contends that many species within the ecosystem are so similar that functioning of the ecosystem is independent of diversity, if major functional groups are present (Tilman and Downing, 1994). Conversely, the diversity-stability hypothesis affirms that a diverse cropping system is able to resist disturbance and recover more quickly following a disturbance because there are more individuals and species available to fulfill various functional roles. Ewel et al. (1991) demonstrate the diversity-stability theory in the following example. An investigation into the changes in nutrient availability during the early phases of tropical succession on volcanic soils following forest felling and burning disturbance was conducted in Costa Rica. Soil fertility loss was greatest in monoculture blocks after 5 years of study. The loss was attributed to exposed soil in open patches within the monoculture resulting in nutrient loss. On the other hand, the species-rich successional plant community was able to combat erosion through plant diversity. Where one plant species left a space, another would colonize and occupy it, thereby preventing exposed soil and nutrient loss. Tilman and Downing (1994) found that species-rich grassland in Minnesota had greater drought resistance and attributed this to the presence of drought resistant species within the plant community. In addition, the highly diverse plots had greater resilience than the species-poor plots.

Higher species diversity leading to stability is a theory which must consider the complexity of the community (i.e., the number of ecological connections between organisms in the community), compartmentalization (i.e., there may be many compartments within an ecosystem, each having a high degree of connectivity within the compartment but not between compartments), and time. Time is important because, in a cropping system, relationships between species in a community may not have enough time to attain stability (Clements et al., 1994).

Stability in a system does not ensure pest suppression below an economic threshold level (Clements et al., 1994). Weeds and arthropods are able to adapt to control measures. In order to preserve control measures, spatial and temporal diversification of agricultural systems are necessary (Jordan and Jannink, 1996).

2.2 Biodiversity, Weeds and Cropping Systems

2.2.1 Biodiversity

Biological diversity, or biodiversity, is defined at many scales including genetic, somatic, spatial, temporal, species and trophic levels (Dekker, 1997; Swanton and Murphy, 1996). In cropping systems, biodiversity is most often seen as the heterogeneity among, and within plant species (Dekker, 1997).

Plant competition is a determinant of biodiversity in a habitat. For example, plant competition for limiting resources predicts that the plant community will have maximal diversity in moderately resource poor habitats (Swanton and Murphy, 1996; Tilman, 1986; Tilman and Downing, 1994). Tilman (1986) has explored the effects of interspecific competition for resources on biodiversity extensively. He defines interspecific competition as competition for limiting resources which can increase growth rate and population density of one species while leading to a decrease in the growth rate and population density of a second species. Tilman (1982) proposed the differential resource utilization model, where both the species and the resource must be known.

Tilman's differential resource utilization model first defines a niche boundary for species by utilizing two essential resources to determine combinations which either allow or disallow species survival and reproduction. Since the population size is considered a constant, it is necessary to establish where resources remain constant. As the species depletes essential resources through consumption, it moves closer to the boundary where it cannot survive, however, resources are constantly renewed and strive to reach a supply point (combination of levels of the two resources present when no consumption occurs) (Begon et al., 1990; Tilman, 1986).

Tilman's model of differential resource utilization can be used to predict the number of species that can coexist at equilibrium, thus it is thought that the number of species = the number of limiting resources. This is not often the case because of spatial heterogeneity in ecosystems. As a result different plants experience a different resource supply, depending on where they are located, thus more species coexist than predicted by this model (Begon et al., 1990; Tilman, 1986).

Weeds increase diversity in a cropping system by exploiting resources which are unexploited by the crop. Diversity ensures the occupation of a site, and allows weeds to exploit new and diverse opportunities in the cropping system (Dekker, 1997). Maintenance of vegetation diversity has also been suggested as means to reduce the magnitude of insect pest problems by supporting increased herbivore, predator, decomposer and detritovre insect species (Norris, 1992; Swanton and Murphy, 1996). Strategies and cropping practices that increase cropping diversity, such as crop rotation, herbicide rotation, tillage rotation and heterogenous crop populations, will reduce the niches and resources left available to weeds (Dekker, 1997).

2.2.2 Measuring Biodiversity

The concept of species diversity is generally accepted as a combination of species number (richness) and their relative abundance (evenness) (Tonhasca, 1993). Two communities with an identical number of species can differ in terms of evenness, thus it is useful to know the proportional or relative abundance of species within the community (Clements et al., 1994). Several diversity indices have been used to express both richness and evenness in a single value (Clements et al., 1994; Tonhasca, 1993). These include the Shannon-Weiner index (Shannon and Weaver, 1949), Simpson's index (Simpson, 1949) and alpha (α) of the log series index (Fisher et al., 1943).

The Shannon-Weiner diversity index indicates the predictability of correctly identifying the next species collected (Krebs, 1989). It is based on the proportional abundance of species and no assumption is made about the underlying species abundance distribution (Magurran, 1988). The index assumes that all species are represented in the sample, and is calculated as follows:

$$H' = -\sum p_i \ln p_i$$

where p_i is the proportion of individuals found in the ith species. Values for Shannon diversity index usually fall between 1.5 and 3.5, rarely exceeding 4.5. Error can result from failure to include all species from the community in the sample, thus it is sensitive to sample size (Krebs, 1989; Magurran, 1988). The Shannon-Weiner index should only be used on random samples drawn from large communities in which the total number of species is known, although this is rarely the case (Krebs, 1989).

Simpson's index is considered a dominance measure because of its affinity with the abundance of common species rather than species richness (Krebs, 1989; Magurran, 1988). Simpson's index measures the probability of two individuals drawn at random from an infinitely large community belonging to different species and is measured as follows:

$$D = \sum p_i^2$$

where p_i is the proportion of individuals in the ith species. The index values range between 0 to almost 1 (Krebs, 1989). As the value of D increases, diversity decreases (Magurran, 1988). When the number of species exceeds 10, the underlying distribution of species is important in determining whether the index is of low or high value.

The most popular of the parametric indices for diversity is the log series α index because of its discriminant ability and because it is relatively uninfluenced by sample size (Magurran, 1988). There is a consensus that this index is less sensitive to common species than Shannon's or Simpson's indices. The log series α measures how many species will be found in both data sets of two samples taken from the same community and how many species will be unique to one data set (Krebs, 1989). The number of species in a given area and the number of each species must first be determined. Often a single species dominates the population with other species being less numerous. This type of data is best fitted by a logarithmic series, which is a series with a finite sum whose terms can be written as a function of two parameters:

$$\alpha x, \alpha x^2/2, \alpha x^3/3, \alpha x^4/4, ..$$

where αx = the number of species in the total catch represented by one individual and $\alpha x^2/2$ = the number of species represented by two individuals, and so on. The sum of the terms in the series is equal to $-\alpha \log_e(1-x)$, which is the total number of species in the catch. We know the logarithmic series for a data set is fixed by the number of species and individuals in the sample, thus the relationship between them is:

$$S = \alpha \log_e(1 + N/\alpha)$$

where S is the number of species in the sample, N is the number of individuals in the sample and α is the index of diversity (Krebs, 1989). The disadvantage of the log series index is it is based purely on species richness and the number of individuals, thus it is unable to discriminate in situations where species richness and number of individuals remain constant but where there is a change in evenness (Magurran, 1988). However, the slope of the log abundance-rank plot, which is a transformation of what the series αx, αx^2, αx^3, is a measure of evenness associated with the log series, and has been suggested as a measure of evenness for insect communities (Southwood et al., 1979).

No one index has been adopted as the most appropriate or practical index of diversity and the choice depends on the data set (Clements et al., 1994; Magurran, 1988). Shannon's and Simpson's are widely used, however there is an increasing adoption of the log series α. A diversity measure should be chosen on the basis of its' ability to discriminate between sites, dependance on sample size, what component of diversity is being measured and whether the index is widely used and understood (Magurran, 1988). Diversity indices must be capable of detecting subtle differences between sites because diversity measures are often used to determine the effects of environmental stress on a community. In a Rothamsted insect survey, log series α, followed by Shannon's, were found to be the most discriminating diversity indices (Taylor, 1978). Independence from sample size is a criterion used in determining the effectiveness of diversity indices because as sampling area or number of samples increases, species richness increases (Magurran, 1988). Only when the data is corrected for sample size can two sites be compared.

Diversity will be affected by either rare species or common species, thus it is important to account for the biases toward species richness, evenness and dominance in diversity indices (Clements et al., 1994; Magurran, 1988). For example, Shannon's is most influenced by rare species, whereas Simpson's is most influenced by common species (Magurran, 1988). The biases reflect the difficulty of combining species richness and relative abundance into a single parameter (Clements et al., 1994). Generally, diversity indices concur with trends in species richness.

Community diversity values are most useful when they can be related to ecosystem processes and properties (Clements et al., 1994). For example, diversity indices for ground beetles may be misleading or redundant because of the insensitivity of these measurements to changes resulting from environmental stress (Clark, 1999). In such cases, species richness may be a more consistent indicator of ground beetle community change. This shortcoming of diversity measurement may decrease, however, with long-term sampling, which prevents short term variation in community structure or meteorological factors from obscuring differences in ground beetle diversity.

Biodiversity can be used as an indicator of cropping system performance. For example, species composition has been used as an indicator of N, soil pH or moisture conditions (deVries et al., 1996). In some situations biodiversity indicators are of limited value. For example, in parts of Europe, where weed comminutes are uniform, typically consisting of nitrophilous and shade tolerant species, the use of weed species diversity as a bioindicator is more restricted (Pysek and Lebs, 1991). Biodiversity is perhaps best used as an indicator of agriculture system sustainability because producers can then modify their cropping system according to the response of biological diversity to cropping system management practices (Swanton and Murphy, 1996).

2.2.3 Using Multivariate Ordinations to Analyse Cropping Systems

Multivariate ordinations are useful analysis tools because they "allow for comparisons between classifications to be made using all occurring species as variables in the analysis " (Ominiski, 1998). Multivariate analysis is well suited to detecting long-term changes in weed and insect populations because it organizes data for description, discussion, understanding and management of plant and insect communities (Benoit et al., 1992).

Pyšek and Lepš (1991) found the evaluation of the effect of fertilizer on the weed community difficult because of many mutually dependent relationships and nonlinear data. They overcame this challenge through the use of canonical correspondence analysis (CCA), which enables an evaluation of the influence of the environment on the composition of the community. CCA can be used for explanatory analysis and for testing hypotheses from controlled experiments. Derksen et al. (1996) indicated that research assessing weed community changes over time must provide information at both the species and community levels. Multivariate techniques, such as canonical discriminant analysis (CDA), were suggested as a provision of statistical information to compare plant communities in their entirety, and to generate biplots to determine associations between species and experimental factors. Clements et al. (1994) determined that principal component analysis (PCA) and CDA can be used to overcome density and frequency biases found in univariate analysis of weed communities because they analyse the community as a whole, thereby accounting for low occurrence species.

Redundancy analysis (RDA) is the canonical form of PCA which has been neglected by ecologists (Jongman et al., 1995). Similar to PCA, RDA attempts to explain variation of species data by fitting axes to the species. In both PCA and RDA, the axes are assumed to have a linear relationship with the species data and they are calculated on the basis of the strength of the relationship (Holliday, 2001, Personal Communication). RDA takes a step beyond PCA by minimizing total residual sum of squares while considering environmental variables (Jongman et al., 1995). A total residual sum of squares is taken to measure how poorly a particular environmental variable explains species data. The best environmental variable is the one which gives the smallest residual sum of squares. In short, RDA differs from PCA in that it constrains axes to have a linear relationship with the environmental variables, thus the RDA axes will explain less variance than PCA axes (Jongman et al., 1995). The relationship of environmental variables to each other is not necessarily linear and it is desirable that they are unrelated (Holliday, 2001, Personal Communication).

RDA is a regression method which measures the proportion of total variance of a given variable set which is predictable from a given canonical variate from another variable set (Kenkel, 2000, Personal Communication). RDA is a direct expression of the interrelatedness of the variable sets themselves. When similar trends exist in two data sets they can be used to predict one another.

RDA ordination diagrams can be interpreted as biplots. The species points and site points jointly approximate the species abundance data and the species points and variable vectors jointly approximate the covariance between species and environmental variables (Jongman et al., 1995). Vectors pointing in roughly the same direction indicate a high positive association, vectors crossing at right angles indicate zero correlation, and vectors pointing in opposite direction indicate strong negative association. Species that lie along or close to the vector of an environmental variable are thought to be positively associated with that variable. The further the species is from the centre of the ordination, the stronger the association with the environmental variables.

Monte Carlo tests are used in RDA to test the significance of environmental variables. The Monte Carlo test assumes a particular random process underlies observed data, or what would be the expected response if the null hypothesis were true (Kenkel, 2000, Personal Communication). It assesses the significance of an observed test statistic by comparing it with a sample test statistic obtained by generating random samples using an assumed model (Kenkel, 2000, Personal Communication; Manly, 1991). If the assumed model implies that all data orderings are equally likely, then a randomized test is used to produce a distribution of test statistics under a null hypothesis which are compared to the observed value of the null model distribution with.

2.3 Weeds

2.3.1 Weed Biology

> " The estimated average annual losses caused by weeds in the 58 commodities (surveyed) were $984 million, with losses of $372 million in Eastern Canada and $612 million in Western Canada. In Eastern Canada, approximately 50% of the total loss occured in hay crops and 33% in field crops, where as in Western Canada, 84% of the total loss occured in field crops" (Swanton et al., 1993)

Due to their negative impact on crop yields, weeds can be defined as plants growing where they are not wanted (Altieri and Liebman, 1988; Barden et al., 1987). A weed can also be defined as a plant whose virtues have yet to be discovered, implying that if a use for a weed can be found, it will no longer be considered a weed (Ross et al., 1985; Young and Evans, 1976). Although the ideal weed may not exist, definable characteristics of a weed include abundant seed production, rapid population establishment, seed dormancy, long-term survival of buried seeds, adaptations for spread, presence of vegetative reproductive structures and the capacity to occupy sites disturbed by human activities. Factors that will contribute to a successful weed include a fairly short innate dormancy of seed, requirement of light to germinate, ability of the seedling to establish at or near the soil surface, and a high relative growth rate under conditions of high N and shade (Chancellor and Froud-Williams, 1986). Seeds will be produced in large numbers and be effectively dispersed by wind or be difficult to clean out of grain, thus being replanted in the farmers field. Grassy weeds often have these characteristics, causing them to be some of the worst weed problems in cereal crops.

Van Acker et al. (2000) conducted a weed survey of Manitoba agricultural fields in 1997. The top 9 species, green foxtail (*Setaria viridis* (L.) Beauv.), wild oat, wild buckwheat (*Polygonum convolvulus* L.), Canada thistle (*Cirsium arvense* (L.) Scop.), redroot pigweed (*Amaranthus retroflexus* L.), wild mustard (*Sinapis arvensis* L.), smartweed species (*Polygonum lapathifolium* L. and *P. scabrum* Moench), perennial sow-thistle (*Sonchus arvensis* L.), and lamb's quarter (*Chenopodium album* L.), accounted for 72% of the total relative abundance.

In a cropping system, the coexistence of weeds and plants with different life cycle durations is a source of diversity (Dekker, 1997). The life cycle of a weed will determine its adaptability to a cropping system, and also the susceptibility of the weed to a control measure (Ross et al., 1985). There are three typical weed life cycles, each having certain control principles unique to each grouping. Annual weeds survive well on disturbed sites which have adequate sunlight, warmth, and time for germination, growth and maturation. These weeds are well adapted to annual cropping systems and open spaces in perennial crops (Ross et al., 1985), and are also found in non-agriculture environments (Altieri and Liebman, 1988). Annual weeds will complete their life cycle in one cropping season, and can be further sub-divided into summer annuals (grow simultaneously with spring planted crops, e.g. redroot pigweed), or winter annuals (grow simultaneously with winter annual crops, e.g. stinkweed (*Thlaspi arvense* L.)) (Ross et al., 1985).

Biennial weeds produce a rosette in the first year of growth and seed in the second year, thus completing their life cycle within a 24 month period (Ross et al., 1985). Although not well adapted to sites which are disturbed annually, they will persist in perennial crops. One example is biennial wormwood (*Artemisia biennis* Willd.), which is native to the northwest U.S. and common in the Great Plains (Whitson et al., 1996)

Perennials weeds are successful because of their alternative strategy of vegetative reproduction (Chancellor and Froud-Williams, 1986). Perennial weeds can be subdivided into categories of simple perennials and creeping perennials (Ross et al., 1985). Simple perennials, such as dandelion (*Taraxacum officinale* Weber in Wiggers), will require two or more years to establish and reproduce, thus becoming a problem in undisturbed perennial crops. Simple perennials will produce shoots and flowers close to the ground, and can therefore survive frequent mowing. Creeping perennials survive under a wide range of conditions as they can form independent plants from both vegetative reproduction and seed, becoming problematic in both annual and perennial crops. As well, the relatively robust growth habit of plants developed from vegetative propugales provides them with a competitive edge over plants that form from seed. Canada thistle is an example of a creeping perennial whose vegetative propagation is successful because of its horizontal roots (Moore, 1975). Canada thistle can survive winter and heavy frosts by utilizing stored food reserves, thus giving rise to an increased number of plants in succeeding years. Classification of weed species into commonly accepted categories of annual, biennial and perennial life histories is not always sufficient to predict the effect of crop rotation on weed populations (Ominski et al., 1999).

The effect of weed competition on crop yield varies between weed and crop combinations. For every unit loss in corn (*Zea mays* L.) yield due to interference from lamb's quarter, twice the number of green foxtail plants are needed to induce an equivalent level of yield reduction (Sibuga and Bandeen, 1980). Many annual weeds emerge in one or more flushes during the spring in temperate climates (Forcella et al., 1993). If a field is plowed when only 10% of non-dormant annual weeds seeds have germinated, 90% of the non-dormant weed seeds remain unaffected. As a result, the producer must still contend with 90% of the potential weed problem. These are usually controlled through post emergent herbicides, depending on the density of weed seedlings. Most arable fields contain a minimum of six weed species, while others may have 25 or more species (Cousens and Mortimer, 1995). For most species there is limited ecological data, both locally and globally.

2.3.2 Weeds as Influenced by Crop Rotation Type and Crop Input Management

2.3.2.1 General

> "Weeds are a problem because they can survive under the disturbed conditions created by man when he grows his crops" (Hay, 1968).

The presence of weeds alters the ability of the crop to withstand stress imposed by other pests (Norris, 1992). For example, competition from weeds can reduce the ability of alfalfa (*Medicago sativa* L.) to tolerate attacks by insects. Weeds infesting a crop must be managed or they can reduce crop yields, hinder harvest operations, and contaminate produce (Powles et al., 1997). Marketing strategies, pricing, ease of use and efficacy of herbicides, has promoted season long, weed free crop systems and farmers that become reliant on chemical herbicides (Altieri and Liebman, 1988; Powles et al., 1997). Few studies have considered diversity within agricultural communities as a weed management tool, mainly because suppression of both weed density and diversity has been the goal in cropping systems (Clements et al., 1994).

Successful farming requires the growth and yield of crop plants, while minimizing the growth and reproduction of weeds (Powles et al., 1997). At a low density, weeds do not affect yield and certain leguminous weeds, such as *Triponello polycersta* L. in northwest India, will stimulate crop growth by fixing N (Altieri and Liebman, 1988). Some weed species may be manipulated for use as beneficial cover crops (Clements et al., 1994). It may be possible to identify weed species that could play beneficial roles by simultaneously promoting biological control and competing with other weeds. It may be advisable from an insect control point of view, to not control a particular weed species because it serves as a resource for beneficial insects (Norris, 1992). It is therefore important to determine if a weed is harmful in a crop before stressing weed control (Altieri and Liebman, 1988).

The largest weed densities and species compositions are often associated with farms or fields that have a history of continuous cropping histories with high crop diversity (Thomas and Leeson, 1999). In the long-term, crop rotation is the primary factor affecting weed species composition in the seedbank (Ball, 1992; Swanton and Weise, 1991). Invariably, each cultural practice in a production system influences the competitive ability of both crop and weed communities, leading to a multitude of complex interactions (Swanton and Weise, 1991). Other factors influencing weed populations are the weather, degree of reduction of soil disturbance, method of straw removal (harvest technology), harvest time, seeding date, fertilizer regime, trends in herbicide usage and the crops grown (Chancellor, 1979; Chancellor and Froud-Williams, 1986; Hallgren, 1996; Swanton and Weise, 1991). Weeds are capable of significant adaptation to biological, mechanical, and cultural control measures, including herbicides (Jordan and Jannink, 1996). Changes in agricultural management practices alter the pattern of disturbance and produce changes in the weed plant communities (Ball, 1992; Blackshaw et al., 1994; Clements et al., 1994; Ghersa et al., 1996; Hay, 1968), as well as shifting relative abundance patterns, (Clements et al., 1994) and influencing the weed seedbank (Ball, 1992).

2.3.2.2 Crops and Crop Rotation

Ecological and agricultural selection pressures determine weed community dynamics by favouring some while and deterring others (Derksen et al., 1998). Types of selection pressure include climatic factors, allelopathic substances, predation, dormancy, crop rotation, crop, herbicide, seeding date, fertilization regime, and tillage system, among others (Altieri and Liebman, 1988; Dale et al., 1979; Derksen et al., 1998). Many researchers agree that the preceding crop is important in determining the number present and the diversity of the weed species (Tereshchuk, 1996). Derksen et al. (1993; 1996) found weather conditions had an important impact on the differences in weed communities, and that crop rotation had a greater impact on weed community than did tillage system (Derksen et al., 1996).

Crop rotation is a cultural weed control tool used to enhance management of weeds by utilizing differences in the morphology, physiology and production practices of the crop grown (Coble, 1996; Edwards and Regnier, 1989; Johnson and Coble, 1986; Weston, 1996). Crop rotation allows rotation of the herbicides used in the crop sequence, providing a broader spectrum of chemical control measures (Johnson and Coble, 1986), though recent developments of herbicide tolerant crops has reduced this option. Rotating crops, in addition to other weed management options associated with rotations, provides a means of preventing a buildup of high populations of weed species that may be highly adapted in monoculture systems (Coble, 1996). Crop rotation introduces conditions and practices not favourable for specific weeds, thus growth and reproduction of the species is hampered (Liebman et al., 1996; Sauerborn, 1996). Crops will compete against weeds through canopy development, crop architecture, life cycle, and allelopathy (Edwards and Regnier, 1989; Sauerborn, 1996).

Most fields will support multiple weed species associations capable of interfering with different crops (Coble, 1996).

Changing crops may eliminate one or more weed species closely adapted to a monoculture practice, but others will quickly invade and colonize on the site (Coble, 1996). The original weeds are often more competitive than other species in similar ecological niches, however secondary weed species can become dominant once the original species are controlled (Johnson and Coble, 1986). The new dominant species have potential for becoming serious problems due to difficulty of control, or to presenting problems other than yield reduction. Weed diversity has been shown to increase under crop rotations compared to monocultures, preventing the domination of a few problem weed species (Doucet et al., 1999).

In Belarus, weed infestation in barley (*Hordeum vulgare* L.) was highest following flax (*Linum usitatissimum* L.) and lowest following winter wheat (Tereshchuk, 1996). When annual grasses used for green forage preceded barley, there was a high but diverse weed population. In Indiana, rotations did not affect weed populations in barley, but reduced weed density in corn and soybean (*Glycine max* (L.) Merr.) rotations compared to monocultures (Legéré et al., 1996). In soybeans, density decreased as the length of rotation increased.

Green foxtail was the most abundant weed in continuous cropping plots in Swift Current, Saskatchewan (Hume et al., 1991). This weed was virtually absent in crop rotations that included fallow periods. Thomas et al. (1996) found weed densities to be higher in a continuous cropping system than in a cropping system which included fallow periods. As well, longer rotations which included a hay crop had different weed communities than shorter rotations without hay. Johnson and Coble (1986) observed the effect of crop rotation sequence when no herbicides were applied. The relative abundance of weeds was greatest in a corn emphasized rotation, followed by rotation containing soybeans or peanuts (*Arachis hypogaea* L.) for 2 of 3 years.

Blackshaw et al. (1994) found that hairy nightshade (*Solanum sarrachoides* Sendtner) was more prevalent when dry beans (*Phaseolus vulgaris* L.) were included in a rotation, while winter annual weeds dominated in rotations that included winter wheat. As well it was found that red root pigweed, a summer annual, was found at greater density in a wheat - lentil (*Lens culinarus* Medikus) or wheat-canola (*Brassica napus* L.) rotation versus a wheat-wheat or wheat-fallow rotation. Perennials appeared in low densities throughout the study. This was attributed to continuous disturbance. Hume (1982) found that stinkweed and redroot pigweed were the most abundant weeds in a wheat-fallow rotation while wild buckwheat was not influenced by rotation.

Over the long-term, factors such as rotation can induce weed species shifts, alter the competitiveness of the weed community, and influence the intensity of weed management required for suppression (Legéré et al., 1996). A negative aspect of crop rotation for some producers is that few economically viable alternative rotational crops exist (Coble, 1996). In the southern USA many farmers grow cotton (*Gossypium* sp.) because no other crop is available which will return close to the net profit of cotton on a significant acreage. As a result, cotton growers tend to grow crops in monoculture despite being aware of the benefits of rotation for pest management. In western Canada, profit margins for grain producers began to narrow in the mid 90's (Van Acker, 2001, Personal Communication). Canola was the only profitable crop, and with few alternatives, canola rotations intensified despite the knowledge of associated disease and insect problems. Currently, profitability of grain and oil seed crops, including canola, in western Canada is low.

2.3.2.3 Forage Legumes in Crop Rotation

Forage legumes promote the growth of subsequent crops; increase soil organic matter; improve soil fertility, aggregation, structure, workability, infiltration; reduce soil erosion; and provide feed for livestock (Entz et al., 2001a). The benefits to subsequent crops are attributed to the addition of N, and to non-N rotation factors such as disease and weed control, and improved water holding capacity (Sheaffer et al., 1989).

Sweet clover (*Melilotus* sp.) is a biennial crop that is used extensively in low-input dryland crop rotations (Entz et al., 2001b). In western Canada, sweet clover has been very successfully used as a summer fallow substitute, either as a cover crop or green manure plow down (Foster and Austenson, 1990). As a green manure it increases soil N by 50-70 kg ha^{-1} and increases organic matter and succeeding cereal grain yield. A disadvantage is the excessive depletion of soil moisture reserves associated with growing sweet clover; it can use 10-25% more water than wheat. When there is favourable rainfall, sweet clover as a green manure crop can equal succeeding grain yields under summer fallow conditions. It also maintains or improves grain protein compared to continuous wheat or fallow.

Alfalfa, the main perennial legume grown in western Canada, is most suited for longer term rotations where it is grown for herbage, seed and pasture (Foster and Austenson, 1990). Where moisture is not limiting, inclusion of alfalfa in a rotation on poorly structured soils or those in low inherent natural fertility is of particular benefit. Alfalfa improves soil tilth and water holding capacity when incorporated into soil (Sheaffer et al., 1989), reduces disease, weed and insect levels, increases soil organic matter, improves soil aggregation and water infiltration, contributes N to subsequent crops, thus improving yields, and is able to extract and utilize NO_3^- that has leached past the rooting zone of most annual crops (Entz et al., 2001a). The N contribution of alfalfa in Manitoba was 84, 148 and 137 kg N ha $^{-1}$ for 1-, 2-, 3–year old stands (Kelner et al., 1997).

In a survey of 253 Manitoban and Saskatchewan farmers, 83% of respondents indicated fewer weeds in grain crops following forages than in annual crop rotations (Entz et al., 1995). Good control was noted for wild oat, Canada thistle, green foxtail and wild mustard and weeds were suppressed for 1, 2 or more years. Many extension publications praise the competitive nature of the alfalfa plant. It has been stated that this competitive ability is sufficient to overcome weed problems (Bell, 1993).

Allelopathy refers to biochemical interactions among plants, including those mediated by microorganisms (Weston, 1996). Allelopathy is an important mechanism of plant interference mediated by the addition of plant produced phytoxins to the plant environment. Chemicals with allelopathic potential are present in virtually all parts of the plants and in most tissues, including leaves, stems, flowers, roots, seeds, and buds. Under appropriate conditions these chemicals may be released into the environment, generally through the rhizosphere, in sufficient quantities to affect neighbouring plants. Interference with weeds has been attributed to allelochemicals of sweet clover crops. They may be best used as living mulches rather than killed residues, to aid in weed suppression over time. Allelopathy in cropping systems was recently reviewed by Weston (1996).

In a double cropping system in which a green manure crop of crimson clover (*Trifolium incarnatum* L.) was followed by sweet corn, the crimson clover supplied N for the sweet corn as well as suppressed weed growth significantly, compared to an application of 45 kg ha^{-1} of N on sweet corn (Dyck and Liebman, 1995). Wetter areas have been observed to greatly benefit from forage in rotation through increased weed control and better yields (Entz et al., 1995).

In a comprehensive survey of weeds in wheat after alfalfa versus wheat in continuous grain rotations in Manitoba, Ominski et al. (1999) found that of the 10 most abundant weeds species in each of continuous cereal fields and alfalfa/cereal fields, seven species (mainly annual dicots) were common to both field types. However, the frequency and relative abundance of wild oat was significantly less when alfalfa was included in the cropping system, supporting previous research (e.g. Siemens, 1963) on the positive influence of forages in wild oat control. The density of wild mustard and members of the buckwheat family (*Polygonum* spp.) was reduced by the inclusion of alfalfa. Alfalfa was also found to suppress Canada thistle, however, densities of dandelion increased, attributed to the prostrate growth of dandelion, making it possible to avoid defoliation by mechanical harvest. Winter annuals, such as stinkweed, were a problem as they could germinate in the fall when alfalfa was dormant, and resume growth in the spring prior to establishment of a healthy alfalfa stand.

Forage systems can lower grassy and broadleaved weed densities by providing season long competition. A decline of wild oat at low and high densities over successive harvest dates in an annual forage system was reported by Schoofs and Entz (2000). Wild oat densities following forages were similar to, or lower than, the sprayed control plots under low and high wild oat pressure. Single-year alfalfa was less able to reduce green foxtail populations in the succeeding crop. Most annual forage systems tested displayed a weakness to at least one weed, usually broadleaved. An exception occured in systems containing winter triticale

(*Triticosecale*) or sorghum-sudangrass (*Sorghum bicolor* (L.) Moench x *Sorghum sundanese* [Piper]) as these provided weed competition for the entire growing season (Schoofs and Entz, 2000).

Widespread use of forage legume based crop rotations declined from the 1930's, coinciding with the development of the inorganic N fertilizer industry following World War II (Sheaffer et al., 1989). Farm enterprises also became less diversified, and forage legumes once used to feed livestock were not needed. Interest in the use of forage legume based crop rotations has revived in recent years because of increased emphasis on sustainable agricultural practices, and government cropland diversion programs. A reduction in wheat acreage resulting from the inclusion of legumes will allow more opportunity for cultural weed control either before seeding, during harvest or after harvest (Foster and Austenson, 1990).

2.3.2.4 Herbicides

Weed science often forms two assumptions: weeds always reduce crop yield and weed control always increases crop value (Bell, 1993). Herbicides often provide complete control of a wide range of weeds while causing little or no harm to the growing crop (Coble, 1996). Herbicide efficacy is often higher than other weed control measures. When properly selected, herbicides are economical, being a lower cost than any other control per unit land area. As well, the time requirement for herbicide use is significantly less than for other cultural control methods. There is an added flexibility of when and how a producer can best manage weeds. Herbicides reduce yield variability, are safe to applicators, pose no threat to food quality, and when appropriate chemical choices are made for the conditions present, do not cause environmental harm (Coble, 1996; Cussans, 1996).

In a long-term IWM study in Urbana, Illinois, Shaw (1982) provided striking evidence of the positive impact of chemical weed control on crop production. Herbicides significantly increased yields, reduced weed seeds in the soil, reduced need for tillage, improved harvesting efficiency, reduced labour requirements, and dramatically increased net farm profit without damaging biological, chemical or physical properties of the soil, and without causing undesirable shifts in weed populations. There was no evidence of any weed species becoming resistant to a specific herbicide in this study.

Prior to herbicide tolerant crops, herbicide choice was dictated by crop rotation (Ball, 1992; Blackshaw et al., 1994). As a result, weed seedbank composition was influenced by allowing a population increase of those species which were less susceptible to the herbicide in use, while decreasing the population of susceptible species (Ball, 1992). Research in Germany has indicated applications of herbicides over a 5 year time period lead to quantitative changes in the structure of weed flora (Mahn and Helmecke, 1979, as cited in Altieri and Liebman, 1988). The number of individuals and development of biomass differed, but species composition was relatively unchanged. In Ontario, species richness of weeds was found to be lowest in herbicide plots and greatest in weedy control plots (Doucet et al., 1999). Post-emergent herbicides may favour higher diversity because of the early emergence times of many weed species (Clements, et al., 1994). Initial species richness in a cropping system weed community is higher than when pre-emergent herbicides are used, and reduction in species richness is less following a post-emergent herbicide. Undoubtedly, the use of herbicides leads to shifts between and within species over time (Hallgren, 1996)

Interspecific selections by herbicides are suggested to be the one of the primary factors contributing to changes in weed flora composition (Altieri and Liebman, 1988), along with primary factors such as tillage practices and cropping systems (Derksen et al., 1996). Rotation of herbicides may select for formally uncommon species. For example, in the United Kingdom, *Lithospermum arvense* L. became more prevalent due to continuous use of urea based herbicides (Altieri and Liebman, 1988). If a susceptible weed disappears, a less susceptible weed may become more prevalent thus herbicides are more likely to change relative importance of a species than to alter the susceptibility of a species. Densities of secondary weeds, such as thymeleaf spurge (*Euphorbia serpyllifolia* Pers.) and hempnettle (*Galeopsis tetrahit* L.), are increasing through encroachment on to open areas in the cropping system previously occupied by dominant weed species, such as wild mustard (Martens, 2001, Personal Communication). Other examples were reported by Hay (1968).

Reducing herbicide use through reduced dosages (i.e. using low rates of application) has variable results on weed communities because it provides safe sites for weed germination and establishment, which are not present in more conventional systems (Clements et al., 1994; Ogilvy et al., 1996). Efficiency ranges from very effective to adequate. The residual levels of weeds following application would likely increase weed seed return and future weed problems, compared with full rate herbicide application (Ogilvy et al., 1996). The tendency towards increased diversity caused by reduced rates and non-residual herbicides may be compensated for with the use of broad spectrum control (Clements et al., 1994). Even the most intensive use of herbicides tends to alter proportional abundance rather than eliminate weeds.

In Poland, herbicides, in combination with appropriate land cultivation techniques, reduced total weed density from 253 plants m^{-2} to 189 plants m^{-2} within a five year rotation cycle (Stupnicka-Rodzynkiewicz, 1996). The main decrease occurred in the number of perennial weed species. There was also a marked difference in the weeds associated with each crop species. Proper use of tillage and herbicides has greatly reduced crop yield losses due to Canada thistle in Canada (Hay, 1968). Skorda et al. (1995) found that when herbicides were not used, the number of broad-leaved weeds decreases over time, but total density remains higher than in plots treated with herbicides once in five years. Herbicide treated plots had higher grain yield than untreated plots.

Herbicide use also results in herbicide tolerant weed problems. Use of the same herbicide or herbicides with similar modes of action applied in successive years will impose selective pressure for increased tolerant and resistant weed species (Altieri and Liebman, 1988; Chancellor, 1979; Coble, 1996; Hallgren, 1996; Sibuga and Bandeen, 1980). The result is a weed shift within and between species toward dominance by difficult to control weed species. For example, green foxtail was the first recognized as resistant to trifluralin herbicide, a group 1 herbicide, in Manitoba in 1988 (Morrison and Devine, 1994). Green foxtail has since developed resistance to multiple herbicide groups. In addition, other weed species, including wild oat, wild mustard, chickweed (*Stellaria media* (L.) Vill.), and Russian thistle (*Salsola iberica* Sennen), have developed herbicide resistance. Herbicide resistance is the greatest negative aspect of herbicide use (Coble, 1996). The evolution of herbicide resistance in weeds thus threatens the effectiveness of herbicides to combat weeds (Powles et al., 1997). Weeds also have other ways of tolerating herbicides, including post-harvest growth and development (Clements et al., 1994). If non-residual herbicides are used in place of residual herbicides, post-harvest growth may be enhanced. Diversity of weeds may provide a buffer against the development of herbicide resistance. If single species outbreaks are prevented, there will be less opportunity for resistant genes to be propagated.

2.3.2.5 Fertilizer

The weed community can be influenced both quantitatively and qualitatively by the use of fertilizer inputs (Hume, 1982; Pyšek and Lebš , 1991). Fertilizers may have three main effects on weeds: 1) N may stimulate germination of weeds 2) nitrophilous weeds could take advantage of increased applied N, while the populations of other weed species could be increased by phosphate (P) and potash (K) and 3) fertilizer may alter the competitive ability of weeds and crops, occasionally favouring the weed to the crops detriment (Chancellor and Froud-Williams, 1986; Pyšek and Lebš , 1991). If weeds escape control, selective forces favour nitrophilous species (Young and Evans, 1976).

Competition between weed and crop occurs when essential growth elements (water, light and mineral nutrients) are limiting (Bell and Nalewaja, 1968a; Bell and Nalewaja, 1968b). Increase in nutrient supply may increase the rate of growth of all species of plants, increasing the competition for light (Pyšek and Lepš, 1991). When competition reduces the availability of a factor necessary for plant growth, a crop yield reduction may occur (Bell and Nalewaja, 1968a; Bell and Nalewaja, 1968b). In a moderately weed infested crop, yield loss may be greater with fertilizer application versus no fertilizer, but the increased yield due to fertilization may override the yield loss effects. When weed populations are above economic threshold, any advantage fertilizer may have provided to a crop is eliminated and yields are reduced (Bowden and Friesen, 1967). Nitrogen fertilizer will significantly increase dry weight of weed herbage as the rate of application increases (Schreiber et al., 1978) unless soil organic matter is high enough at germination to saturate the need for external fertilizers (Fawcett et al., 1978).

Some ruderal plants may tend to become arable weeds because of there affinity for fertilizer. Fertilizer can alter the weed community composition, as increased leaf area of well fertilized crops may favor shade tolerant species (Chancellor and Froud-Williams, 1986). An awareness of fertilizer requirements of particular weed species would facilitate the design of fertilizer management systems that do not promote the more nutrient competitive members of weed communities (Clements et al., 1994).

Weed communities differed between three rotations (wheat-fallow, wheat-fallow-fallow, continuous wheat) when fertilizer was applied to plots in a Saskatchewan long-term rotation study (Hume, 1982). Fertilizer use increased the density and dry weight of green foxtail while decreasing the density of thymeleaf spurge and Canada thistle. Fertilizer did not increase the abundance of lamb's quarter, wild buckwheat and redroot pigweed, but did increase the mass of the plants. Interactions between weed species may have resulted in the unexpected result of reduced Canada thistle with increased fertilizer application. Fertilizer and rotation interactions affected weed communities, as adding fertilizers decreased differences between the weed communities of the three rotations.

The effect of N on the composition of weed communities was investigated in barley fields in Czechoslovakia (Pyšek and Lepš, 1991). Regardless of the type of fertilizer used, there was a significant decrease in the species richness, diversity and evenness when 70 kg of N ha^{-1} was applied versus no application.

Jornsgard et al. (1996) studied the effects of N fertilizer on the growth and density of natural weed populations in spring barley and winter wheat, in the absence of herbicide. They observed that an increased level of applied N did not enhance weed germination, tended to decrease the total weed biomass, and had a differential effect on the biomass of individual weed species in both crops. Seed production of weeds was positively correlated to plant size thus N applied in one year affected the seed production and seed pool for the years following. These results were attributed to those weed species which had lower N optima than the crop, e.g., lamb's quarter, thus competing for other resources in a more efficient manner. The authors further suggested that fertilizer usage can be exploited in an IWM system. By lowering the N applied to a crop, the majority of weed species are favoured within the cropping system and will ultimately change the composition of the weed population by increasing diversity.

Bischoff and Mahn (2000) found weed mortality to be higher in fertilized than unfertilized plots, even if surviving weeds had greater biomass and seed production. The high mortality increased the risk of extinction of smaller populations of weed species. Low growing weed species were shaded out in dense canopies and weeds that would normally benefit from higher N availability had minor chances to establish. Therefore, in this case, a large N supply had a negative effect on the regeneration of weed populations.

2.4 Ground Beetles (Coleoptera: Carabidae)

2.4.1 Biology of Ground Beetles

Ground beetles are the third largest family of beetles with more than 2000 known species occurring in North America (Borror et al., 1992; Thompson, 1977). Typical ground beetle communities within an cropping system have 80% of their total population comprised by four species. Tonhasca (1993) indicated that such species dominance suggested early succession in a community and felt it useful to determine the roles of the dominant species, as well as their relative abundance.

Ground beetles are non-specialized beetles, often regarded as beneficial insects due to their predaceous or omnivorous nature (Ellsbury et al., 1998; Lindroth, 1961-1969; Pavuk et al., 1997). Although few species feed on crop seeds and seedlings, they will consume other insects in all stages of life cycles, carrion and/or plant materials (Table 2.1). Ground beetles predate on a variety of insect pests (Borror et al., 1992; Clark et al., 1997; Theile, 1977; Tonhasca, 1993; Work et al., 1998). *Pterostichus melanarius* (Illiger) consumes carrot weevil (*Listronotus oregonensis* [LeConte]), and aphids (Homoptera: Aphididae) in sugar beets (*Beta vulgaris* L.) and cereal systems (Clark et al., 1997). *Poecilus lucublandus* (Say) consumes lepidopteran eggs and black cutworm (*Agrotis ipsilon* Hufnagel). *Agonum placidum* (Say) consumes lepidopteran eggs and larvae. *Amara* and *Harpalus* species are considered phytophagous (Hengeveld, 1980). *Harpalus pensylvanicus* DeGeer is primarily a seed eater with little potential as an insect predator (Tonhasca, 1993). *Harpalus* spp. feed on seeds of foxtail (Ellsbury et al., 1998). *Pterostichus lucublandus* Say, *Agonum cupreum* Dejean, *A. placidum*, *Amara apricaria* Paykull, *Amara avida* Say, and *Harpalus amputatus* Say ate viable eggs of *Euxoa ochrogaster* Gunée in laboratory trials (Frank, 1971). *P. lucublandus and H. amputatus* both attacked and killed fifth instar cutworm larvae.

Ground beetle morphology may vary according to their diet or environment (Borror et al., 1992; Theile, 1977). In general, there is little variation in ground beetle body structure. Species tend to be dark, shiny and somewhat flattened with striate elytra (Borror et al., 1992).

Table 2.1 Codes, scientific names, diet and habits of ground beetle species occurring in the Glenlea long-term cropping systems study from 1995 to 1999

Code	Scientific Name	Diet and Habits
AGON_CUP	*Agonum cupreum* Dejean	Able fliers. In North American fields have been observed feeding on Elateridae and Chrysomelidae and eggs of Anthomyiidae. *A. cupreum* will feed on ladybugs. *A. placidum* will feed on some Lepidoptera and their eggs, as well as maize kernels, slugs and pieces of ham.
AGON_DEC	*Agonum decentis* Say	
AGON_MAN	*Agonum mannerheimi* Dejean	
AGON_PLA	*Agonum placidum* Say	
AGON_PUN	*Agonum punticeps* Casey	
AGON_TRIG	*Agonum trigeminum* Lindroth	
AMAR_APR	*Amara apricaria* Paykull	Carnivorous larvae, adults feed on seeds, frequently of Cruciferae. Most of these *Amara* would feed on small seeds, and but not crop seeds. *A. apricaria* is omnivorous , feeding on other beetles, eggs of some Lepidoptera and grass seeds. *A. farcta* will feed on some species belonging to the fly or beetle families. *A. littoralis* will feed on dead flies and grasshopper eggs. *A. obesa* larvae eat grasshopper eggs
AMAR_AVI	*Amara avida* Say	
AMAR_CAR	*Amara carinata* Leconte	
AMAR_CUP	*Amara cupreolata* Putzeys	
AMAR_FAR	*Amara farcta* Leconte	
AMAR_LIT	*Amara littoralis* Mannerheim	
AMAR_OBE	*Amara obesa* Say	
ANIS_SAN	*Anisodactylus sanctaecrucis* Fabricius	Eats soil insects and weed seeds
BEMB_SPP	*Bembidion* spp	Eats insect eggs and small active insects
BRAD_CON	*Bradycellus congener* Leconte	Eats ladybugs
CALO_CAL	*Calosoma calidum* Fabricius	Eats large insects, e.g. caterpillars
CHLAE_SE	*Chlaenius sericeus* Forster	Very active flier, eats insects
CYMI_NEG	*Cymindis neglecta* Haldeman	In captivity, eats pieces of ham and apple
DICA_CAU	*Dicaelus sculptilis* Say	Feed on snails when studied in captivity
HARP_AMP	*Harpalus amputatus* Say	Larvae are carnivorous, adults feed on seeds, roots and insects. None of the species are know to damage crop plants. *H pensylvanicus* is very abundant near grasshopper egg beds, and many feed on the eggs; it is also known to feed on weed seeds.
HARP_ERR	*Harpalus erraticus* Say	
HARP_FUL	*Haraplus fulvilabris* mannerheim	
HARP_HER	*Harpalus herbivagus* Say	
HARP_PEN	*Harpalus pensylvanicus* DeGeer	
HARP_VEN	*Harpalus ventralis* Leconte	

PTER_COR	*Pterostichus corvus* Leconte	Primarily carnivorous. *P. corvus* and *P. femoralis* will eat grasshopper eggs and other soil dwelling insect stages. *P melanarius* eats larger insects, molluscs and earthworms; it is a European species that is well adapted to agricultural situations
PTER_FEM	*Pterostichus femoralis* Kirby	
PTER_LUC	*Pterostichus lucublandus* Say	
PTER_MEL	*Pterostichus melanarius* Illiger	
STEN_COM	*Stenolophus comma* Fabricius	An active flier that is omnivorous, and may eat germinating seeds of crops. Efficient predator of cabbage maggot immature stages

(Larochelle, 1990; Lindroth, 1961-1969)

Antennae are filiform, long and slender, and 11-segmented (Lindroth, 1961-1969; Theile, 1977). Ground beetles have strong mandibles which are more or less curved. The coxae of the hind legs are fused with the first abdominal sternites, which usually number six. Legs are slender, for running, with five tarsal segments. Most have reduced hind-wings, preventing some ground beetles from being good and able fliers (Lindroth, 1961-1969). Most ground beetles run fast on the ground or dig into the soil, and few are arboreal. Species of ground beetles may travel several metres a day. When studied it is important to have plots which surpass patch size threshold (Tonhasca, 1993), which is dependent on emigration rate of the insect as well as the perimeter:area ratio (Kareiva, 1985).

Ground beetles are commonly found under stones, logs, leaves, bark, debris or running along the ground (Borror et al., 1992). Factors determining location and habitat selection are highly diversified, often depending on abiotic factors. These include biotic food availability, macro-climate temperature, microclimate temperature, humidity and light, and soil conditions (Bommarco, 1998; Lindroth, 1961-1969; Work et al., 1998). It is not apparent whether the mutual dependence of factors on one another, combined action of all factors, the action of only some factors or action by one factor govern distribution (Theile, 1977).

Temperature plays a role in ecological and geographical distribution of ground beetles. An estimated 70% of ground beetles prefer temperatures between 15 and 20°C (Theile, 1977). A small percent prefer 30-40°C, with some dry grassland species preferring 40-50°C. Some alpine-subalpine species prefer temperature below 10°C. Baars (1979) found ground beetle activity would end earlier when weather was warmer throughout the ground beetle reproductive season, than if weeks of cold weather intervened.

The difference in ground beetle fauna may also correspond to ecosystem differences in habitat features that affect microclimate (Work et al., 1998). Humidity and moisture are some of the important factors governing habitat choice (deVries et al., 1996; Theile, 1977). The large majority of species from wet habitats prefer moisture, while the majority of species found in dry environments prefer dryness. Dense vegetation is a more favourable habitat for beetles due to the microclimate it provides (Kielhorn et al., 1999). This concurs with data sets from *Calluna*-dominated heaths of the North York Moors National Park in the United Kingdom (Gardner, 1991). Ordinations indicated vegetation and site wetness influenced ground beetle distribution.

Light is important in the daily activity of ground beetles as species which prefer the dark are night active, whereas light preferring species are day active and those species which are indifferent to light intensity are both day and night active (Theile, 1977). Forest ground beetles are usually night active, whereas field species are usually day or day and night active.

Soil characteristics are an important factor determining ground beetle habitat because of the development of larvae in the soil and the time spent by adults on or in the soil (Luff and Rushton, 1988). In upland grasslands undergoing pasture improvement, ground beetle diversity was related to the amount of soil disturbance experienced. Soil properties which may influence ground beetle distribution include soil pH value, sodium chloride and calcium content (Theile, 1977).

There is no generalized life cycle for ground beetles. In all temperate zones, ground beetles reproduce only once a year. The time of reproduction can be quite variable but according to Theile (1977), it is distinguished by 5 types of annual rhythms:

1) Spring breeders which have summer larvae and hibernate as adults

2) Species which have winter larvae and reproduce from summer to fall with no adult dormancy

3) Species with winter larvae, the adults emerge in the spring and undergo aestivation dormancy prior to reproduction

4) Species with flexible reproductive periods. Spring and fall reproduction can occur side by side in one population. Larvae develop well under winter or summer conditions. Time of reproduction varies according to climate and weather

5) Species which require more than one year to develop

P. lucublandus and *A. placidum* are considered spring breeders. *P. melanarius* is an autumn breeder which overwinters as larvae (Clark et al., 1997).

Several species have multi-year life cycles however the majority of those found in Manitoba which overwinter in agricultural habitats as adults, live for one year with a few living into the second spring (Holliday, 2001, Personal Communication). The females lay eggs in the soil or other dark, moist places one or more times a year (Dole, 1991). The larvae begin searching for prey shortly after hatching.

2.4.2 Ground Beetle Species Identification

The majority of work on ground beetle identification and biology of individual species has been conducted by C. H. Lindroth (1969). *Pterostichus* spp. are stout with short appendages varying in size between 4 and 28 mm. Their habitat variation is diverse with many hygrophilous (prefer humid denser vegetation), some are xerophilous (prefer less densely covered areas) living in open country such as prairie, or tundra. Some species are decided forest insects, while a few species are confined to living along running waters.

Agonum spp. vary in size between 4.2 and 16 mm (Lindroth, 1961-1969). The upper body is usually dark with a metallic reflection. The forebody is narrow with a broad elytra. The forebody and elytra are often contrasting in colour, with some species having bicoloured elytra. The antennae and legs are long and slender. *Agonum* spp. are hygrophilous, frequently occurring where vegetation is rich. A few species, such as *A. placidum* and *A. cupreum*, prefer open country and are almost xerophilous. Many species are able fliers.

Harpalus spp. vary from 5.8 to 25.5 mm in length (Lindroth, 1961-1969). *Harpalus* spp. have stout bodies, abroad thorax and short legs. Their colouring is dark with paler body margins and elytra sutures. Few species have a pronounced metallic lustre. *Harpalus* spp. are xerophilous, being most abundant in open dry country on sandy soil. Many of the species remain concealed during the daytime. *Harpalus* spp. select habitat similar to *Amara* spp., where there is an abundant food source of seeds and pollen.

Amara spp. are medium to large in size (Lindroth, 1961-1969). Ranging from 3.9 to 14.33 mm. *Amara* spp. are stout with a broad thorax and short legs, similar to the *Harpalus* spp. It is a difficult genus due to considerable individual variability displayed by the morphology of species. Despite this variability, all *Amara* spp. are xerophilous. Most occur in open country with sparse but tall vegetation, often with a pronounced weed type. *Pterostichus*, *Agonum*, *Harpalus*, and *Amara* spp. are common to Manitoba cropping systems (Holliday, 2000, Personal Communication).

2.4.3 The Use of Ground Beetles as Bioindicators

Bioindicator are organisms within an ecosystem which are sensitive to changes in the environment, and their populations are affected by disturbance. Ground beetles are excellent bioindicators of habitat perturbation (Dritschilo and Wanner, 1980; Kromp, 1989; Larsen et al., 1996; Work et al., 1998), such as nutrient enrichment, as some are sensitive to pollutants and the majority are highly selective of their habitat (Larsen et al., 1996). Their widespread occurrence in a broad range of ecosystems, and their well-known ecological demands are the basis for their value as bioindicators in monitoring environmental change (Kielhorn et al., 1999). Although many dominant arthropod species may be present in two ecosystems, observing the differences in the less abundant species may be a better indicator of the differences between the two ecosystems (Work et al., 1998). This should be interpreted carefully as ecological interpretations are limited to presence-absence statements. Rare species may be present but may be under-represented because of low occurrence and/or reduced activity compared with more dominant species.

The maintenance of maximum biological diversity within the cropping system is important as biodiversity is an index of the health of the cropping system (Cussans, 1996). In days past, coal miners would bring small caged birds into the pit. If and when the birds would die of asphyxiation, it was time to seek the surface. As agriculturalist, we can regard a healthy flora and fauna in the same manner. This index of health is also one that can be understood by the non-agricultural population.

2.4.4 Use of Pitfall Traps for the Study of Ground Beetles

Pitfall traps are the most widely used method for sampling assemblages of ground-dwelling invertebrates because of their convenience and cost efficiency (Cromar et al., 1999). It has been reported that pitfall trapping used for direct estimation of populations and to compare fauna of different sites must be considered critically (Cromar et al., 1999; Greenslade, 1964; Luff and Rushton, 1988). Catches by these traps depend on density, locomotor activity, a species ability to perceive the trap edge, size, climbing ability, mobility and ground cover. Faunal diversity is generally correlated with floral diversity thus it would be expected to find the highest number of ground beetle species in a highly diverse vegetation. Thomas and Marshall (1999) found that pitfall traps did not demonstrate this. The addition of a suction sample was able to show the expected correlation. The authors recommended that when sampling in different vegetation another sampling method, in addition to pitfall trapping, be utilized.

Work et al. (1998) confirmed that pitfall traps under-represented ground beetle faunas and the use of multiple trapping would increase inventories without requiring the survey of an additional site (Greenslade, 1964). Pitfall traps do not measure abundance of ground beetles, but rather activity density. If the habitat is densely vegetated, movement of ground beetles would be impeded. The catch of ground beetles in such a habitat would appear reduced compared to an open habitat, despite having similar total populations. An unfavourable habitat may elevate ground beetle activity increasing the total capture thus leaving a false impression of a favourable habitat (Baars, 1979). For example, in a sweet clover green manure-winter wheat rotation, catches may be reduced in the spring sown clover (Holliday, 2001, Personal Communication). Higher catches in the winter wheat could be attributed to a longer undisturbed period prior to trapping. These types of problems have led to wariness in using words such as activity, abundance, population and density in reference to data obtained from pitfall traps.

Pitfall traps lend themselves to large scale field collection with relatively little habitat disturbance (Terrell-Nield et al., 1990), however they tend to capture larger, more vagile ground beetles (Pavuk et al., 1997). Larger species can move easily between smaller plots, especially prior to weed vegetation becoming dense (Scheller et al., 1984). The studied plots were 18.3 m by 18.3 m with a 3.1 m boarder between plots. It is recommended that larger more spatially separated plots be used when studying ground beetle community structure in order to detect significant differences. Trap dimensions must be carefully considered. A trap without any attractive or repellent effect should capture soil surface animals approximately proportional to the diameter of the trap (Baars, 1979). A preservative and detergent should be used. Depletion effects are not of importance if trap intervals are more than 10m.Whole season trapping may relate closely to the actual density of ground beetles and does not under-represent short activity season species.

2.4.5 Ground Beetles as Influenced by Crop Rotation Type and Crop Inputs Management

2.4.5.1 General

The effects of individual management practices on ground beetles appear to depend on and interact with many other factors (Clark, 1999). These include site history, crop type, landscape characteristics, ground beetle community characteristics, and the specific combination of management practices used. Responses vary considerably with species, spatial and temporal scale, geographical location as well as unidentified variables (Hance et al., 1990). Spring disturbances, such as pesticide application, may detrimentally affect spring breeders more than autumn breeders because autumn breeders are usually not active on the soil surface at the time of application. Clark et al. (1997) reported that treatments receiving high inputs and conventional tillage had the highest levels of spring breeders' *P. lucublandus* and *A. placidum*. Spring breeders may be able to recolonise fields more easily after spring tillage.

Ground beetles have been found to be potentially important natural pest control agents in cropping systems (Clark et al., 1997). Consequently, the ability to conserve ground beetle populations and enhance their abundance in agricultural landscapes could lead to less reliance on therapeutic pest control measures. Organic methods of farming are generally considered to be less detrimental than conventional methods to predaceous and omnivorous arthropods, particularly to epigeic predators such as ground beetles (Clark, 1999; Kromp, 1989). Cover crops, manure and compost amendments, and avoidance of pesticides may conserve or promote predators in organic farming (Clark, 1999). In addition, elevated soil organic matter levels resulting from many years of organic management may enhance the detritus-based food web, resulting in greater predator abundance and/or diversity. Although organic matter is higher in reduced and no-till systems, and detrite levels are high, Carcamo (1995) captured a larger total ground beetle population in conventionally tilled plots than in reduced-tillage plots in central Alberta. However diversity and evenness of ground beetles species was higher in the reduced-till system attributed to higher vegetational diversity and greater structural heterogeneity. The capture of *A. placidum* in North Dakota was highest in annual cropped plots which had been conventionally tilled (Weiss et al., 1990). This was compared with no-till and reduced tillage plots under either continuous cropping, annual cropping or annual fallow, or conventional tillage under either continuous cropping or annual fallow.

Organically farmed (mechanical weed control, green manure or compost, no fungicides) wheat fields in Austria had higher numbers of ground beetle beetles than conventional farmed fields (Kromp, 1989). Of the 10 most abundant ground beetle species, five were common to both farm systems while the remaining five occurred frequently in organically farmed systems but were rare or absent from conventional farm systems. Organically farmed wheat crops were less homogeneous in density causing greater microclimate heterogeneity near the ground thus accommodating both xerothermophilic (prefer less densely covered areas) and hygrophilic (prefer humid denser stands) species. As well, increased weediness in the organic system provided nutrition for seed feeding ground beetle species, such as *Amara* and *Harpalus* (Cromar et al., 1999; Kromp, 1989).

Organic systems may provide better conditions for juveniles of spring breeders and adults of autumn bred ground beetles (Kromp, 1989). In a long-term comparison of four farming systems treatments to study agronomic, biological and economic aspects of conventional and alternative farming in California, the mean cumulative catch of ground beetles in the organic system was twice that of the conventional system, though not always significantly higher (Clark, 1999). The organic system had more beetles only after mid-season. Prior to this sampling time no differences in capture were observed. Species richness (the number of species) was similar between systems, although 6 of the 17 species collected were found only in the organically managed plots. There were no significant differences in diversity according to Shannon's and Simpson's indices. Similar findings have been recorded by Dritschilo and Wanner (1980) where the capture of ground beetles was compared on four pairs of conventional and organic farms (no pesticides or synthetic fertilizers). Organic farms had significantly higher capture of ground beetles, twice as many species, but diversity did not differ between systems when measured by the Shannon-Wiener index.

Distribution responses of ground beetles are a result of changes in microhabitat, affected by disturbances through physical and chemical stimuli (Tonhasca, 1993). Studies comparing agricultural management systems have typically shown that organic and low-input production systems are associated with greater ground beetle capture over conventional productions systems (Clark et al., 1997).

2.4.5.2 Crops and Crop Rotation

The status of the crop affects most species of ground beetles. Any factor, whether cultural, abiotic or biotic, which lengthens the growth period of the crop has potential to interact with all insects in the crop (Norris, 1992). Crop type will influence ground beetle abundance. The use of crop rotation and cover crops, therefore, tends to promote greater overall ground beetle abundance (Clark et al., 1997); however, the use of crop monoculture at the expense of plant diversity has seriously affected the abundance, diversity and efficiency of predator arthropods (e.g. ground beetles) closely linked to local habitats and plant diversity thus limiting their potential as pest control agents (Lys et al., 1994; Purvis et al., 1984). Insect diversity and abundance can be increased by raising the diversity and the area of non-crop vegetation (Thomas and Marshall, 1999)

The nature of the crop will influence the population size of ground beetles. In Ontario fields, a crop rotation of clover (*Trifolium* sp.) - clover- alfalfa was found to have few ground beetles (0.9 per trap per day) (Rivard, 1966). In a rotation of winter wheat-clover-winter wheat, peak catches occurred in seasons of winter wheat (1.9 and 1.7 per day per trap) with fewer individuals trapped per day (1 per trap per day) in seasons with clover. Trapping occurred between mid-May and late October, thus if the clover was spring seeded, the higher catch in winter wheat might result from a larger undisturbed period (Holliday, 2001, Personal Communication). Captures of ground beetles were highest in cereal crops, cultivated crops, legumes and pasture in decreasing order (Rivard, 1966).

Vegetative ground cover throughout most of the year, particularly in late summer, can influence ground beetle abundance (Clark, 1999). Although a dense vegetation often creates a favourable microclimate, a dense vegetation can impede ground beetle surface activity by increased habitat resistance (Kielhorn et al., 1999). Habitat resistance affects trapping efficiency. This may bring doubts to conclusions by Rivard (1966) concerning higher captures in cereals (Holliday, 2001, Personal Communication).

The inclusion of perennial crops and forages influences the species of ground beetles present in the cropping system. In California, the capture of *P. melanarius* increased in the second year of a perennial alfalfa hay crop. *P. lucublandus* and *A. placidum* were collected in similar numbers from annual crops of wheat, corn and soybean (Clark et al., 1997). The largest captures occurred in legume and barley plots under organic management and no tillage. Similar findings occurred in South Dakota, where *P. lucublandus* was the dominant species in a wheat crop of a corn-soybean-wheat under seeded to alfalfa-alfalfa plot (Ellsbury et al., 1998). Diversity, as measured by Shannon-Weiner Index, relative diversity and hierarchical richness index of ground beetles was higher in corn and soybean crops than in wheat and alfalfa crops . In Sweden, the inclusion of annual and perennial crops within a rotation increased landscape heterogeneity, providing alternative resources for insect reproduction, food, refuge and overwintering for ground beetles moving between these habitats (Bommarco, 1998).

2.4.5.3 Herbicides

Herbicides decrease plant diversity leading to a decrease in alternative food sources for ground beetles (Bommarco, 1998), and reduced diversity and abundance of farmland arthropods (Thomas and Marshall, 1999). These effects may propagate up the food chain to affect higher trophic levels in the cropping system, including a decline in abundance and range of farmland birds.

Systems that reduce or eliminate pesticides promote greater overall ground beetle abundance (Clark et al., 1997). Management practices to mitigate damage from one type of pest (e.g. weeds) may have direct effects on another type of non-target organism (e.g. ground beetles) (Norris, 1992). Herbicides may affect populations indirectly, as reduced foliage increases surface temperatures and decreases soil moisture resulting in an unfavourable habitat (Brust, 1990). Arthropod density in weedy fields was found to be up to three times greater than in weed free fields in a 1970's study of cereal ecosystems in West Sussex, England (Potts and Vickerman, 1974). The relative proportion of *H. pensylvanicus* and diversity of ground beetles was greatest in low input plots attributed to habitat preference for a weedier environment (Ellsbury et al., 1998). In a study by Brust (1990), one and two weeks after paraquat and glyphosate were applied to plots, there were significantly fewer large ground beetles than in control areas attributed to the relatively green cover on control plots, thus maintaining an environment suitable for the ground beetle. Catches of ground beetles slowly increased 28 days after treatments were applied. Purvis et al. (1984) found the highest catches of Coleoptera to occur in weedy plots. This is in agreement with Clark et al. (1997), who found greater capture of *A. placidum* in conventionally tilled systems not receiving herbicides or fertilizers.

Management practices generally cannot be categorized as having positive or negative effects on ground beetles (Clark et al., 1997). Some practices or systems favour some species while others species remain unaffected. For example, a study by Clark et al. (1997) indicated the abundance of *P. melanarius* was unaffected by fertilizer, herbicide or tillage in barley and legume plots.

2.4.5.4 Fertilizer

Fertilizers have been found to positively affect ground beetles (Clark et al., 1997; Purvis et al., 1984). Farmyard manure increased activity (predation, diversity, catches) of ground beetles because it served as an alternative food source and favorably altered the microclimate (Purvis et al., 1984). When the manure dried up its influences were gone and the catches and diversity of ground beetles diminished. In a study by Larsen et al. (1996), significantly fewer ground beetles were found in untreated control plots (2.1 individuals/trap/day) than in fertilized plots (4.2 individuals/trap/day). Diversity was greater in fertilized plots, although evenness was lowest as *H. pensylvanicus* represented 42% of captured species. The increased abundance and diversity are likely an indirect result of increased plant growth caused by nutrient enrichment.

Other studies have indicated no effect of fertilizer on ground beetles. In a roadside habitat of various grass and legume combinations, no significant difference in capture or diversity was found with or without fertilizer application (Snodgrass and Stadelbacher, 1989). On a reclaimed mine spoil in Germany, faunal composition was not changed by mineral fertilizers (Kielhorn et al., 1999). Increased numbers of ground beetles were observed in plots where sewage sludge or manure was applied.

2.4.6 Weed and Ground Beetle Associations

Significant, positive correlation between floral and fauna diversity is known to exist (Thomas and Marshall, 1999). Within a national park study, the distribution of plants and ground beetles was influenced by similar factors but the response of the two groups of organisms differed (Gardner, 1991). Plant species composition and structure of overstory and understory vegetation typically have a major influence on diversity, abundance and species composition of insect communities (Work et al., 1998). Tolerance of some weeds is beneficial to the cropping system. In a diversified plant community, there is an increase in the effectiveness of biological control of weeds and other pests (Clements et al., 1994), polyphagous herbivores and a more stable arthropod population (Altieri and Liebman, 1988; Cussans, 1996). The result is reduced frequency and severity of explosive epidemics of insect pests. Weeds can facilitate or interfere with specialized herbivores of crops or natural enemies by supplying alternative hosts for the herbivore or its natural enemy. Most specialized herbivores have a decreased population density in weed crop mixtures, while polyphagous herbivore densities tend to increase in these situations (Altieri and Liebman, 1988). There are numerous examples where the presence of weeds growing in the crop alters the number of phytophagous insects and reduces crop damage (Norris, 1992). Reduced crop damage was due to a combination of weeds providing an alternative food resource, and weeds attracting an increased presence of predator insects.

Many studies have shown that it is possible to stabilize the insect community of a cropping system by designing and constructing vegetational architecture that supports populations of natural enemies or have direct deterrent effects on pest herbivores. Thus by manipulating weed communities, weed control practices or cropping systems, it is possible to affect the ecology of insect pests and associated natural enemies (Altieri, 1994). In an Alberta study, vegetation was thought to influence the population size of ground beetles through humidity of the habitat due to differing canopy structures altering the microclimate

(Carcamo and Spence, 1994). The structural diversity of ground cover in cropping systems can influence a habitat favorably resulting in increased predation. For example, in unsprayed headland plots, weed diversity was increased, higher densities of weeds occurred, greater weed biomass and higher percent weed cover was observed which supported significantly higher densities of non target arthropods and predatory arthropods (especially polyphagous species and their alternative prey) (Chiverton et al., 1991). Tillage practices may affect arthropods indirectly through changes in weed populations (Carcamo, 1995). Fields under reduced tillage have increased plant diversity and greater structural heterogeneity. Both plant diversity and structural heterogeneity enhance the diversity of ground beetles (Carcamo, 1995) and create a favourable environment for species such as *H. pensylvanicus* (Tonhasca, 1993).

Postdispersal weed seed predation is potentially an important source of weed seed loss that can reduce seed supply and seedling emergence in old field, pasture, forest and desert environments (Cardina et al., 1996; Weiss et al., 1990). It may also be an important source of weed seed loss in arable fields however little is known about seed predating organisms in agricultural systems. The principal seed predators in agricultural fields include large and small ground beetles. Ground beetles are responsible for half of the total seed predation occurring in agricultural fields (Cardina et al., 1996). In Ontario agricultural systems, weed seed predation was found to be low in the spring, increasing in mid summer and decreasing as winter approached (Cromar et al., 1999). Increased amounts of ground cover may influence the quantity of seed predation by providing habitat for seed predators.

In a study by Lund et al. (1977), the number of seeds damaged by ground beetles varied with seed species. Seed species that remained virtual undamaged included field bindweed (*Convolvulus arvensis* L.), velvet leaf (*Abutilon theophrasti* Medicus) and fall panicum (*Panicum dichotomiflorum* Michx.), while seed species that were readily damaged included giant foxtail (*Setaria faberii* Herrm.), redroot pigweed, lamb's quarter, chickweed (*Stellaria media* (L.) Vill.) and Kentucky bluegrass (*Poa pratensis* L.). Green foxtail, redroot pigweed, lamb's quarter and chickweed are included in the top 20 weeds in Manitoba fields (Thomas et al., 1998), suggesting that ground beetles may be used for weed management in cropping systems in Manitoba. Shape and size of seeds may affect handling and consumption of weed seeds, as smaller sized seeds are damaged in the largest quantities (Lund et al., 1977).

3.0 MATERIALS AND METHODS

3.1 Experiment Design

The rotation under investigation was established on approximately 10 ha at the Glenlea Research Station, Manitoba in 1992 (Figure 3.1). The soil type is a rego black chernozem with 9-26-66% sand, silt and clay, respectively.

The experiment was a randomized complete block design in a split plot arrangement. Crop rotation was the main plot, while crop input management was the subplot. Main plots measured approximately 90m by 60m, with subplots measuring approximately 45m by 30 m each. Rotations were as follows:

Rotation 1: spring wheat-pea-wheat-flax

Rotation 2: spring wheat and legume establishment-sweet clover-wheat-flax

Rotation 3: spring wheat and legume establishment-alfalfa-alfalfa-flax

using flax as a "test crop" in the fourth year of rotation. Flax was chosen as a test crop for its poor competitive ability with all weed types. Yields will drop drastically as weed densities increase (Bell and Nalewaja, 1968a; Bowden and Friesen, 1967; Hay, 1968). The influence of crop rotation and crop inputs on weeds and ground beetles should therefore be evident.

Each main plot was subdivided into four subplots with treatments of fertilizer and herbicide inputs as follows; fertilizer and herbicide (f+h+), fertilizer and no herbicide (f+h-), no fertilizer and herbicide (f-h+), no fertilizer and no herbicide (f-h-).

Only 1995, the first test crop, and succeeding years were used in the analysis. Weed dynamics may require four years or more to stabilize following a change in management

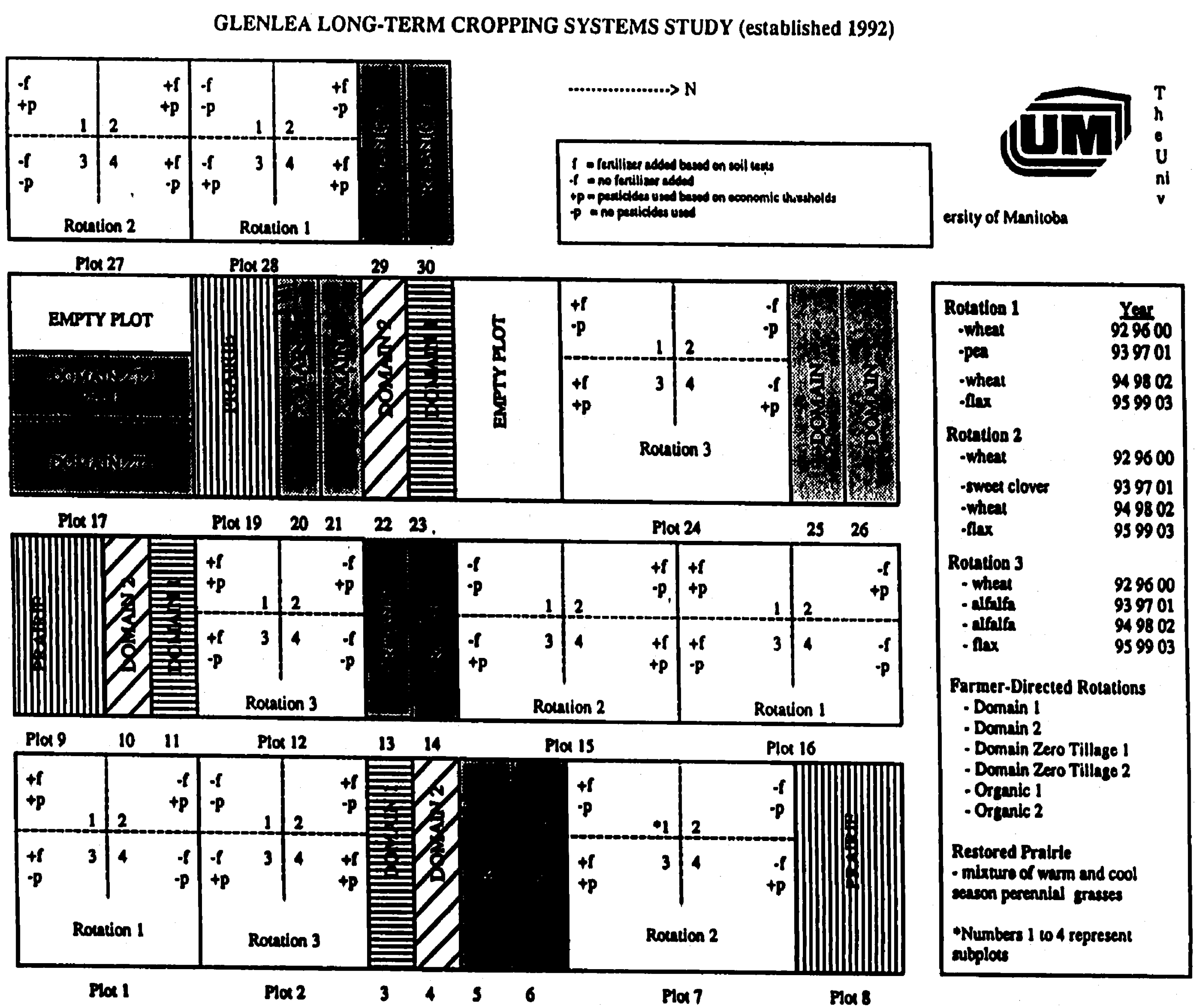

Figure 3.1 Glenlea long-term cropping systems study map.

practices (Liebman et al, 1996). The first 3 years of study would not likely demonstrate associations between weeds and cropping systems. The first test crop year was used as a bench mark from which to compare succeeding populations.

One prairie grass system plot was established in each replicate of the Glenlea long-term cropping systems study in 1993. Prairie grass plots were seeded to a mixture of cool and warm season grasses, including big bluestem (*Andropogan gerardii* Vitman), indiangrass (*Sorghastrum nutans* [L.] Nash), switchgrass (*Panicum virgatum* L.), western wheatgrass (*Pascopyrum smithii* [Rydb.] Löve), northern wheatgrass (*Elymus canadensis* L.) and slender wheatgrass (*Elymus trachycalulus* [Link] Gould ex Shinners). Species were typical of the tallgrass prairie which once dominated southern Manitoba. The prairie was burned twice, once in the spring of 1995 and a second time in the spring of 1997. It is useful to compare features of agriculture and natural systems in the pursuit of more ecological approaches to pest management (Clements et al., 1994).

3.2 Field Management

For annual crops, the tillage regime typically involved 2 deep tillage (chisel plow) operations and harrowing in the fall, and light cultivation and harrow operation immediately prior to seeding in the spring. Where herbicides were used in rotations, less tillage was used. For example, flax stubble in 1996 was not tilled in the f+h+ and f-h+ subplots, and the following wheat crop was directly seeded into the flax stubble. No tillage was conducted after wheat harvest when a legume understory crop was present (i.e. 1992 and 1996, during the sweet clover and alfalfa establishment years). During alfalfa termination events in 1994 and

1998, the f+h+ and f-h+ subplots received applications of glyphosate, which meant less tillage was required to terminate the stand. For alfalfa termination, an average of 6 tillage operations in fall (tandem disk and chisel plow) were used in f+h- and f-h- subplots, and 3-4 tillage are used in the f+h+ and f-h+ subplots.

All grain crops were windrowed and threshed using a commercial grain combine. The straw was removed from plot areas by baling. Chaff collection at time of grain harvest was conducted in all plots in order to minimize the transfer of weed seeds between subplots. Sweet clover was green manured approximately mid-July when plants were in full blossom. Alfalfa crops were harvested three times in the first year of production and twice in the second year.

Fertilizer was added to f+h+ and f+h- subplots based on soil test recommendations. Phosphorus (P) was seed placed and nitrogen (N) was applied with the seed (to upper limit for the respective crops) and the remainder was broadcast (ammonium nitrate; ammonium sulfate when S required) immediately after crop row closure. In this way the broadcast N had minimal effect on weed competitiveness

Herbicides were typically applied in-crop to the f+h+ and f-h+ subplots as required and according to recommended rates. No herbicide was applied to any subplots during sweet clover and alfalfa establishment years, as well as during plow down of sweet clover green manure. No seed treatments were used. Insecticide was used in the h+ subplots of rotation 2 only once to control sweet clover weevil in 1993.

Spring wheat, peas and flax were direct seeded and sweet clover and alfalfa were broadcast seeded to spring wheat in legume establishment years (i.e., 1992, 1996). Refer to Table 3.1 for detailed information on crop seeding, fertilizer and herbicide application, harvest

Table 3.1 Summary of field operations at the Glenlea long-term cropping systems study from 1995-1999.

				Rate											
				Rotation 1				Rotation 2				Rotation 3			
Year	Operation	Product	Date	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-
1995															
	Seeding(kg ha-1)														
		Flax (cv. Norland)	May 29	28	28	28	28	28	28	28	28	28	28	28	28
	Fertilizer (kg ha^{-1})														
		N	May 19	67	67	.[z]	.	67	67	.	.	34.5	34.5	.	.
		P_2O_5	May 11	30	30	.	.	30	30	.	.	30	30	.	.
	Herbicide [y]														
		Poast	June 22	x[z]	.	x	.	x	.	x	.	x	.	x	.
		Buctril M	June 22	x	.	x	.	x	.	x	.	x	.	x	.
		Refine	June 22	x	.	x	.	x	.	x	.	x	.	x	.
		Roundup	August 31	x	.	x	.	x	.	x	.	x	.	x	.
	Harvest														
		Swathed	September 12	x	x	x	x	x	x	x	x	x	x	x	x
		Combined	September 25	x	x	x	x	x	x	x	x	x	x	x	x
		Baled	September 27	x	x	x	x	x	x	x	x	x	x	x	x
	Tillage														
		Cultivator	May 27	x	x	x	x	x	x	x	x	x	x	x	x
		Deep-tillage	September 27	.	x	.	x	.	x	.	x	x	x	x	x
		Deep-tillage	October 10	x	x	x	x	x	x	x	x	x	x	x	x
		Harrow	October 11	x	x	x	x	x	x	x	x	x	x	x	x
1996															
	Seeding (kg ha-1)														
		Wheat (cv. Katepwa)	May 30	100	100	100	100	100	100	100	100	100	100	100	100
		Sweet Clover (cv.Norgold)	May 29	.	.	.	.	12	12	12	12	.	.	.	.
		Alfalfa (cv. OAC Minto)	May 29	.	.	.	.	.	.	.	.	10	10	10	10
	Fertilizer (kg ha^{-1})														
		N	May 30	25.6	25.6	.	.	25.6	25.6	.	.	25.6	25.6	.	.
		N	June 26	40	40	.	.	.	.	.	.	.	.	.	.
		P_2O_5	May 30	25.6	25.6	.	.	25.6	25.6	.	.	25.6	25.6	.	.
	Herbicide														
		Roundup	May 27	x	.	x	.	.	.	.	.	x	.	x	.
		Achieve 10G	June 24	x	.	x	.	.	.	.	.	.	.	.	.
		Refine Extra	June 28	x	.	x	.	.	.	.	.	.	.	.	.
		MCPA	June 28	x	.	x	.	.	.	.	.	.	.	.	.
		Roundup	October 9	x	.	x	.	.	.	.	.	.	.	.	.
	Harvest														
		Swathed	August 30	x	x	x	x	x	x	x	x	x	x	x	x
		Combined	September 4	x	x	x	x	x	x	x	x	.	.	.	.
		Combined	September 8	.	.	.	.	.	.	.	.	x	x	x	x
		Baled	September 9	x	x	x	x	x	x	x	x	x	x	x	x
	Tillage	Cultivator	May 29	x	x	x	x	x	x	x	x	x	x	x	x
		Harrow	May 30	x	x	x	x	x	x	x	x	x	x	x	x
		Deep-tillage	September 13	.	x	.	x	.	.	.	.	.	.	.	.
		Deep-tillage	October 15	.	x	.	x	.	.	.	.	.	.	.	.
		Harrow	October 18	.	x	.	x	.	.	.	.	.	.	.	.
1997															
	Seeding (kg ha-1)														
		Pea (cv. Grande)	June 3	110	110	110	110	.	.	.	.	.	.	.	.
	Fertilizer (kg ha^{-1})														
		N		4.2	4.2	.	.	.	.	.	.	.	.	.	.
		P_2O_5		20	20	.	.	.	.	.	.	.	.	.	.
	Herbicide														
		Odyssey	June 30	x	.	x	.	.	.	.	.	.	.	.	.
	Harvest														
		Mechanical Hay Harvest	July 9	.	.	.	.	.	.	.	.	x	x	x	x
		Tandem Disk Plowdown	July 10	.	.	.	.	x	x	x	x	.	.	.	.
		Tandem Disk Plowdown	July 16	.	.	.	.	x	x	x	x	.	.	.	.
		Mechanical Hay Harvest	August 12	.	.	.	.	.	.	.	.	x	x	x	x
		Swathed	September 15	x	x	x	x	.	.	.	.	.	.	.	.
		Combined	September 15	x	x	x	x	.	.	.	.	.	.	.	.
		Chaff Collected and Chopped	September 15	x	x	x	x	.	.	.	.	.	.	.	.
	Tillage														
		Cultivator	June 2	x	x	x	x	.	.	.	.	.	.	.	.
		Harrow	June 2	x	x	x	x	.	.	.	.	.	.	.	.
		Deep-tillage	August 27	.	.	.	.	x	x	x	x	.	.	.	.
		Tandem Disk	September 24	x	x	x	x	x	x	x	x	.	.	.	.
		Harrow	October 24	x	x	x	x	x	x	x	x	.	.	.	.
1998															
	Seeding (kg ha-1)														
		Wheat (cv. AC Barrie)	May 27	100	100	100	100	100	100	100	100	.		.	.
	Fertilizer (kg ha^{-1})														
		N	May 27	23	23	.	.	23	23	.	.	.	.	.	.

		N	July 8	67	67	.	.	54	54	.	.	.	.	.	.
		P_2O_5	May 27	23	23	.	.	23	23	.	.	.	.	.	.
	Herbicide														
		Achieve 40G	July 1	x	.	x	.	x		x	.	.	.	.	.
		Buctril M	July 1	x	.	x	.	x		x	.	.	.	.	.
		2,4-D	September 21	.	.	.	.	.	.	.	.	x	.	x	.
		Roundup	September 21	.	.	.	.	.	.	.	.	x	.	x	.
	Harvest														
		Mechanical Hay Harvest	June 23	.	.	.	.	.	.	.	.	x	x	x	x
		Mechanical Hay Harvest	August 11	.	.	.	.	.	.	.	.	x	x	x	x
		Swathed	September 21	x	x	x	x	x	x	x	x	.	.	.	.
		Combined	September 16	x	x	x	x	x	x	x	x	.	.	.	.
		Baled	September 18	x	x	x	x	x	x	x	x	.	.	.	.
	Tillage	Cultivator x2	May 26	x	x	x	x	x	x	x	x	.	.	.	.
		Tandem Disk	September 6	.	.	.	.	.	.	.	.	x	x	x	x
		Deep-tillage	October 1	.	.	.	.	.	.	.	.	x	x	x	x
		Deep-tillage	October 2	.	.	.	.	.	.	.	.	x	x	x	x
		Cultivator	October 9	x	x	x	x	x	x	x	x	.	.	.	.
		Deep-tillage	October 23	x	x	x	x	x	x	x	x	.	.	.	.
		Harrow	October 28	x	x	x	x	x	x	x	x	.	.	.	.
		Deep-tillage	October 29	.	.	.	.	.	.	.	.	.	x	.	x
		Harrow	October 29	.	.	.	.	.	.	.	.	.	x	.	x
1999															
	Seeding (kg ha-1)														
		Flax (cv. Norland)	May 28	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8
	Fertilizer (kg ha^{-1})														
		N	May 27	50	50	.	.	38.9	38.9	.	.	33.4	33.4	.	.
		P_2O_5	May 27	22.3	22.3	.	.	22.3	22.3	.	.	22.3	22.3	.	.
		S	May 27	15.6	15.6	.	.	15.6	15.6	.	.	15.6	15.6	.	.
	Herbicide														
		Poast	July 12	x	.	x	.	x	.	x	.	x	.	x	.
		Buctril M	July 12	x	.	x	.	x	.	x	.	x	.	x	.
	Harvest														
		Swathed	September 23	x	x	x	x	x	x	x	x	x	x	x	x
		Combined	September 27	x	x	x	x	x	x	x	x	x	x	x	x
		Baled	September 28	x	x	x	x	x	x	x	x	x	x	x	x
	Tillage														
		Cultivator	May 28	x	x	x	x	x	x	x	x	x	x	x	x
		Harrow	May 28	x	x	x	x	x	x	x	x	x	x	x	x
		Deep-tillage	October 12	x	x	x	x	x	x	x	x	x	x	x	x
		Harrow	October 21	x	x	x	x	x	x	x	x	x	x	x	x

[z] indicates subplot received the referred operation
[y] recommended rates (Manitoba Agriculture and Food, 2001)
[x] "." indicates subplot did not receive referred field operation

and tillage field operations.

3.3 Measurements

3.3.1 Yield

In 1999, grain yields were determined from 4, 1m^{-2} randomly selected quadrats in each subplot which were subsequently processed with a Hege small plot combine (Hege Maschinen GmbH, Domäne Hohebuch, D-74638, Waldenburg, Germany). In 1995 through 1998 grain yields were determined by harvesting a 10m strip of crop with a Hege. Grain was cleaned, weighed and dried at 65 ^{o}C for 72 hours so that yield data could be expressed as 0% moisture. For alfalfa, 3, 1 m^{-2} of dry matter were harvested prior to mechanical haying. Sweet clover dry matter was harvested one time only, prior to green manuring operations.

3.3.2 Crop Production

Total dry matter (DM) production was determined from 3, 1m^{-2} randomly selected quadrats within each subplot prior to harvest operations. Crop and weed plants were separated, dried at 55 ^{o}C for 72 hours and weighed to determine dry material yield for crop and weeds. In 1999, weeds were separated into species prior to drying at 55 ^{o}C for 72 hours.

3.3.3 Weed Population Assessment

Weed seedling density and community composition was assessed immediately prior to in-crop herbicide use each year. A preselected quantity of quadrats were randomly placed throughout each subplot and weed seedlings were identified and counted. The number of the quadrats used varied among years (Table 3.2). In 1999, weed seedling densities and community compositions were assessed three times over the cropping season (pre-seeding, pre in-crop spray, and pre-harvest).

Table 3.2 Quantity and number of quadrats used to evaluate weeds in each year of study.

Year	# of Quadrats	Qaudrat Size
1995	5	1 m^{-2}
1996	4	0.25 m^{-2}
1997	4	1 m^{-2}, 0.1 m^{-2} for green foxtail[Z]
1998	3	1 m^{-2}, 0.25 m^{-2} for some green foxtail
1999	10	0.1 m^{-2}, 1 m^{-2} for Canada Thistle

[Z] If density of green foxtail > 1000 seedlings m^{-2}, 0.1 m^{-2} quadrat was used

Data was standardized to plants per m^{-2} before statistical analysis was conducted. Values were averaged over each subplot.

3.3.4 Ground Beetle Assessment

Pitfall traps were used to trap insects throughout the duration of the Glenlea long-term cropping systems study (1992-1999). Pitfall traps were established in subplots following crop emergence each year. Pitfall traps were placed in the middle of the subplot, with a distance of 10 m between pitfall traps. Soil was excavated to a depth such that plastic cups (approximately 500 ml in volume) were level with the ground. Cups were half filled with a preservative solution. Between 1995 and 1998, a propylene glycol water (50% v:v) solution was used in the pitfall traps. In 1999, a saturated salt solution with detergent was used in the pitfall traps. The switch was for four reasons: 1) a result of the rapid evaporation of propylene glycol in pitfall traps 2) propylene glycol left a gummy residue on insects, creating difficulties for specimen identification 3) it was not always easy to get the desired amount of propylene glycol 4) salt is relatively inexpensive. Although each preservative may have influenced the species collected, all traps within years used the same preservatives thus no within year influences should have occurred (Holliday, 2001, Personal Communication).

A plywood covering was placed approximately 2.5 cm above the pitfall trap to prevent damage to the pitfall trap by rodents, mammals and rainfall. Sites were marked with a metal stake to identify location throughout the cropping season. Insects were collected every 7 to 14 days between pitfall trap establishment and crop harvest, at which time pitfall traps were removed (Table 3.3). Insects were strained from solution and placed in air tight container with 70% ethanol for preservation. Collections were placed in a fridge until such a time as identification could occur.

Insects were identified and separated by order prior to counting. Ground beetles were placed in an air tight container with ethanol for preservation while awaiting species identification. Ground beetles were identified to the species level and counted per pitfall trap. Values were averaged for the two pitfall traps per subplot prior to data analysis. All sampling dates were used in the analysis for test crop years. Only the final sampling date was used for analysis in 1996 to 1998 due to variations in sampling procedure and duration.

Table 3.3 Initial and final collection dates, and number of sampling periods of ground beetle population assessment

Year	Initial Date	Final Date	Total Sampling Period
1995	June 30	August 11	4
1996	August 22	August 28	2
1997	August 18	August 18	1
1998	July 28	August 25	3
1999	June 30	August 25	5

3.4 Statistical Analysis

3.4.1 Univariate Analysis

Data from each field season was summarized by calculating the mean yield, crop, weed and total DM, weed and ground beetle species density, Shannon-Weiner and Simpson diversity indices, and evenness for weed and ground beetle populations for each rotation X crop input treatment combination and prairie grass system. Mean yield, DM and species densities were the summed total of the average density per subplot divided by the total number of subplots per replication. Shannon-Weiner index (H), Simpson (G) indices were calculated to determine the diversity of each plot. A large Shannon-Weiner value indicates high diversity, where as a low Simpson's value indicates high diversity. Hill's evenness was used to measure the degree to which the abundance of species were equal within a community (Kenkel, 2000, Personal Communication) and was calculated as follows:

$$N1 = e^{H} \text{ and } N2 = 1/G, \text{ thus Hill's} = (N2-1)/(N1-1)$$

where N1 = a nonlinear transformation of H, e = base of natural log, H = Shannon-Weiner index value, N2 = transformation of G, and G = Simpson's index value.

All analysis was conducted using Statistical Analysis System (SAS) version 6.12 for Windows (SAS Institute Inc. Cary, North Carolina). The experiment was analyzed as a randomized complete block in a split plot arrangement using analysis of variance (ANOVA), procedures to detect significance ($p<0.05$). Homogeneity of error variance was tested using Levene's test. Levene's test is superior to other tests for homogeneity when data is suspected of being non-normally distributed (Milliken and Johnson, 1992). Log transformations were used on all data and transformed data was tested for homogeneity of variance using Levene's test. Often, significant differences of residual error were still detected on transformed data. ANOVA is very robust for data with unequal variances (Milliken and Johnson, 1992). One method for dealing with data when variances are unequal is to ignore the fact that they are unequal and calculate the same F-statistic or t-tests that are calculated in the case of equal variance. Studies have shown this to be acceptable, particularly if sample sizes are equal or almost equal in number. If larger sample sizes correspond to the populations with the larger variances then this is an effective method of handling the data with unequaled variances. Log transformed data with heterogeneous error were used in ANOVA procedures, however actual values are presented in the Results and Discussion section.

3.4.2 Multivariate Analysis

To detect differences between the pre in-crop spraying weed and insect communities of each rotation, species density data were subjected to multivariate data analysis using Canonical Community Ordination Version 4 (CANOCO 4) for Windows (Microcomputer Power, Ithaca, New York). Codes used for weed and beetle species are given in Tables 3.4 and 2.1, respectively.

Redundancy analysis (RDA) was performed on log transformed weed and beetle species data. A two dimensional RDA biplot was generated for weed and beetle variable sets from 1995 to 1999. Prairie data was not used in weed biplots because of absent data in 1995. Biplots including and not including prairie data were generated for beetle data to demonstrate the influence the prairie had in RDA analysis. When an environmental variable was strongly correlated with the first axis, biplots of the second and third or third and fourth axes were generated to determine the influence other environmental variables had on species. A biplot for 1995 and 1999 was produced containing a variable set which included all weed and beetle species in order to identify associations between weed and beetle species.

In all biplots, species which did not have strong discriminating power were placed close to the origin. This created clutter in the biplot, thus rare species (weeds, if < 5 occurred; beetles, if < 10 occurred) were suppressed but not excluded in RDA analysis.

Monte Carlo tests, as outlined in the literature review, were used in RDA to test the significance of results.

Table 3.4 WSSA-approved codes, scientific names, common names, and life cycle for weed species occurring in the Glenlea long-term cropping systems study in 1995 to 1999.

Code	Scientific Name	Common Name	Life Cycle
AMARE	*Amaranthus retroflexus* L.	Redroot Pigweed	Annual Dicot
AVEFA	*Avena fatua* L.	Wild Oats	Annual Graminoid
CHEAL	*Chenopodium album* L.	Common lamb's quarter	Annual Dicot
CIRAR	*Cirsium arvense* (L.) Scop.	Canada Thistle	Perennial Dicot
ECHCG	*Echinochloa crus-galli* (L.) Beauv.	Barnyardgrass	Annual Graminoid
TLS[z]	*Euphorbia serpyllifolia* Pres.	Thymeleaf spurge	Annual Dicot
GAETE	*Galeopsis tetrahit* L.	Common Hempnettle	Annual Dicot
KCHSC	*Kochia scoparia* (L.) Schrad.	Kochia	Annual Dicot
POLCO	*Polygonum convolvulus* L.	Wild Buckwheat	Annual Dicot
POLPE	*Polygonum persicaria* L.	Ladysthumb	Annual Dicot
SETLU	*Setaria glauca* (L.) Beauv.	Yellow Foxtail	Annual Graminoid
SETVI	*Setaria viridis* (L.) Beauv.	Green Foxtail	Annual Graminoid
SINAR	*Sinapis arvensis* L.	Wild Mustard	Annual Dicot
TAROF	*Taraxacum officinale* Weber in Wiggers	Dandelion	Perennial Dicot
THLAR	*Thlaspi arvense* L.	Stinkweed (Field Pennycress)	Annual Dicot

[z] No WSSA approved code available. TLS will be used for all tables and ordinations when present

4.0 RESULTS AND DISCUSSION

4.1 Environmental Parameters

In 1995 to 1999, mean growing season air temperature was within 1.5°C of the long-term average (Table 4.1). Mean air temperature from May to September varied between years. May was cool in 1995 and 1996, while June was warm in 1995, 1996 and 1997, compared with other years. July, August and September were similar in mean monthly temperature each of the five years.

Total precipitation was lower than the long-term average in 1995 and 1997. Total precipitation in 1996 and 1998 were similar to the long-term average, whereas 1999 had greater precipitation than the long term average. Precipitation was lowest in 1997 and greatest in 1999. In May of 1997, precipitation was 1% of the long-term average, whereas in 1996, 1998 and 1999 precipitation was two to three times greater than the long-term average for May. Dry months within years included June in 1995 and 1996, July in 1995, and August and September in 1998. Precipitation within months was greater than the long-term average for 1995 and 1996 in August, and September for 1995.

4.2 Dry Matter Production and Crop Grain Yield

4.2.1 Dry Matter Production

Crop and weed dry matter (DM) production were measured at the time of crop

Table 4.1 Monthly mean air temperature (C) and precipitation (mm) at Glenlea, Manitoba in 1995 to 1999 and the 30 year average[z].

	Temperature (C)						Precipitation (mm)					
	1995	1996	1997	1998	1999	30-yr. Avg.	1995	1996	1997	1998	1999	30-yr. Avg.
May	10.7	10.6	Missing	13.7	12.5	11.9	54.2	90.7	0.4	141.0	115.8	56.4
June	21.0	19.0	19.4	16.2	16.5	16.6	25.2	23.3	58.6	78.7	106.4	94.9
July	19.9	19.1	19.5	19.6	19.8	19.4	33.6	68.1	83.4	83.3	76.1	70.6
August	20.0	19.7	18.2	20.7	18.5	18.1	99.9	112.2	43.7	18.6	81.2	60.5
September	12.7	13.4	14.5	15.1	11.4	12.3	75.0	59.4	43.4	12.6	68.2	52.7
Average	16.9	16.4	14.3	17.1	15.7	15.7	287.9	353.7	229.5	334.2	447.7	335.1

[z] Environment Canada

harvest in test crop years (i.e., 1995 and 1999). Only one significant rotation X treatment interaction was observed; in 1995, where rotation type and crop inputs had a significant effect on weed DM (Table 4.2). As no other significant interactions occurred, means were separated by a Fisher's protected LSD to further investigate significance of main effects (Table 4.3). Crop, weed and total DM, and grain yield were significantly affected by crop input management for 1995 and 1999.

4.2.1.1 Weed DM

The significant rotation X treatment interaction, which occurred in 1995, was attributed to difference in weed DM for h+ and h- subplots within each rotation system. The DM of weeds in f+h+ and f-h+ subplots was approximately 20 times less than the f+h- and f-h- subplots in the alfalfa containing rotation, while only 10 times less within the green manure rotation (Table 4.2). In the small grains rotation, however, weed DM within the f-h+ subplot was approximately 65 times less than in the corresponding f-h- subplot. Weed DM within the f+h+ subplot was approximately 13 times less than that found within the f+h- subplot. Therefore, weed DM was greater in f+h- and f-h-subplots than the corresponding subplots not receiving herbicide, and the annual rotation > the green manure rotation > alfalfa rotation for weed DM.

In 1995, rotations containing forage legumes had significantly less weed DM compared with rotation 1, the small grain rotation (Table 4.3). Literature is available comparing the influence of different forages on weed DM (Bell, 1993; Schoofs and Entz, 2000), however literature comparing weed DM in rotations with forages to those without

Table 4.2 Dry matter ($g\ m^{-2}$) and grain yield ($kg\ ha^{-1}$) for Glenlea long-term cropping systems study test crop 1995 and 1999. Statistical analysis for dry matter 1999, and yield 1995 and 1999 performed on log transformed data. Means considered significant when $p<0.05$.

		1995				1999			
		Dry Matter				Dry Matter			
Rotation	Inputs	Crop	Weed	Total	Yield	Crop	Weed	Total	Yield
Rotation 1	f+h+	452.5	16.5	469.1	1876.8	423.8	6.3	431.4	1378.3
	f+h-	213.2	217.1	430.3	975.0	216.6	194.7	414.8	600.3
	f-h+	282.1	1.8	283.9	1312.3	264.2	8.7	274.9	1050.8
	f-h-	237.3	117.9	355.2	960.9	153.6	123.7	266.5	605.6
Rotation 2	f+h+	468.3	13.7	482.0	1808.6	608.6	3.9	613.6	1826.7
	f+h-	271.3	110.4	393.6	1233.7	384.7	171.2	545.3	1099.8
	f-h+	275.2	3.8	279.0	1109.9	396.3	5.6	402.6	1584.3
	f-h-	262.3	32.8	295.1	1022.8	246.9	124.3	379.5	993.4
Rotation 3	f+h+	439.3	3.4	442.8	1712.3	559.6	19.9	560.8	1453.9
	f+h-	357.2	51.1	408.3	1291.8	396.8	167.9	582.0	998.3
	f-h+	385.6	2.4	388.0	1550.4	538.6	1.7	540.7	1531.8
	f-h-	321.8	43.2	365.0	1373.3	455.7	112.2	563.2	1378.9
Rotation (R)		0.1906	0.0305	0.709	0.0747	0.0556	0.9401	0.0889	0.0915
Treatment (T)		0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.0001
R X T		0.2212	0.0124	0.0927	0.1575	0.1031	0.7637	0.1039	0.1922
SEM		30.96	20.69	26.10	117.01	47.52	19.03	43.16	156.12

Table 4.3 Dry matter (g m^{-2}) and grain yield (kg ha^{-1}) for Glenlea long-term cropping systems study test crop 1995 and 1999. Statistical analysis for dry matter 1999, crop DM : total DM ratio, and yield 1995 and 1999 performed on log transformed data. Means with the same letter are not significantly different LSD ($p<0.05$).

		1995					1999				
		Dry Matter			Crop DM:		Dry Matter			Crop DM:	
Rotation		Crop	Weed	Total	Total DM	Yield	Crop	Weed	Total	Total DM	Yield
	Rotation 1	296.3	88.3 a	384.6	0.79 b	1281.2	264.56	83.34	346.9	0.75 b	908.8
	Rotation 2	319.3	40.2 b	362.5	0.88 a	1293.7	409.11	76.26	485.23	0.83 a	1376.1
	Rotation 3	376.0	25.0 b	401.0	0.93 a	1481.9	487.69	75.42	561.69	0.87 a	1340.7
	SEM	25.53	10.75	31.60	0.019	63.42	30.14	16.66	40.67	0.020	101.29
Inputs	f+h+	453.4 a	11.2 c	464.6 a	0.98 a	1799.2 a	530.68 a	10.03 b	535.24 a	0.99 a	1553 a
	f+h-	280.6 b	126.2 a	410.7 b	0.69 c	1166.8 b	332.71 bc	177.95 a	514.04 a	0.63 b	899.5 b
	f-h+	314.3 b	2.6 c	317.0 c	0.99 a	1324.2 b	399.69 b	5.34 b	406.08 b	0.98 a	1389 a
	f-h-	273.8 b	64.6 b	338.4 c	0.82 b	1119.0 b	285.41 c	120.04 a	403.07 b	0.67 b	992.7 b
	SEM	17.88	11.95	15.07	0.023	67.55	27.44	10.99	24.92	0.032	90.14

forages is not available.

In 1995, weed DM was greatest in f+h- subplots followed by the f-h- subplots (Table 4.3). Subplots receiving herbicide (i.e., f+h+, f-h+) did not significantly differ from one another.

In 1999, weed DM in the f-h- subplot was double that in 1995 and no longer significantly differed from the weed DM of the f+h- subplot (Table 4.3). In 1999, subplots receiving herbicide remained statistically the same.

The combination of fertilizer use and no herbicide use resulted in the highest weed population. Di Tomaso (1995) reported numerous studies which indicated weeds accumulated higher concentrations of nutrients, such as N, than crops, thereby quickly depleting soil nutrients levels and reducing crop yield. Friesen et al. (1960) found weeds to compete effectively with grain crops for available N thereby reducing grain yield and protein. In the present study, the abundance of weeds in the absence of herbicide use would compete with the crop for fertilizer, thereby increasing the biomass of the weed population. In studies by Bischoff and Mahn (2000) and Schreiber et al. (1978), fertilizer was found to significantly increase weed biomass. In the present study, the absence of herbicide over a long-term period allowed the weed population to increase, strengthening its competition for resources with the crop. After two rotation cycles, fertilizer was no longer a strong influence on weed DM.

4.2.1.2 Crop DM

In 1995, crop DM was greatest in f+h+ subplots while the remaining subplots did not differ significantly (Table 4.3). In 1999, a similar trend occurred except the f-h- subplot had significantly lower DM than subplots receiving herbicide. The results suggest that herbicide use, in the long-term, had a positive effect on crop productivity.

The use of herbicide in the f+h+ subplots would have reduced the weed population resulting in reduced crop-weed competition. The crop would have utilized its' energy for DM production, rather than for competition, thereby resulting in greater crop DM. The use of synthetic fertilizer would have further increased crop DM.

In the long-term, the absence of herbicide in the f-h- subplots allowed for an increased weed density thus resulting in increased crop-weed competition, thereby reducing crop DM. In addition, the absence of fertilizer would prevent the crop from adequately competing with the increased weed population (Jornsgard et al., 1996).

4.2.1.3 Total DM

In 1995 and 1999, subplots with fertilizer had significantly greater total DM than those subplots which had not received fertilizer (Table 4.3). In 1995, the f+h+ subplot had the greatest total DM as herbicides helped reduce weed competition, and fertilizer increased crop DM. The f+h- subplot had significantly greater total DM than the f-h+ and f-h- subplot which was attributed to a greater weed DM within the f+h- subplots. Although the presence of weeds may have reduced potential crop DM accumulation in the f+h- subplots, the addition of fertilizer increased the DM of both crop and weeds, contributing to a significantly greater total DM than observed in those subplots which had not received fertilizer. Tilman (1987) found biomass to significantly increase with increased N attributed to reduced competition for N but increased competition for light. It was interesting to note that the subplot receiving both herbicide and fertilizer had the greatest total DM, but had the lowest weed DM and density, with no difference in weed diversity between subplots. The results suggest that if greater ground beetle activity were observed in subplots other than f+h+, the increase would be due to factors other than DM.

In 1995 and 1999, the ratio of crop DM to total DM was greatest in f+h+ and f-h+ subplots (Table 4.3). In 1995, the f+h- subplot had the lowest crop DM to total DM ratio. It was useful to observe the crop DM to total DM ratio because it indicated which system was better utilizing its resources for yield potential. Observing only total DM does not add value from an agronomic prospective, however a greater total DM is of ecological benefit because it will create a favourable habitat for beneficial insects, such as ground beetles (Kielhorn et al., 1999). The present study indicated that the f+h+ system would be beneficial both ecologically and agronomically, while the f-h+ system appears to have more agronomic than ecological benefits.

4.2.2 Crop Grain Yield

In 1995, grain yield was only weakly affected (p=0.074) by the main effect of rotation (Table 4.2). However, grain yield was strongly affected by management of crop inputs. The f+h+ subplot provided the greatest yield, while remaining subplots did not significantly differ (Table 4.3).

In 1999, grain yield was once again weakly affected (p=0.091) by rotation (Table 4.2), while the effects of crop inputs was very strong. Subplots which received herbicide had a significantly larger yield, with the yield of the f+h+ subplot not significantly differing from the f-h+ subplot (Table 4.3). The results suggest yield was significantly reduced because of the larger weed population in the absence of herbicides (f+h- and f-h- subplots).

In 1995, it was evident that the use of both fertilizer and herbicide was required to realize yield benefits. In 1999, herbicide was the only crop input necessary in order to realize a yield benefit. Herbicide reduced weed density thereby reducing crop-weed competition. The crop was better able to use available resources for grain production, rather than competition with weeds.

Grain and legume yields for 1996, 1997, and 1998 can be found in Table B.1, B.2 and B.3, respectively.

4.3 Weeds as Influenced by Crop Rotation Type and Crop Input Management

4.3.1 Weed Population Assessment

4.3.1.1 1995 Weed Population Assessment

In 1995, weed populations were assessed only once, prior to in-crop spraying. Eleven weed species were identified. Redroot pigweed and hempnettle were significantly influenced by a rotation X treatment interaction (Table 4.4). The largest population of hempnettle appeared in the f+h+ subplot of rotation 1. The appearance of hempnettle in cultivated fields of southern Manitoba is infrequent and occurs in low densities (O'Donovan and Sharma, 1987). Control of dominant species associated with rotation 1 may have allowed hempnettle to become dominant (Martens, 2001, Personal Communication). Similar findings with

Table 4.4 Weed population density (plants m^{-2}) at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means considered significant when $p<0.05$.

Rotation	Inputs	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	AVEFA	GAETE	Volunteer	ECHCG	Total
Rotation 1	f+h+	0	0	1	1	1	4	1	0	2	0	4	0	3	16
	f+h-	0	1	1	3	1	1	2	2	1	0	0	0	5	16
	f-h+	0	0	0	1	1	0	0	0	2	0	0	0	3	7
	f-h-	0	1	0	3	0	1	1	0	1	0	0	0	5	12
Rotation 2	f+h+	0	0	7	1	1	1	1	0	2	0	0	0	1	15
	f+h-	0	0	4	2	0	1	0	0	0	0	0	0	2	11
	f-h+	0	0	3	2	0	1	0	0	1	0	0	0	3	10
	f-h-	0	0	2	1	0	0	0	0	0	0	0	0	2	6
Rotation 3	f+h+	0	0	1	1	0	0	0	0	0	0	0	0	1	4
	f+h-	0	1	1	3	0	0	0	0	0	0	1	0	1	7
	f-h+	0	1	1	1	0	0	0	1	0	0	0	0	2	6
	f-h-	0	0	0	3	0	0	0	1	0	0	0	1	1	6
Rotation (R)		.[z]	0.2554	0.0136	0.5161	0.031	0.4937	0.5239	0.2824	0.3679	.	0.2304	0.1289	0.1748	0.0275
Treatment (T)		.	0.1228	0.0217	0.0095	0.2091	0.4342	0.1654	0.5227	0.0025	.	0.0285	0.1233	0.7498	0.2707
R X T		.	0.2484	0.518	0.2142	0.1781	0.5898	0.3812	0.3937	0.0472	.	0.0315	0.0911	0.9906	0.2127
SEM		0.0	0.4	0.8	0.6	0.3	1.1	0.5	0.5	0.5	0.0	0.6	0.1	1.2	2.9

[z] Values of 0 for all analysed variables yielded no statistical probability

broadleaf signalgrass (*Brachiaria platyphylla* (Griseb.) Nash) were observed in North Carolina by Johnson and Coble (1986).

Despite a significant rotation X treatment interaction, redroot pigweed was not significantly influenced by rotation. Redroot pigweed was not observed in rotation 3. This was not consistent with work by Ominski et al. (1999), who found no significant differences in populations of redroot pigweed between alfalfa-cereal and continuous cereal fields. Although redroot pigweed appeared in all subplots of rotation 1 in the present study, it was favoured by subplots in both rotations 1 and 2 with herbicide inputs. Herbicide efficacy may have been poor, however, redroot pigweed may be an example of a weed that increases in the presence of herbicide use. Research by Rojas-Garciduenas and Kommedahl (1960) found that when redroot pigweed was treated with 2,4-D, 50% fewer seeds were produced compared with untreated plants. Seeds, however, had greater germination percentage than seeds from unsprayed plants.

Stinkweed and lady's thumb were significantly affected by rotation (Table 4.4). When the means were separated by a Fisher's's protected LSD, it was apparent that stinkweed was greatest in rotation 2 (Table 4.5). Firstly, as a winter annual, stinkweed flowers within 30 to 50 days of germination and produces mature seeds by early July (Best and McIntyre, 1975). Sweet clover was green manured in early July in the second year of the rotation cycle which would leave sufficient time for stinkweed seed production prior to tillage in this system. Secondly, as stinkweed germinated in the fall, released N from sweet clover would benefit the developing seedlings. Klebesadel (1969) found that the larger the stinkweed seedling was at the onset of winter, the greater the number of seed pods produced in the following year.

The significant rotation effect on lady's thumb was attributed to the presence of lady's

Table 4.5 Weed population density (plants m^{-2}) at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means with the same letter are not significantly different LSD ($p<0.05$).

		THLAR	POLCO	POLPE	AMARE	GAETE	Total
Rotation							
	Rotation 1	0 b	2	1 a	1	1	13 a
	Rotation 2	4 a	2	0 ab	1	0	11 a
	Rotation 3	1 b	2	0 b	0	0	6 b
SEM		0.6	0.3	0.1	0.7	0.3	1.1
Inputs							
	f+h+	3 a	1 c	0	2 a	1 a	12
	f+h-	2 ab	3 a	0	0 b	0 b	11
	f-h+	1 b	1 bc	0	1 b	0 b	8
	f-h-	1 b	2 ab	0	0 b	0 b	8
SEM		0.4	0.4	0.2	0.3	0.3	1.7

thumb in rotation1 but not in rotation 3. Lady's thumb is an erect plant which does well in cultivated sites (Whitson et al., 1996). The ground cover provided by the alfalfa hay crop in the second and third year of the rotation cycle, in addition to the reduced cultivation compared with rotation 1, may have prevented lady's thumb from establishing. In addition, the removal of the hay in rotation 3 would have removed the lady's thumb plant, preventing seed shed. Ominski et al. (1999) found the density of *Polygonum* spp to be significantly reduced in alfalfa-cereal fields versus continuous cereal fields.

The management of crop inputs significantly affected stinkweed, wild buckwheat, redroot pigweed and hempnettle populations in 1995 (Table 4.4). Stinkweed populations were greatest in the f+h+ subplots, not differing from the f+h- subplots (Table 4.5). Stinkweed is widespread and adapted to a wide range of environmental conditions. The results of the present study were surprising as the distribution of stinkweed is known to be unaffected by climate, soil type (Best and McIntyre, 1975) or fertilizer application (Hume, 1982).

Wild buckwheat was most abundant in the f+h- subplots and least abundant in the f+h+ subplots demonstrating the importance of herbicide in controlling wild buckwheat populations under high soil fertility conditions. The competitive ability of wild buckwheat is affected by several factors including density of weed and crop, crop type and soil fertility (Hume et al., 1983).

Hempnettle and redroot pigweed were most abundant in the f+h+ subplots. Hempnettle has likely encroached in open species left by dominant weed species which were controlled by herbicide (Martens, 2001, Personal Communication). Hempnettle weed would utilize available fertilizer resources to increase biomass, seed production and density. Redroot is a C_4 plant and is nitrophilous (Weaver and McWilliams, 1980), and may therefore emerge late (compared to weed species identified in the present study) and benefit from previously applied fertilizer. However, redroot pigweed is known to increase emergence when herbicide is applied (Rojas-Garciduenas and Kommedahl, 1960).

In 1995, total weed population density was significantly influenced by rotation but not by crop input management (Table 4.4). Rotations 1 and 2 had the most weeds, not significantly differing from one another, while rotation 3 had the fewest weeds (Table 4.5). Rotation 3 was effective in reducing the weed population because of the additional cultural control methods it provides through removal of weeds in hay production, as well as the suppressive nature of alfalfa on some weed species (Ominski et al., 1999).

4.3.1.2 1999 Weed population Assessment

4.3.1.2.1 Pre-Seeding Assessment

Thirteen weed species were identified in the long-term cropping systems study prior to seeding. Wild mustard, wild buckwheat, Canada thistle and wild oat were significantly influenced by a rotation X treatment interaction (Table 4.6).

The significant rotation X treatment interaction for wild mustard was attributed to differing distribution of wild mustard density among crop input subplots of each rotation system. In rotation 1, wild mustard was greatest in unsprayed subplots (36 to 145 times greater in f+h- and f-h- subplots versus f+h+ and f-h+ subplots, respectively) attributed to greater viable weed seed return when wild mustard was left chemically uncontrolled. Wild

Table 4.6 Weed population density (plants m^{-2}) at pre-seeding weed population assessment at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie was statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	TLS	AVEFA	SETLU	GAETE	Volunteer	ECHCG	Total
Rotation 1	f+h+	0	4	25	4	0	0	0	0	0	0	0	0	8	6	0	47
	f+h-	0	142	56	79	2	2	2	3	0	0	43	0	2	4	7	340
	f-h+	0	1	12	2	0	1	0	0	0	0	2	0	2	7	0	27
	f-h-	0	145	36	61	0	3	3	0	0	0	3	0	0	7	0	258
Rotation 2	f+h+	0	3	220	7	0	2	0	0	0	0	1	0	3	4	0	242
	f+h-	0	34	199	69	0	2	2	1	0	0	0	0	0	4	0	337
	f-h+	0	4	159	6	0	2	0	0	0	0	0	0	2	7	0	181
	f-h-	2	27	184	70	0	3	2	0	0	0	1	0	0	3	0	300
Rotation 3	f+h+	0	11	40	21	0	2	0	7	0	0	0	0	0	1	0	95
	f+h-	0	104	182	54	0	7	0	2	0	0	0	0	3	2	0	358
	f-h+	0	21	49	19	0	5	0	9	0	0	0	0	1	2	0	107
	f-h-	0	91	107	29	0	6	0	10	0	0	0	0	0	8	0	258
Prairie		0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3
Prairie vs Rotations		.[z]	0.4494	0.0028	0.0012	0.4547	0.078	.	0.0428	.	.	0.5977	.	0.2054	0.0467	.	0.0032
Rotation (R)		0.4444	0.3127	0.0321	0.2188	0.0372	0.1682	0.0471	0.0745	0.4444	.	0.0505	.	0.7396	0.4418	0.5688	0.0808
Treatment (T)		0.4155	0.0001	0.0333	0.0001	0.7371	0.1396	0.0001	0.8556	0.4155	.	0.0501	.	0.0287	0.7803	0.4034	0.0001
R X T		0.4552	0.05	0.6465	0.0033	0.8524	0.5965	0.0065	0.2061	0.4552	.	0.008	.	0.3843	0.628	0.5019	0.0027
SEM		0.7	32.2	31.7	15.8	0.5	1.7	0.5	2.2	0.1	0.0	8.2	0.0	1.7	2.5	2.1	40.6

[z] Values of 0 for all analysed variables yielded no statistical probability

mustard was also greatest in unsprayed subplots of rotations 2 and 3, however the ratio of wild mustard in h- subplots to corresponding h+ subplots was much lower (i.e., between 4 to 11 times greater in f+h- and f-h- subplots versus f+h+ and f-h+ subplots, respectively) demonstrating the need for chemical management in a non-robust system (e.g., simple annual crop rotation). Van Acker and Oree (1999) found the weed seed return of wild mustard was greater than that of wild oat in unmanaged canola. In the present study, it was hypothesized that weed seeds easily accumulated in the seedbank over time due to lack of cultural control in rotation 1, thus increasing the plant population in years following. Fewer wild mustard plants were observed in rotation 2 compared with rotation 1, which was attributed to the allelopathic nature of sweet clover (Weston, 1996), and the plow down of sweet clover for green manure two years previously thereby limiting the number of weed seeds returned to the seedbank. The distribution of wild mustard plants between subplots of rotation 3 was similar to rotation 2, however densities were closer in value to rotation 1. Wild mustard plants in rotation 2 would be disturbed annually by tillage, whereas wild mustard in the f+h- and f-h- subplots of rotation 3 would have had a two year period without tillage disturbance or chemical control. In the absence of control, wild mustard plants could have had a greater weed seed return to the weed seedbank in rotation 3 than rotation 2, thereby explaining the greater densities observed in rotation 3 over rotation 2.

The rotation X treatment interaction for wild buckwheat was attributed to the different responses of wild buckwheat to management of crop inputs between the three rotations. Wild buckwheat plant densities in rotations 1 and 2 were 20-30 times higher in h- subplots than in h+ subplots. Density of wild buckwheat in f+h+, f-h+ and f-h- subplots in rotation 3 were similar to one another. Higher abundance of wild buckwheat when only fertilizer inputs were used supports findings that N will stimulate germination of weeds (Chancellor and Froud-Williams, 1986).

The rotation X treatment interaction for Canada thistle was attributed to the presence of Canada thistle in rotations 1 and 2 but not in rotation 3. Canada thistle appeared only in the h- subplots of rotations 1 and 2 as herbicide was an effective control of Canada thistle. In the absence of cultural control with alfalfa, herbicide was an important management tool for Canada thistle.

The rotation X treatment interaction for wild oat was attributed to the fact that herbicide was required to control wild oat in rotation 1 but was not required for wild oat control in rotations 2 and 3. The use of forage crops has been found to control wild oats when used in crop rotation (Banting, 1974; Ominski et al., 1999). In rotation 1, the number of wild oat plants significantly increased when fertilizer inputs were used. Fertilizer enhances the growth and competitive ability of wild oats (Ross, 2001; Sharma and Vanden Born, 1978). Soil fertility has been found to be a greater factor than moderate densities of wild oat in crop yield loss by wild oats (Bowden and Friesen, 1967)

Stinkweed, Canada thistle and wild oat were significantly influenced by rotation in 1999 (Table 4.6). As in 1995, stinkweed was most common in rotation 2 followed by rotation 3 and rotation 1 (Table 4.7). Canada thistle was present in rotations 1 and 2, though not at significantly different densities. The absence of Canada thistle in rotation 3 was attributed to the removal of Canada thistle by mechanical haying of alfalfa which may have reduced the population of the weeds in succeeding years. The perennial alfalfa hay crop experienced no tillage disturbance for a two year period. This likely diminished vegetative regeneration of Canada thistle from root pieces. The allelopathic nature of the alfalfa may also have

Table 4.7 Weed population density (plants m^{-2}) at pre-seeding weed population assessment at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means with the same letter are not significantly different LSD ($p<0.05$).

		SINAR	THLAR	POLCO	CIRAR	AVEFA	GAETE	Total
Rotation								
	Rotation 1	73	32 c	37	1 a	12 a	3	168
	Rotation 2	17	191 a	38	1 a	1 b	2	265
	Rotation 3	57	95 b	31	0 b	0 b	1	205
SEM		19.3	31.2	9.6	0.3	3.9	1.2	36.7
Inputs								
	f+h+	6 b	95 bc	11 b	0 c	1 a	4 a	128 b
	f+h-	93 a	146 a	68 a	1 b	14 b	2 ab	345 a
	f-h+	9 b	73 c	9 b	0 c	1 b	2 a	105 b
	f-h-	88 a	109 ab	53 a	2 a	2 ab	0 b	272 a
SEM		18.6	18.3	9.1	0.3	4.7	1.0	23.5

suppressed the weed, preventing seed set and regeneration from roots. Ominski et al. (1999) indicated a reduced abundance of Canada thistle when alfalfa was present in rotation compared with continuous cereal rotations. Hodgson (1968a) reported a 192% increase in Canada thistle in four years of continuous spring wheat versus a 1% decrease in alfalfa mowed for hay. It was interesting to note that green manure in rotation 2 was not efficient in managing Canada thistle. Canada thistle can regenerate from root pieces spliced by the tillage, creating more plants and spreading the area of infestation (Moore, 1975; Ross et al., 1985).

Flax is a poor competitor with wild oats (Bell and Nalewaja, 1968a). Wild oat was greatest in rotation 1 but was minimal or non existent in rotations 2 and 3. As mentioned previously, the use of forage crops in rotation has been found to control wild oats due to microsite limitations of wild oat seed in a perennial crop (Banting, 1974; Ominski et al., 1999; Van Acker, 2001, Personal Communication). Allelopathy, harvest through mechanical haying or plowing down in the green manure, may have contributed to the management of wild oat in rotations 2 and 3. Rotation 1 does not include hay removal, mid-season tillage, or allelopathic crops, thus limiting this rotation's ability to manage a wild oat infestation without herbicides.

Wild mustard, stinkweed, wild buckwheat, Canada thistle, wild oat and hempnettle were all significantly affected by crop input regime (Table 4.6). In subplots not receiving herbicides, wild mustard, wild buckwheat and wild oat, had significantly more plants than those that did receive herbicide (Table 4.7). Studies by Ball (1992) and Swanton and Weise (1991) indicate that as the weed seedbank increases overtime, the population of weeds increased (Ball, 1992; Shaw, 1982).

The highest stinkweed plant population occurred in the f+h- subplots. Conversely, the f-h+ subplot had the fewest stinkweed plants. Weed control through herbicide use limited the seed return from weeds in preceding years and the lack of fertilizer likely limited the emergence and growth of stinkweed in the f-h+ subplots. Previous studies indicated that stinkweed is unaffected by fertilizer (Best and McIntyre, 1975; Hume, 1982). The results from this study indicated the importance of herbicide in controlling stinkweed, and demonstrated how fertilizer can significantly affect the weed population. The results also indicated that while a pesticide-free production (PFP) system may have increased stinkweed problems, organic and conventionally managed systems will not differ in stinkweed densities.

Consistent with data from 1995 (Table 4.4), hempnettle was most abundant in the f+h+ subplot. The results indicate hempnettle had encroached upon open spaces left by primary weed species which were controlled by herbicide. In addition, the results suggest hempnettle would benefit from added fertilizer. Hempnettle was not present in the f- or h- subplots (Table 4.6) suggesting that hempnettle was unable to maintain its presence in the weed community without the aid of chemical inputs. Hempnettle species may prove to be an increasingly significant problem during succeeding rotational cycles.

Canada thistle population was greatest in f-h- subplots. Competition between weed and crop occurs when essential elements, such as mineral nutrients, are lacking (Bell and Nalewaja, 1968a; Bell and Nalewaja, 1968b). Canada thistle uses nutrients needed by the crop (Hodgson, 1968b). In the f+h+ and f+h- subplots the crop is able to take advantage of the addition of fertilizer and compete with Canada thistle thus reducing the abundance of Canada thistle. This is supported Hume (1982) who found the abundance of Canada thistle to decrease when fertilizer was used.

4.3.1.2.2 Pre In-crop Spraying Assessment

Fifteen weed species were identified prior to in-crop spraying in 1999. Of these species, wild mustard, lady's thumb, Canada thistle and redroot pigweed were significantly influenced by a rotation X treatment interaction (Table 4.8).

Wild mustard occurred in larger densities in unsprayed subplots compared to sprayed subplots in rotations 1 and 2. Wild mustard is known to compete for both light and N (Blackman and Templeman, 1938). Within rotation 3, f+h- subplots had the greatest number of wild mustard plants. It is likely that in hay crop years, plants not harvested for hay would be able take advantage of a competition-free environment for light to increase biomass and seed production. In succeeding years, the absence of herbicide would benefit wild mustard by allowing an increased population to compete for N fertilizer.

Lady's thumb was affected by a rotation X treatment as the distribution of lady's thumb species among subplots differed between rotations. In rotation 2, lady's thumb did not appear in the f-h+ subplot, and increased in number as the amount of inputs decreased. Despite lady's thumb having been strongly influenced by crop inputs in rotation 2, crop inputs appeared to have had no influence on lady's thumb distribution in rotation 3. In rotation 1, the small grains rotation, lady's thumb increased from 0 or 1 plants per m^{-2} in other subplots to 9 plants per m^{-2} in the f+h- subplot. Preliminary results from greenhouse studies on weed responses indicate a considerable increase in green smartweed (a close relative of lady's thumb) DM to increased N and P (Blackshaw, 2001, Personal Communication).

The number of Canada thistle plants identified increased from pre-seeding weed assessment, although the pattern of distribution remained the same. The rotation X treatment

Table 4.8 Weed population density (plants m^{-2}) at pre in-crop spraying weed population assessment at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie was statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	TLS	AVEFA	SETLU	GAETE	Volunteer	ECHCG	Total
Rotation 1	f+h+	172	0	3	1	0	1	0	0	5	1	0	0	0	0	6	189
	f+h-	782	99	7	7	9	3	2	0	19	0	6	0	0	0	7	942
	f-h+	78	1	6	0	1	0	0	0	5	1	1	0	0	0	6	98
	f-h-	436	58	8	6	1	1	5	0	3	1	0	0	0	0	14	532
Rotation 2	f+h+	43	2	29	4	1	2	0	0	7	0	0	2	0	0	0	91
	f+h-	72	13	25	18	2	3	4	1	12	0	2	1	0	0	0	154
	f-h+	31	3	16	3	0	1	0	0	6	1	0	1	0	0	1	64
	f-h-	64	19	12	9	3	1	8	0	4	0	0	8	0	0	0	128
Rotation 3	f+h+	14	6	9	5	1	2	0	1	0	0	0	0	0	2	0	40
	f+h-	52	45	13	24	1	7	0	3	2	0	0	0	0	1	0	148
	f-h+	15	11	7	3	1	1	0	1	0	0	0	0	0	2	0	42
	f-h-	56	19	12	9	1	5	1	3	3	0	0	0	0	0	0	110
Prairie		0	0	1	1	0	0	0	3	0	0	0	0	0	0	0	5
Prairie vs Rotations		0.0001	0.0773	0.0195	0.1049	0.1633	0.0933	0.4547	0.0523	0.0008	0.4547	0.4547	0.4547	0.4547	0.0273	0.5425	0.0001
Rotation (R)		0.0051	0.4587	0.2294	0.0178	0.771	0.2224	0.0384	0.0267	0.1639	0.3697	0.2246	0.4444	0.0494	0.0048	0.4888	0.0013
Treatment (T)		0.0001	0.0001	0.26	0.0001	0.0011	0.0222	0.0001	0.2381	0.0003	0.2251	0.1492	0.6794	0.6653	0.1166	0.7007	0.0001
R X T		0.1375	0.0093	0.2392	0.7263	0.0235	0.9391	0.0029	0.727	0.0015	0.8945	0.5733	0.3306	0.9104	0.7095	0.7856	0.0603
SEM		71.2	13.7	4.0	3.6	1.5	1.7	0.7	0.8	3.5	0.4	1.6	2.1	0.2	0.4	2.4	72.0

interaction for Canada thistle was similar to that observed in the pre-seeding weed assessment (Table 4.6). Canada thistle plants appeared in the f-h- subplots in rotations 1, 2 and 3, confirming the problem Canada thistle would be in an organic cropping systems (Entz et al., 2001b).

The rotation X treatment interaction for redroot pigweed was attributed to the difference in distribution of redroot pigweed between subplots within rotations 1 and 2, and rotation 3. Redroot pigweed density was greatest in the f+h- subplots of rotations1 and 2. In rotation 3, redroot pigweed appeared only where herbicide had not been applied (i.e., f+h- and f-h- subplots). The results suggested that in an annually cultivated field, redroot pigweed would occur despite herbicide use and that in the absence of herbicide, redroot pigweed would benefit from added N. This is contrary to findings by Hume (1982) who indicated redroot pigweed was not significantly influenced by fertilizer. The present study also suggested that the inclusion of a perennial alfalfa hay crop would decrease redroot pigweed densities, however herbicide would be required for complete control. Redroot pigweed is known to be relatively susceptible to most herbicides (Weaver and McWilliams, 1980).

Green foxtail, wild buckwheat, Canada thistle and dandelion were significantly influenced by rotation (Table 4.9). Despite initial significance in ANOVA, there was no significant differences in hempnettle densities between rotation when separated by rotation means. Volunteer crops were also significantly influenced by rotation, however the only volunteer assessed was alfalfa seedlings in rotation 3.

The density of green foxtail was significantly greater in rotation 1 than rotation 2, which had significantly more green foxtail than rotation 3 (Table 4.9). Green foxtail is a serious weed problem in Manitoba (Van Acker et al., 2001) and is commonly a problem in

Table 4.9 Weed population density (plants m^{-2}) at pre in-crop spraying weed population assessment at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means with the same letter are not significantly different LSD ($p<0.05$).

		SETVI	SINAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	GAETE	Volunteer	Total
Rotation												
	Rotation 1	367 a	39	3 b	3	1	2 b	0 b	8	0 a	0 b	440 a
	Rotation 2	53 b	9	8 a	2	2	3 a	0 b	7	0 a	0 b	109 b
	Rotation 3	34 c	20	10 a	1	4	0 c	2 a	1	0 a	1 a	85 b
SEM		55.4	7.6	1.4	0.7	1.0	0.6	0.3	3.5	0.0	0.2	55.0
Inputs												
	f+h+	76 b	3 b	3 c	1 b	2 b	0 b	0	4 b	0	1	107 c
	f+h-	302 a	52 a	16 a	4 a	4 a	2 a	1	11 a	0	0	415 a
	f-h+	41 b	5 b	2 c	1 b	1 b	0 b	0	4 b	0	1	68 c
	f-h-	185 a	32 a	8 b	2 b	2 ab	4 a	1	3 b	0	0	256 b
SEM		41.1	7.9	2.1	0.9	1.0	0.4	0.4	2.0	0.1	0.2	41.6

small grain crops (Whitson et al., 1996). The continuous small grain crops in rotation 1 selected for green foxtail by providing a similar habitat and plant life cycle in each rotation phase. Studies indicate green foxtail becomes a problem on continuously cropped land (Hume et al., 1991) and that forages suppress green foxtail for 1, 2, or more years (Entz et al., 1995).

Wild buckwheat was most abundant in rotations 2 and 3. Nitrogen will stimulate germination of wild buckwheat (Chancellor and Froud-Williams, 1986). The added N from previous years of forage legumes may therefore have contributed to the appearance of wild buckwheat within these rotations.

Canada thistle was significantly affected by rotation in 1999. Compared with the results of 1995, rotations had separated from one another in 1999, with rotation 2 having the most ($p < 0.05$) Canada thistle plants. As the root system fragmented as a result of tillage and green manure, Canada thistle may have increased from clones which emerged by vegetative propagation (Moore, 1975). Lower Canada thistle density in rotation 3, compared to rotation 2, may have resulted from the removal of Canada thistle plants with the alfalfa hay crop and lack of tillage. Alfalfa in rotation is also known to reduce shoot density, relative abundance, and frequency of Canada thistle (Ominski et al., 1999).

As expected (Chepil, 1946; Ominski et al., 1999) dandelion was present in rotation 3, but not in rotations 1 and 2 (Table 4.9). It was likely able to establish and maintain its presence in rotation 3 because its prostrate growth would allow it to avoid defoliation during mechanical hay harvest. Seeds would be able to germinate following harvest on exposed soil, as dandelion has no periodicity for germination (Chepil, 1946). Plants able to mature before the end of the cropping season could shed seed thereby increasing the amount of seed deposited in the weed seedbank for succeeding years.

Green foxtail, wild mustard, wild buckwheat, lady's thumb, lamb's quarter, Canada thistle, and redroot pigweed were significantly influenced by crop inputs (Table 4.9). Wild mustard populations were highest in h- subplots, as observed in the pre-seeding weed population assessment (Table 4.7). Similar observations for green foxtail and lamb's quarter occurred.

The greatest density of wild buckwheat occurred in the f+h- subplots, followed by the f-h- subplots. This was similar to assessments in 1995 and the earlier assessment in 1999. Although fertilizer could contribute to increased plant biomass, it was clear that the absence of herbicide control allowed for an increase in the overall wild buckwheat population. Subplots receiving herbicide did not differ from one another indicating that when controlled by herbicides, fertilizer did not influence the number of plants observed in a subplot. Canada thistle remained absent from subplots receiving herbicide.

Lady's thumb and redroot pigweed responded similarly to crop inputs with the greatest number of seedlings occurring in the f+h- subplots. All other subplots did not differ in plant density. This suggests that, similar to lamb's quarter, in the absence of herbicide the amount of nutrients available to lady's thumb and redroot pigweed determines the abundance of these weed species within a cropping system.

4.3.1.2.3 Pre-Harvest Assessment

When the weed community was assessed prior to harvest, Canada thistle and dandelion were the only species to be significantly influenced by a rotation X treatment interaction (Table 4.10). Canada thistle demonstrated the same pattern of distribution as in

Table 4.10 Weed population density (plants m^{-2}) at pre-harvest weed population assessment at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie was statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	TLS	AVEFA	SETLU	GAETE	Volunteer	ECHCG	Total
Rotation 1	f+h+	3	1	9	1	0	0	0	0	1	0	0	0	0	0	0	14
	f+h-	23	4	0	2	0	0	1	0	2	1	0	5	0	0	0	39
	f-h+	1	0	3	0	0	0	0	0	0	1	0	0	0	1	0	6
	f-h-	42	3	0	2	0	0	2	0	0	1	0	12	0	0	0	63
Rotation 2	f+h+	1	1	35	0	0	1	0	0	2	1	0	0	0	0	0	41
	f+h-	2	6	49	3	0	0	1	4	4	1	0	0	0	0	0	70
	f-h+	1	0	6	1	0	0	0	0	0	1	0	0	0	0	0	10
	f-h-	7	2	5	2	0	0	2	2	0	4	0	0	0	0	0	24
Rotation 3	f+h+	2	2	4	0	0	0	0	3	0	0	0	0	0	0	0	12
	f+h-	1	19	11	2	0	0	0	2	0	0	0	0	0	0	0	35
	f-h+	1	6	3	2	0	0	0	2	0	0	0	0	0	0	0	15
	f-h-	1	3	6	2	0	0	0	4	1	1	0	0	0	0	0	19
Prairie		0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2
Prairie vs Rotations		0.0901	0.543	0.0547	0.8022	.	0.1889	.	0.3688	0.0371	0.5977	.	.	.	.	.	0.047
Rotation (R)		0.2836	0.2249	0.1619	0.9709	1	0.8403	0.0099	0.4356	0.2319	0.0924	0.4444	0.4444	.	0.2844	.	0.364
Treatment (T)		0.0052	0.0402	0.0885	0.1338	0.3304	0.4155	0.0001	0.0529	0.0074	0.0645	0.4155	0.2746	.	0.1501	.	0.002
R X T		0.0648	0.9459	0.396	0.932	0.5233	0.7083	0.0001	0.0441	0.1022	0.5498	0.4552	0.5833	.	0.1975	.	0.4144
SEM		9.3	4.2	9.0	1.0	0.2	0.3	0.2	0.9	0.7	0.7	0.1	3.2	0.0	0.2	0.0	15.9

[z] Values of 0 for all analysed variables yielded no statistical probability

all previous 1999 weed population assessments. The vegetatively propagated seedlings of Canada thistle are produced through fragmentation of Canada thistle roots by tillage (Moore, 1975; Ross et al., 1985), thus in the absence of tillage between years of alfalfa hay Canada thistle was not fragmented and thereby was not able to produce new Canada thistle seedlings. Dandelion was present in unsprayed subplots of rotation 2 and in all subplots of rotation 3. This indicated that herbicide had a strong influence on the distribution of dandelion in rotation 2, but not in rotation 3.

Canada thistle was the only weed significantly influenced by rotation at the pre-harvest measurement (Table 4.10). No Canada thistle was present in rotation 3, but densities occurred in rotations 1 and 2 (Table 4.11). Canada thistle was the only plant to be significantly influenced by rotation at all weed population assessment times in 1999.

Green foxtail, wild mustard, Canada thistle, dandelion and redroot pigweed were significantly influenced by crop inputs (Table 4.11). Green foxtail was most abundant in the f-h- subplots. This was similar to earlier assessments in 1999. Wild mustard was also distributed between subplots in a similar manner to those at pre-spraying weed assessment, with the most weeds occurring in unsprayed plots. Canada thistle was distributed the same as in the pre-seeding weed population assessment with f-h- subplots having the greatest Canada thistle density. Redroot pigweed appeared to be more influenced by fertilizer use than by the absence of herbicide use, as the greater density occurred in subplots receiving fertilizer. Dandelion was significantly influenced by crop input treatments with the largest populations occurring where herbicide was not applied.

Table 4.11 Weed population density (plants m^{-2}) at pre-harvest weed population assessment at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means with the same letter are not significantly different LSD ($p<0.05$).

		SETVI	SINAR	CIRAR	TAROF	AMARE	Total
Rotation							
	Rotation 1	17	2	1 a	0	1	36
	Rotation 2	3	2	1 a	1	2	43
	Rotation 3	1	8	0 b	3	4	21
SEM		8.7	3.0	0.4	1.3	0.5	11.2
Inputs							
	f+h+	2 bc	1 b	0 c	1 b	1 ab	22 b
	f+h-	9 ab	10 a	1 b	2 a	2 a	54 a
	f-h+	1 c	2 b	0 c	1 b	0 b	10 b
	f-h-	17 a	2 ab	1 a	2 ab	1 b	47 a
SEM		5.4	2.4	0.1	0.5	0.4	9.2

4.3.1.2.4 Total Weed Population

Total weed population was significantly influenced by a rotation X treatment interaction at the pre-seeding measurement only (Table 4.6). In rotation 1, weed population total in the h- subplots was approximately 10 times that of h+ subplots. The magnitude of difference between sprayed and unsprayed subplots was lower in rotation 2 and 3 versus rotation 1.

The large populations of weeds in unsprayed subplots in rotation 1 demonstrated the limitations of a small spring grains rotation in the absence of chemical weed control, deeming it a fragile system. Rotation 3 was a more robust system because the weed population density was less variable between sprayed and unsprayed subplots as a result of the competitive ability of alfalfa. Weed suppression in rotation 2 may not differ greatly between subplots because plow down of the sweet clover may have increased the number of seeds in the weed seedbank across all subplots, maintaining the total weed population in following years. In addition, all subplots in rotation 2 remained unsprayed in legume establishment and green manure years, and lower N rates were applied in green manure year thereby increasing the total weed population across all subplots similarly.

A rotational effect was observed for the total weed population density at the pre in-crop spraying weed population assessment (Table 4.8). The weed population density was greatest in rotation 1, while no differences in density were observed between rotations 2 and 3 (Table 4.9). The results demonstrated that forage legumes in rotations 2 and 3 were an effective cultural control for suppressing weed populations over time. Other research has established that weeds are suppressed following forages in rotation (Banting, 1974; Entz et al., 1995; Hodgson, 1968a; Ominski et al., 1999).

Management of crop inputs had the most consistent significant influence over total weed population density. For example, crop input was the only effect to be significant at all three weed population assessment times in 1999, with the lowest weed density occurring in h+ subplots (Tables 4.6, 4.8 and 4.10). The combination of f+ and h- resulted in the highest total weed densities. Over time, the lack of weed control would have increased the weed population density and the weed seedbank. The nutrients provided by the fertilizer may have aided the weed plants in germination, growth, and weed seed return.

4.3.2 Diversity

Weed diversity at in-crop spraying was assessed using two diversity indices. The Shannon-Weiner diversity index is biased towards rare species, while Simpson's diversity index is biased to common species (Magurran, 1988). Both indices were used in order to prevent bias representation of weed community diversity. In 1995, Shannon's and Simpson's diversity indices, and evenness were not significantly affected by rotation, crop inputs or rotation X treatment interaction (Table 4.12). Diversity effects may not have been significant because the systems may not have stabilized in one rotation cycle. In 1999, however, significant differences occurred among the Shannon's, Simpson's and evenness indices in the cropping systems (Table 4.13).

In 1999, the only significant rotation X treatment interaction for weed diversity occurred for the Simpson's diversity index at the pre-seeding weed community assessment. In rotations 1 and 3, the indices were relatively similar between crop input treatments. In rotation 2, weed diversity in h+ subplots was approximately 50% less than weed diversity in h- subplots. An explanation for the effect of herbicide treatment on weed diversity is as follows: Herbicides reduced the number of weeds present in rotation 2 (Table 4.8) and as the

Table 4.12 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for weed population at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means considered significant when $p<0.05$.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	1.59	0.25	0.77
	f+h-	1.70	0.22	0.81
	f-h+	1.25	0.35	0.78
	f-h-	1.29	0.36	0.71
Rotation 2	f+h+	1.48	0.32	0.68
	f+h-	1.47	0.28	0.78
	f-h+	1.52	0.26	0.81
	f-h-	1.29	0.33	0.79
Rotation 3	f+h+	1.40	0.33	0.78
	f+h-	1.25	0.39	0.80
	f-h+	1.40	0.32	0.75
	f-h-	1.18	0.37	0.76
Rotation (R)		0.6032	0.6906	0.9951
Treatment (T)		0.3347	0.5199	0.7583
R X T		0.4538	0.5742	0.8053
SEM		0.139	0.056	0.064

Table 4.13 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for weed population at pre-seeding, pre in-crop spraying, and pre-harvest weed population assessments at the Glenlea long-term cropping systems study, 1989, as influenced by crop rotation type and crop input management. Statistical analysis preformed on log transformed data. Means considered significant when $p<0.05$.

		Pre-seeding			Pre in-crop spraying			Pre-harvest		
Rotation	Inputs	Shannon's	Simpson's	Evenness	Shannon's	Simpson's	Evenness	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	1.17	0.40	0.73	0.40	0.83	0.41	0.81	0.54	0.73
	f+h-	1.35	0.33	0.74	0.72	0.68	0.46	1.28	0.34	0.79
	f-h+	1.26	0.36	0.72	0.73	0.66	0.50	0.91	0.47	0.79
	f-h-	1.19	0.40	0.69	0.74	0.64	0.51	1.32	0.37	0.70
Rotation 2	f+h+	0.61	0.73	0.44	1.35	0.36	0.64	0.76	0.62	0.55
	f+h-	1.07	0.44	0.67	1.62	0.28	0.63	1.15	0.51	0.47
	f-h+	0.54	0.77	0.41	1.38	0.38	0.64	1.10	0.44	0.77
	f-h-	1.02	0.48	0.64	1.48	0.33	0.65	1.63	0.24	0.85
Rotation 3	f+h+	1.38	0.30	0.79	1.60	0.24	0.79	0.96	0.45	0.79
	f+h-	1.09	0.44	0.67	1.48	0.29	0.72	1.19	0.37	0.80
	f-h+	1.33	0.33	0.72	1.50	0.29	0.73	0.64	0.66	0.44
	f-h-	1.25	0.37	0.70	1.41	0.34	0.64	1.45	0.28	0.83
Rotation (R)		0.0128	0.0228	0.0736	0.0084	0.0088	0.0307	0.8929	0.9889	0.3907
Treatment (T)		0.3889	0.414	0.4323	0.4107	0.744	0.9621	0.0106	0.0133	0.4488
R X T		0.0634	0.037	0.0729	0.2896	0.3491	0.4586	0.6278	0.3167	0.0765
SEM		0.138	0.066	0.064	0.127	0.057	0.050	0.211	0.094	0.110

number of weed species decreased, the proportion of some species increased, thus reducing diversity. No significant difference in diversity due to Shannon's diversity index was observed. The weed population within rotation 2 had consistently larger numbers of stinkweed than the other two rotations (Table 4.6), thereby accounting for the significance observed within Simpson's and not Shannon's, as Shannon's is biased towards rare species.

Shannon's and Simpson's indices were significantly affected by rotation at the pre-seeding and pre in-crop spray weed assessments (Table 4.14). Before seeding, weed diversity was highest in the annual grain and alfalfa containing rotations. Lower diversity in the green manure rotation was attributed to the dominance of stinkweed (Table 4.6).

Prior to in-crop spraying, rotations 2 and 3 had the greatest diversity according to Shannon's and Simpson's indices (Table 4.14). Lower diversity in rotation 1 was likely due to the dominance of green foxtail and wild mustard, versus more balanced numbers of weed species in rotations 2 and 3 (Table 4.8). Evenness within the weed population was also significantly affected by rotation at this measurement time. The dominance of green foxtail in rotation 1 reduced the evenness of the weed population in rotation 1 (Table 4.14). Higher evenness levels in rotation 3 means less chance for herbicide selection for resistant weeds.

Shannon's and Simpson's diversity indices were significantly influenced by crop inputs at the pre-harvest weed community assessment (Table 4.14). The lowest level of diversity occurred in subplots receiving herbicides. Herbicides reduced the total density of weed species (Table 4.11), however, stinkweed was the dominant weed within h+ subplots (Table 4.10) thereby reducing weed population diversity. The dominance of stinkweed at the pre-harvest measurement suggests in-crop herbicide use selected for the winter annual stinkweed, which resulted in lower diversity. Diversity was highest in the f-h- subplots. The long term

Table 4.14 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for weed population at pre-seeding, pre in-crop spraying, and pre-harvest weed population assessments at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis preformed on log transformed data. Means with the same letter are not significantly different LSD ($p<0.05$).

		Pre-seeding			Pre in-crop spraying			Pre-harvest		
		Shannon's	Simpson's	Evenness	Shannon's	Simpson's	Evenness	Shannon's	Simpson's	Evenness
Rotation										
	Rotation 1	1.24 a	0.37 b	0.72	0.65 b	0.7 a	0.47 c	1.08	0.43	0.75
	Rotation 2	0.81 b	0.61 a	0.54	1.45 a	0.34 b	0.64 b	1.16	0.45	0.66
	Rotation 3	1.26 a	0.36 b	0.72	1.5 a	0.29 b	0.72 a	1.06	0.44	0.72
SEM		0.061	0.042	0.046	0.114	0.050	0.041	0.135	0.057	0.040
Inputs										
	f+h+	1.05	0.48	0.65	1.12	0.48	0.61	0.84 b	0.54 a	0.69
	f+h-	1.17	0.40	0.69	1.27	0.42	0.61	1.21 ab	0.41 ab	0.69
	f-h+	1.04	0.49	0.62	1.20	0.44	0.62	0.88 b	0.52 a	0.67
	f-h-	1.16	0.42	0.68	1.21	0.44	0.60	1.47 a	0.29 b	0.80
SEM		0.080	0.038	0.037	0.074	0.033	0.029	0.122	0.054	0.063

absence of herbicide use contributed to the accumulation of weed species which prevented dominant species, thereby increasing diversity of the weed population. Higher weed diversity in organic systems may be functionally beneficial by preventing dominance of a weed species thereby reducing the difficulty in managing a dominant weed species.

Tilman (1986) hypothesised that fertilizer in the absence of herbicide would reduce weed diversity. In the present study, weed diversity did not significantly decrease in the f+h- subplot versus all other subplots. Tilman's theory indicates that weed diversity should have increased in systems without fertilizer. In the present study, this was only true of the f-h- subplot.

4.3.3 RDA Biplots for Weed Community Composition

4.3.3.1 1995 Weed Community Composition (Flax Test Crop)

In 1995, the first RDA ordination axis was positively correlated with rotation 2 (0.7641) and negatively correlated with rotation 3 (-0.5613). Rotation 1 was strongly correlated with the second axis. Together, the first two axes explained 29.9% of the variation observed in the weed community. As the three rotations were correlated with these axes, it can be said that the three rotations were accounting for most of the variation observed in the first two axes. Herbicide and fertilizer had their strongest correlation with the 3rd and 4th axis, respectively (h+: 0.3807, h- -0.3807, f+: -0.5521 f-: 0.5521).

The four axes accounted for 41% of the variation observed in the 1995 weed community composition. The axes also explained 78.47%, 47.8% and 49.17% of the variation within stinkweed, redroot pigweed and volunteer species, respectively. All other species had less than 45% of their variation explained by the four axes. The first axis and all four combined axis of the RDA biplot were considered significant under a Monte Carlo randomization test indicating structure within the weed community.

In 1995, rotation strongly influenced the weed population (Figure 4.1). Rotations were separated in the first 2 axes of the ordination. Rotation 2 and 3 separated from one another on the first axis while rotation 1 separated from the forage-containing rotations on the second axis. Rotations 2 and 3 likely separated based on the biennial and perennial nature of the respective forage crops within each of rotations 2 and 3. The inclusion of forage legumes may be responsible for the separation between rotations 2 and 3, and 1.

Weeds associated with rotation 1 included barnyard grass, hempnettle, Canada thistle, and lady's thumb. Intermediate to rotations 1 and 2 were redroot pigweed and lamb's quarter. Stinkweed appeared to be strongly associated with rotation 2. Weeds associated with rotation 3 included dandelion, wild mustard and wild buckwheat.

Rotation 3 and f-h- demonstrated similar weed species associations (Figure 4.1). Weeds strongly associated with the f-h- and perennial hay crop systems included dandelion, wild mustard and wild buckwheat. Weeds present in the f+h+ subplots included lamb's quarter and redroot pigweed. Weeds in f-h- and f+h+ ordination space were negatively associated with one another indicating these types of management systems would likely differ in weed community composition. In general, crop inputs had a less significant effect on weed community composition in 1995 than did crop rotation.

Within the RDA, the influence of crop management was relatively unimportant in the first two axes. Figures 4.2 and 4.3 were used to decipher the influence of h+, h-, f+ and f-,

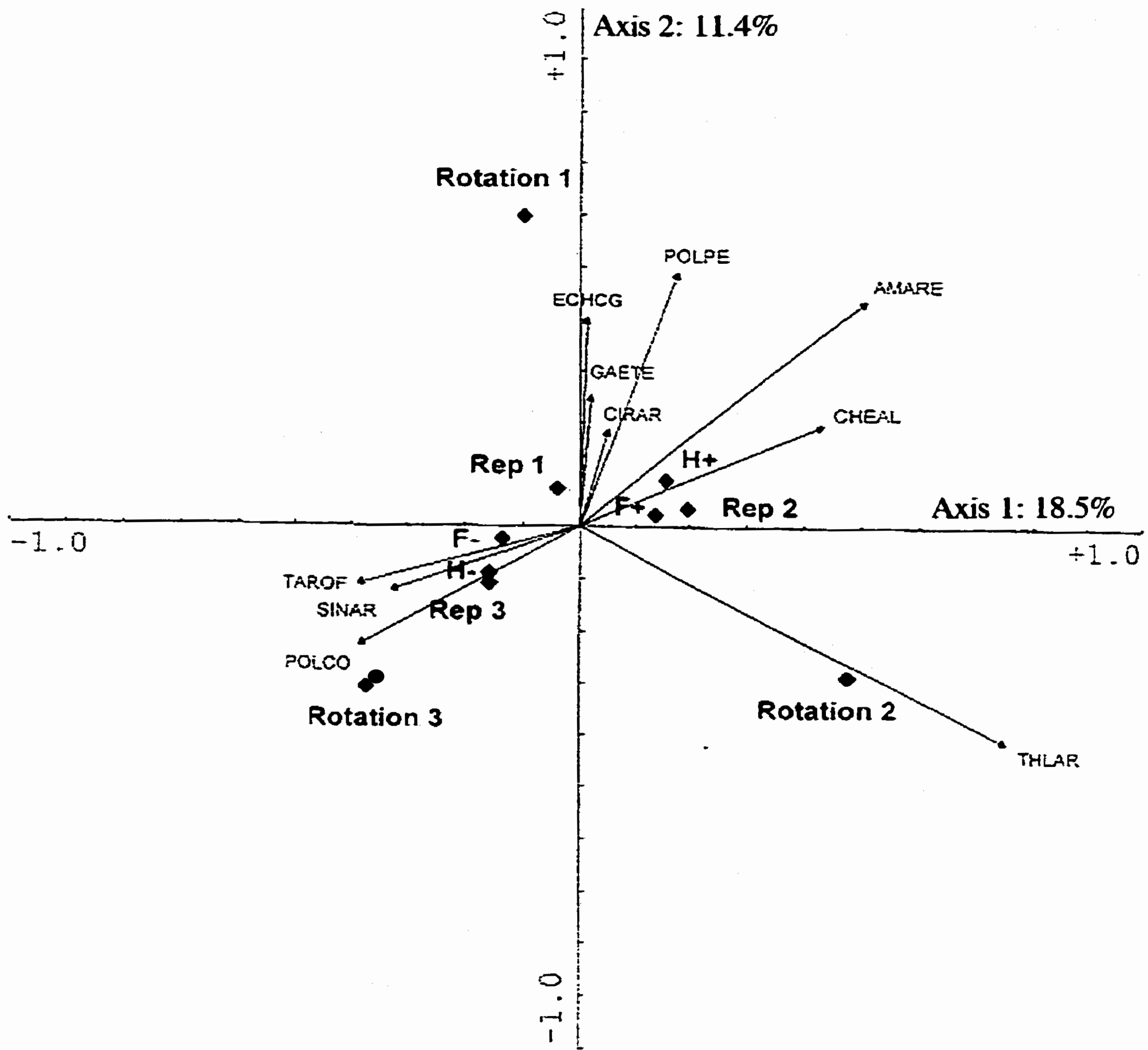

Figure 4.1 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1995. The first and second axes are presented and account for 29.9% of the total variation.

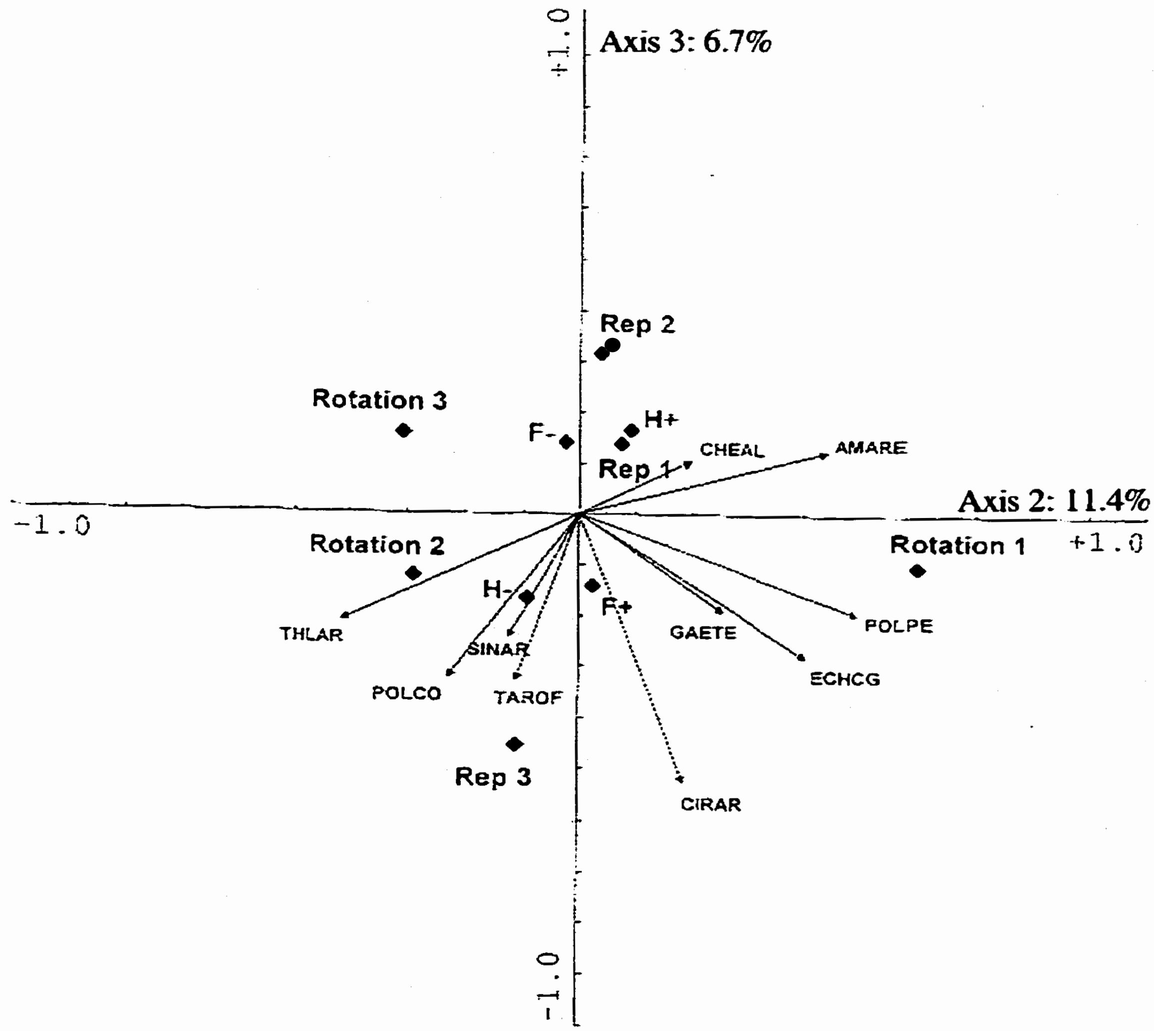

Figure 4.2 Redundancy analysis ordination for weed community composition at the Glenlea long-term cropping systems study, 1995. The second and third axes are presented and account for 25.2% of the total variation.

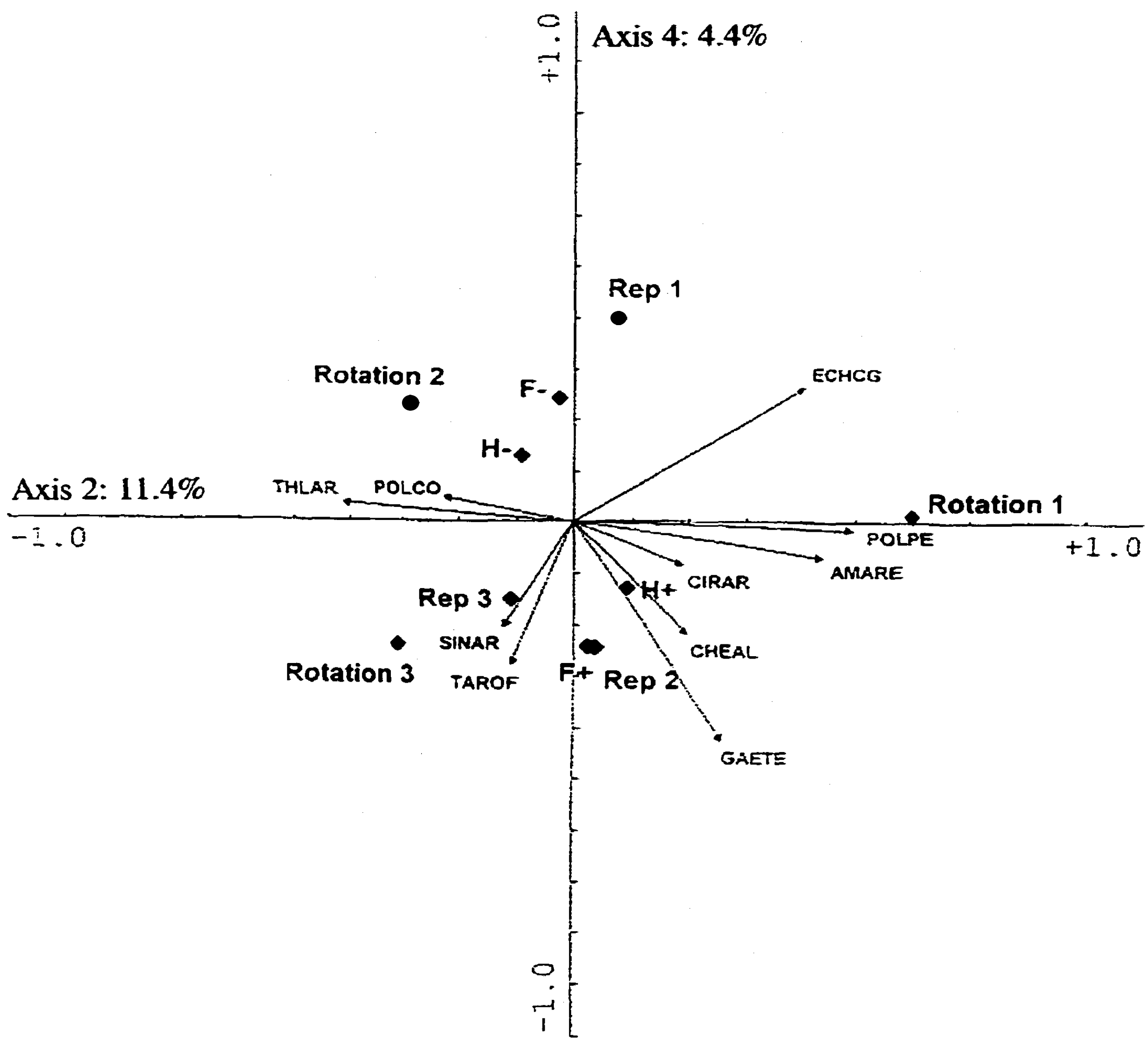

Figure 4.3 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1995. The second and fourth axes are presented and account for 15.8% of the total variation.

on weed community composition. Rotation remained the strongest influence on weed community composition but the effects of crop input management became clearer. Herbicide was separated by the second and third axes (Figure 4.2). When herbicide was present the only weeds associated were lamb's quarter and redroot pigweed. Stinkweed, wild buckwheat, wild mustard, and dandelion were associated with the absence of herbicide use. Fertilizer use was associated with wild mustard, dandelion, hempnettle, lamb's quarter and Canada thistle (Figure 4.3). The lack of fertilizer use was associated with no weeds indicating minimal weed density when fertilizer was not used, thereby suggesting that fertilizer use encouraged weeds while the absence of fertilizer limited weed density. It is known that fertilizer stimulates germination of weeds, thereby increasing weed density (Chancellor and Froud-Williams, 1986; Pyšek and Lebš , 1991), and if weeds escape control or herbicide is not used, selective forces favour nitrophilous weed species (Young and Evans, 1976).

4.3.3.2 1996 Weed Community Composition (Wheat Monoculture and Underseeded to Sweet Clover and Alfalfa)

In 1996, herbicide was strongly associated with the first axes (h+: 0.9752, h-: -0.9752) suggesting it had the strongest influence on weed community composition in 1996. Rotations 2 and 3 were most strongly associated with axis two (rotations 2 -0.7722, rotation 3 0.6903) The first two axes of the 1996 weed community RDA ordination explained 39.8% of the variation observed. Rotation 1 was associated with the third axes (0.9238). Fertilizer had its strongest correlation with the fourth axes suggesting it had minimal influence on weed community composition.

All four ordination axes accounted for 46.9% of the variation observed in the weed community. Of the weed species, 64.3% , 51.86%, 62.15% and 48.5% of the variation in wild mustard, stinkweed, wild buckwheat, redroot pigweed respectively was explained by ordination. The first axis and all four combined axis of the RDA biplot were considered significant under a Monte Carlo randomization test indicating structure within the weed community.

The influence of herbicide use on the weed community composition was greater in 1996 relative to 1995 (Figure 4.4). The use or absence of herbicide was separated on the first axis. Rotations 2 and 3 had separated on the second axis. The close proximity of rotation 1, f+ and f- to the centre of the ordination suggests that these systems did not strongly influence the weed community composition.

Rotation 3 was associated with dandelion, and stinkweed was once again associated with rotation 2, as was lamb's quarter, redroot pigweed and Canada thistle. Rotation 1 was associated with green foxtail, more so in the absence of herbicide and use of fertilizer.

Wild mustard and wild buckwheat were strongly associated with the absence of herbicide inputs. Canada thistle and stinkweed were associated with fertilizer. Lamb's quarter and redroot pigweed were associated with both the use of herbicide and fertilizer.

Rotation 3 was associated with f-, and neither were strongly associated with any weed species present. Since the ordination space indicates the pattern of species appearance, the two systems were having the same effect on the weed community.

To observe the influence all rotations had on weed community composition, it was more informative to look at the second and third axes, where the rotations were most strongly correlated, and herbicide had less influence on weed community composition. Species

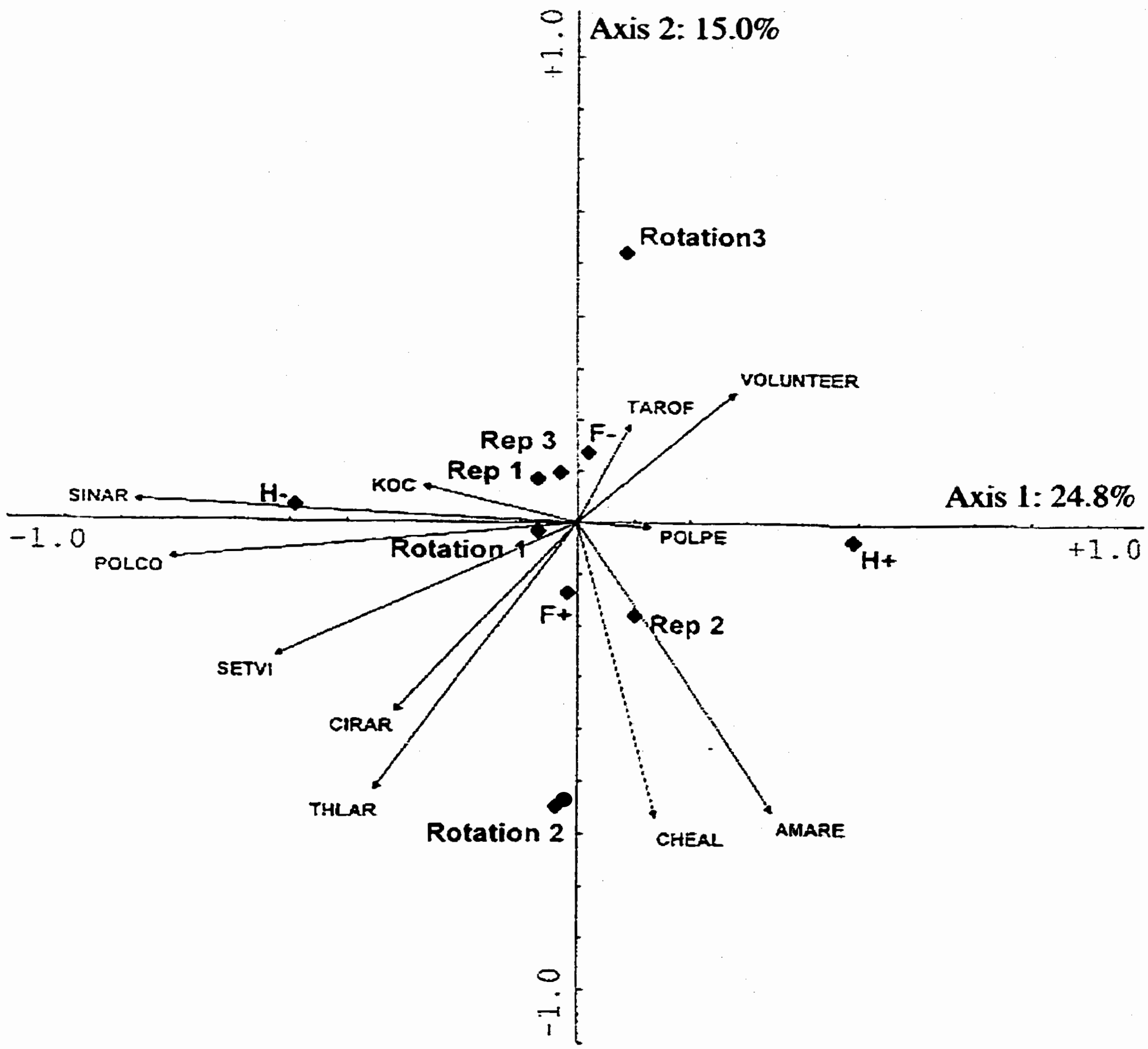

Figure 4.4 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1996. The first and second axes are presented and account for 39.8% of the total variation.

associations differed slightly from that observed on axis one and two, however the ordination was similar to that of axes one and two of 1995 (Figure 4.5). Rotation 2 and 3 separated on the second axis while rotation 1 separated from rotations 2 and 3 on the third axis. Dandelion was associated with rotation 3, stinkweed was associated with rotation 2 and Lady's thumb was associated with rotation 1. The maintenance of the rotation and weed associations between rotational phases demonstrates the strength of the associations.

The effect of fertilizer on weed community composition was demonstrated on the second and fourth axes (Figure 4.6). When fertilizer was absent, more volunteers (i.e. underseeded alfalfa, sweet clover and flax) were present. Canada thistle and green foxtail indicated a strong relationship with the presence of fertilizer.

In figures 4.4, 4.5 and 4.6, the only weeds associated with rotation 3 were dandelion and underseeded alfalfa indicating little threat from other prominent weed species in this type of robust cropping system.

4.3.3.3 1997 Weed Community Composition (Legume Year)

In 1997, rotations 1 and 3 were correlated with the first axis (0.9675 and -0.5623, respectively) and herbicide had a strong correlation with the second axis (h+: 0.937, h-: -0.937). The first two ordination axes accounted for 64.2% of the variation observed in the weed community composition. Rotation 2 had its strongest correlation with axis 3 (-0.6172), while fertilizer remained correlated with the fourth axis (f+: -0.6062, f-: 0.6062). With the exception of fertilizer, all environmental variables had shifted associations with ordinations axes over years, thus shifting their importance in determining weed community

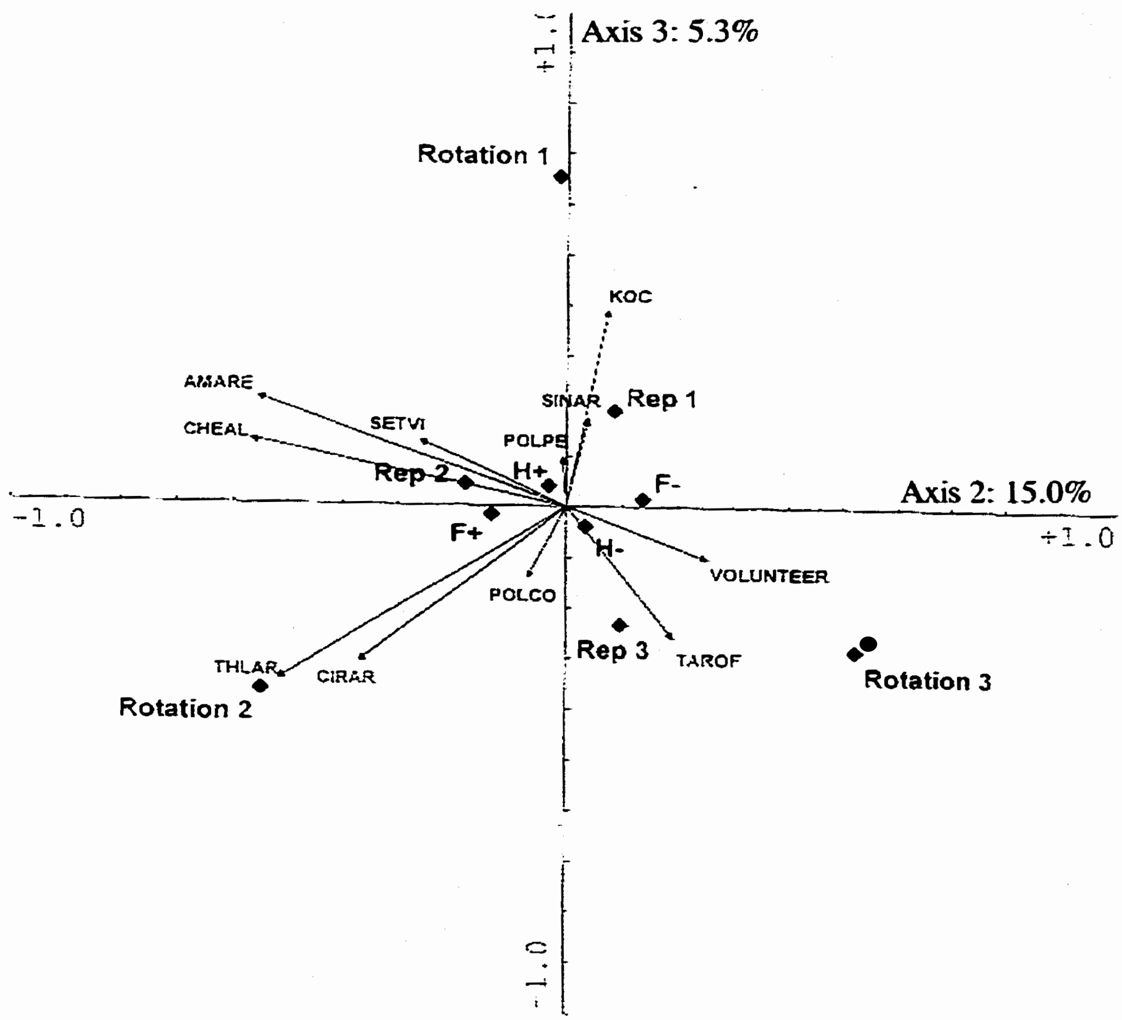

Figure 4.5 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1996. The second and third axes are presented and account for 20.3% of the total variation.

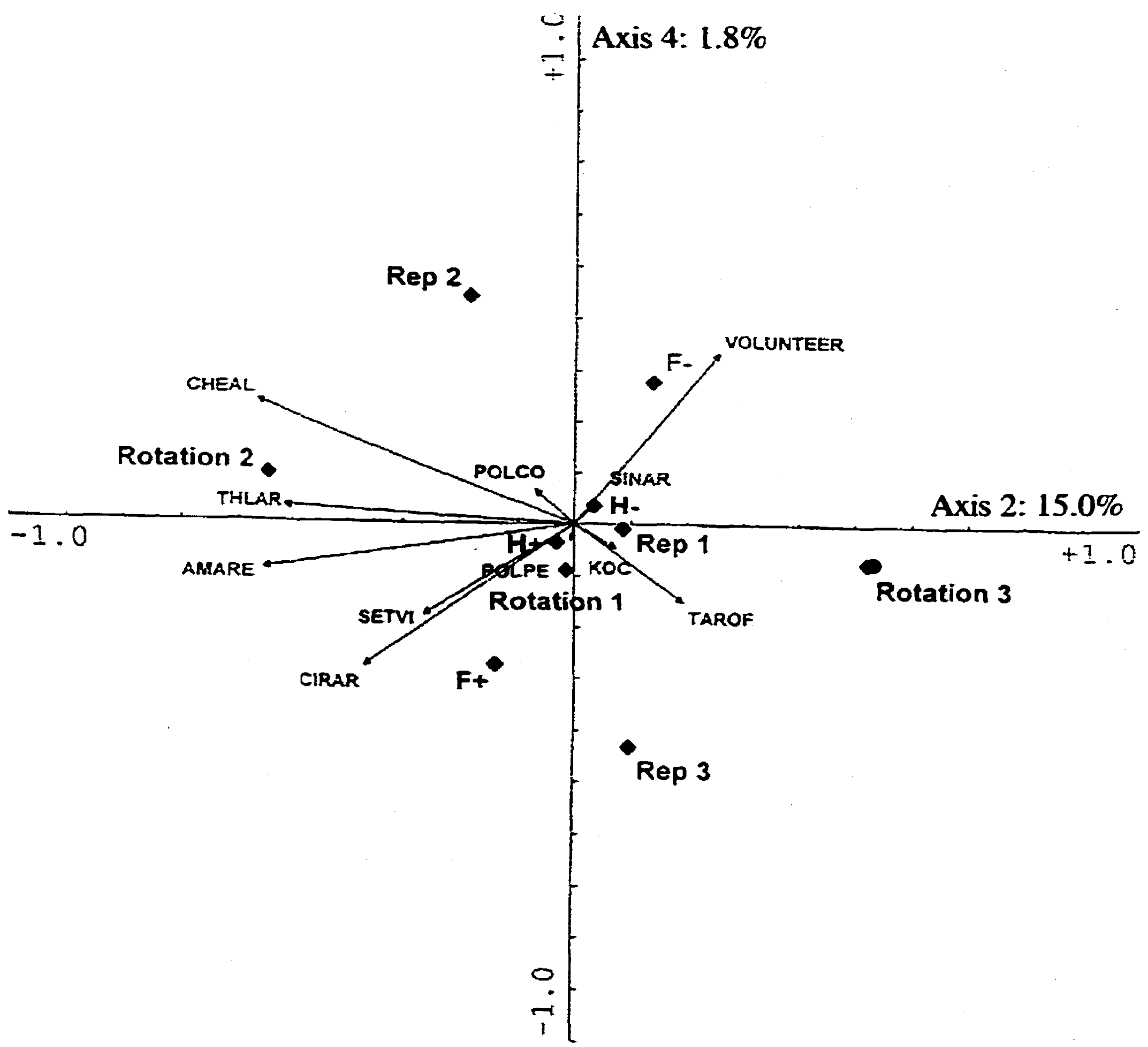

Figure 4.6 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1996. The second and fourth axes are presented and account for 16.8% of the total variation.

composition.

All four axes accounted for 67.8% of the variation observed in weed community composition. The species with greater than 45% of their variation explained by the four ordination axes include green foxtail (60.89%), wild mustard (59.17%), stinkweed (90.18%), wild buckwheat (73.29%), Canada thistle (71.46%), dandelion (70.32%), redroot pigweed (66.97%) and thymeleaf spurge (58.46%). In year two of the second rotation cycle, crop input was an important factor in determining weed community composition, although rotations were accounting for greater variability in the weed community (Figure 4.7). Rotations 2 and 3 were separated from rotation 1 on the first axis. Rotation 3 appeared to lie at the opposite end of a continuum with rotation 1, indicating dissimilarity in their weed community composition. Herbicide treatments were separated on the second. Fertilizer was having minimal effects on weed community composition within the first two axes of the 1997 ordination.

The similar placement of rotations 2 and 3 in ordination space indicated similarities of weed community composition in the two rotation systems. Weeds strongly associated with rotations 2 and 3 included dandelion and stinkweed, which was consistent with ordinations of previous years. Lamb's quarter, redroot pigweed, green foxtail and lady's thumb were associated with rotation 1. Where herbicide was used, few weeds were detected. Consistent with previous ordinations, the absence of herbicide in the cropping system drew a strong association with Canada thistle and wild mustard.

Axes 1 and 3 where studied to observe the weed community composition as affected by all rotations, axes one and three were used. Rotation 2 and 3 separated from rotation 1 on the first axis, while rotations 2 and 3 separated on the third axis (Figure 4.8). Similar to the

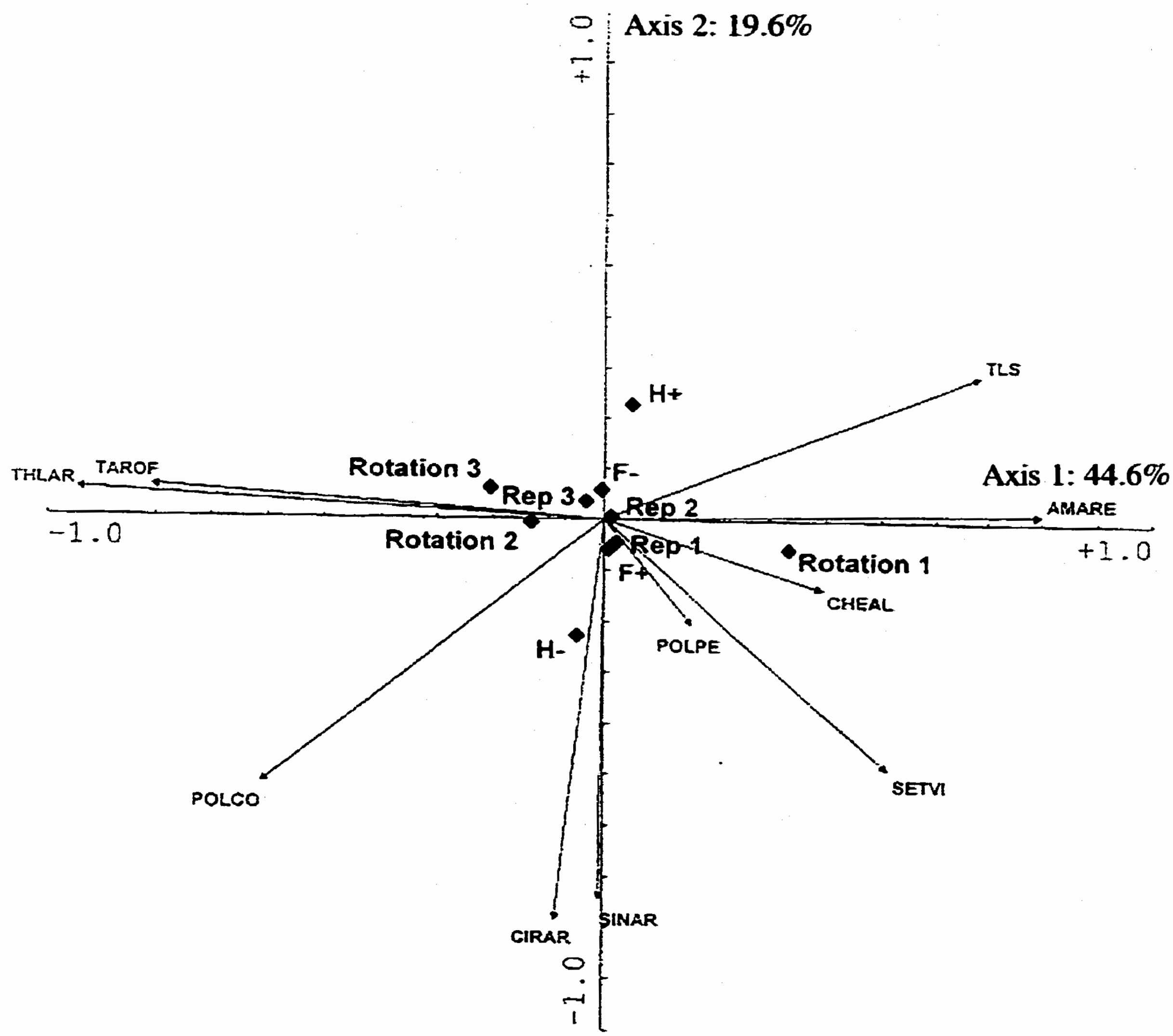

Figure 4.7 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1997. The first and second axes are presented and account for 64.2% of the total variation.

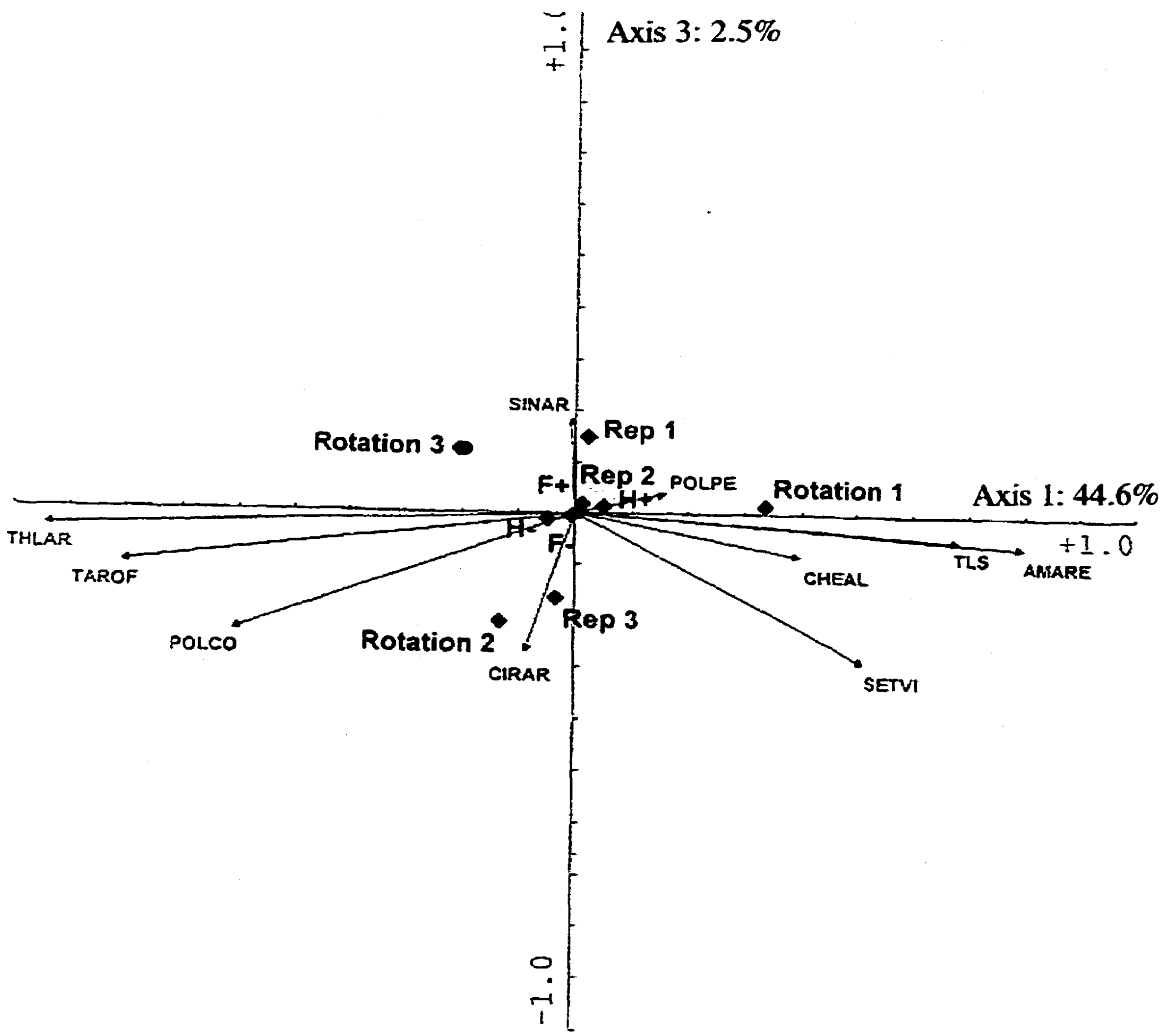

Figure 4.8 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1997. The first and third axes are presented and account for 47.1% of the total variation.

first and second axes of the 1997 weed ordination, lady's thumb, redroot pigweed, thymeleaf spurge, lamb's quarter and green foxtail were all associated with rotation 1. Rotation 2 was strongly associated with Canada thistle. Species associated with both rotations 2 and 3 included wild buckwheat, dandelion and stinkweed. Wild mustard was associated with both rotations 1 and 3.

Axes two and four were used to identify the influence fertilizer was having on weed community composition (Figure 4.9). The absence of fertilizer use was not associated with identified weed species suggesting minimal weed densities in the absence of fertilizer use. Weeds most strongly associated with fertilizer use included lady's thumb and redroot pigweed. The wild buckwheat vector layed between h- and f+ indicating a preference for an environment which lacks chemical control but remains fertile. It was likely that in a PFP system where crops was fertilized but not sprayed, wild buckwheat would become a problem over time.

4.3.3.4 1998 Weed Community Composition (Wheat, Wheat Following Sweet Clover Plowdown and Alfalfa)

In 1998, weed community composition assessment was not collected for rotation 3 and was consequently left out of the 1998 analysis (Figure 4.10). In 1998, herbicides and rotations were strongly correlated with axis 1 and 2 (h+: -0.8304, h-: 0.8304, rotation 1: 0.8561, rotation 2: -0.8561) respectively, thus most of the variation observed in the weed community can be attributed to rotation system and crop input management. The first two axes of the ordination diagram explain 57.9% of the variation of species Fertilizer was

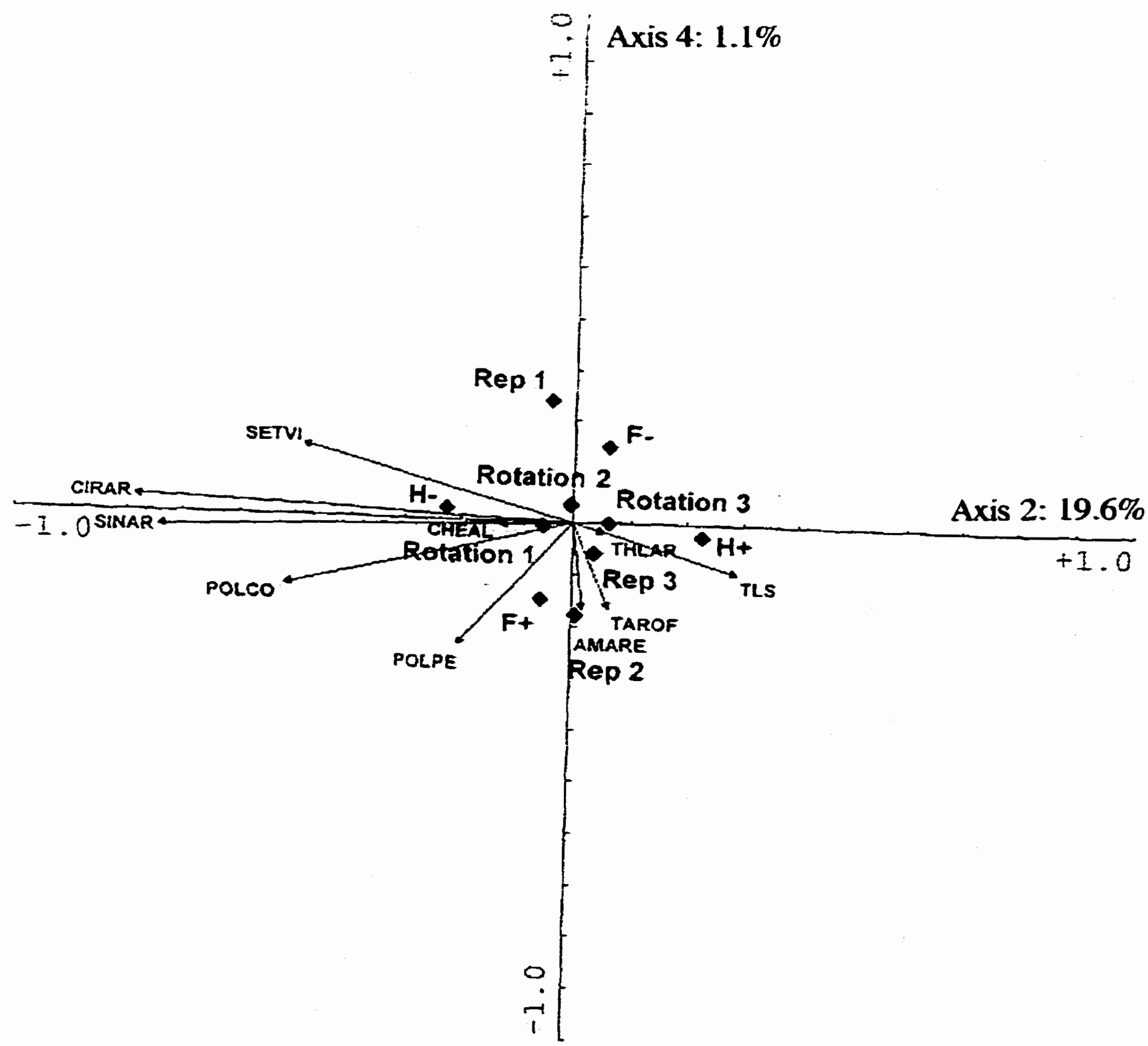

Figure 4.9 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1997. The second and third axes are presented and account for 20.7% of the total variation.

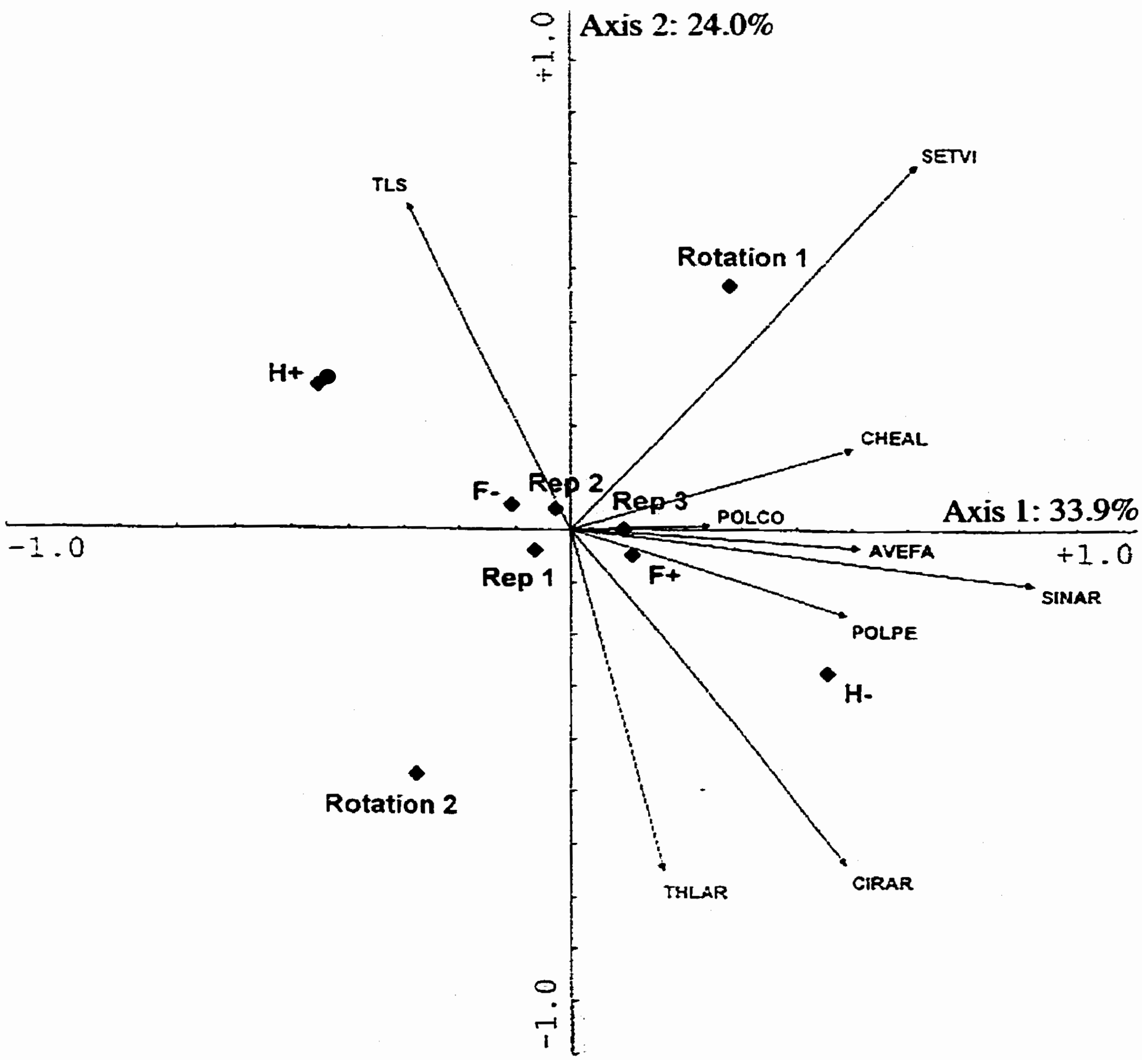

Figure 4.10 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1998. The first and second axes are presented and account for 57.9% of the total variation.

correlated with the third axis (f+: 0.8652, f-: -0.8652)..

The four ordination axes explained 61.7% of the total variation observed in the weed community composition. The number of species whose explained variation was greater than 45% included green foxtail (86.92%), wild mustard (69.4%), stinkweed (51.37%), Canada thistle (67.32%), thymeleaf spurge (52.17%) and lamb's quarter (48.04%)

Rotation and herbicide input management strongly influenced weed community composition. Herbicide input management and rotations were separated by the first and second axes. Fertilizer inputs were located close to the centre of the ordination diagram indicating minimal influence on the weed community composition.

Green foxtail was associated with rotation 1, while stinkweed and Canada thistle were associated with rotation 2. The vectors for lamb's quarter, wild buckwheat, wild oat, wild mustard and lady's thumb were between rotations 1 and 2. All listed species were found in both rotations 1 and 2, although in higher densities in rotation 1 (Table B.6). The species were more likely influenced by the presence of fertilizer and absence of herbicide use, both of which fell into the same ordination space as these weed species vectors. Herbicide use was not strongly associated with weeds suggesting minimal weed densities when herbicides were used. The vector for thymeleaf spurge appeared to be pulled in the direction of h+ system, suggesting greater abundance when herbicide was used.

The h+ subplots of rotation 1 may have been the main contributor to the strong influence of herbicide on weed community composition in 1998 because at the time of weed seedling assessment the h+ subplots of rotation 2 had not received herbicide since 1995. Although herbicide had a greater influence on weed community composition than fertilizer, it was interesting that herbicide and fertilizer environmental variables lay in the same direction. This may indicate that fertilizer strengthened the influence of the absence of herbicide in determining weed community composition. The same was true for the herbicide use and absence of fertilizer use.

It was important to examine the first and third axes of the ordination to understand the influence crop inputs were having in the weed community composition (Figure 4.11). Fertilizer and herbicide management were separated into the four quadrants of the ordination. The f + variable was associated with stinkweed and lamb's quarter while f- had no strong weed species associated. The absence of herbicide use was associated with all identified the weed species, excluding thymeleaf spurge. The build up of weed seedbank over time when herbicide was not used to manage the weed population and prevent weed seed return aided in strengthening the association.

4.3.3.5 1999 Weed Community Composition (Flax Test Crop)

In 1999, the pre in-crop measurement of weeds was used for RDA. Herbicide had its strongest correlation with axis one (h+: -0.9608, h-: 0.9608) while rotations 1 and 3 were strongly associated with axis 2 (0.9155, -0.6702 respectively). The first 2 axes of the ordination accounted for 42.2% of the variation observed in the weed community. Rotation 2 had a strong association with axis 3 (0.902). Fertilizer was not strongly correlated with any axis, suggesting that it was not an important determining component of weed community composition.

The four ordination axes explain 53% of the total variation observed in the weed community. The total percent variation has increased between the test crop years indicating

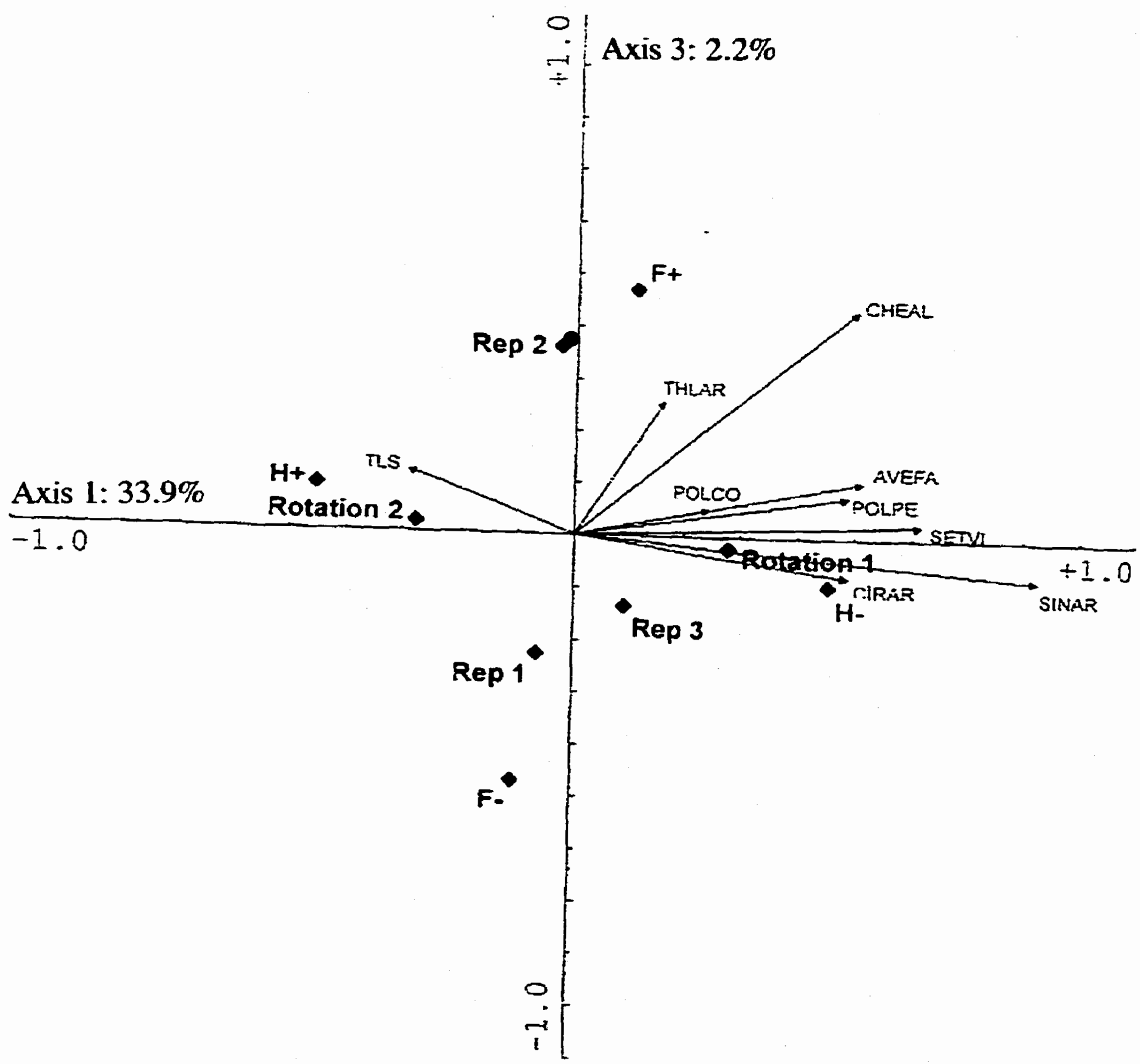

Figure 4.11 Redundancy analysis ordination diagram for weed community composition at the Glenlea long term cropping systems study, 1998. The first and third axes are presented and account for 36.1% of the total variation.

the that a greater amount of species distribution pattern was associated with rotation type and management of crop inputs in 1999 than in 1995. The increase in the variation accounted for by the four axes also indicated that the influence of rotation and crop input effects on weed community composition strengthened over time (i.e., from 1995 to 1999). These findings indicate the long time period required for cropping system communities to reach a stabilized equilibrium from which accurate observations can be made. Tilman (1986) found that the short term dynamics of a plant community following disturbance differ greatly from the long term equilibrium effects of the same disturbance.

In 1999, the four axes accounted for greater than 45% of the variation in nine weed species. These included Canada thistle (70.88%), green foxtail (84.58%), wild mustard (59.77%), wild buckwheat (69.69%), dandelion (47.17%), redroot pigweed (51.69%), yellow foxtail (48.41%), volunteer crops (57. 6%) and barnyard grass (47.53%).

Herbicide and rotation were clearly strong determinants of the weed community composition in 1999. However, the association of herbicide use with the first axis indicates it was a more important factor (Figure 4.12) than rotation. Management of herbicide was separated on the first axis. Rotations 1, 2 and 3, which had separated along the second axis, appeared to lie along a continuum where rotation 1 and 3 differed the most. It can be hypothesized that the difference in weed communities in continuous grains rotations are distinctly different than those of a crop rotation which includes a forage. Fertilizer input management had minimal effect on weed community composition as indicated by its location on the ordination (i.e., close to centre of ordination).

Weed species associated with rotation 1 included hempnettle, green foxtail, and wild oat. Most grassy weeds were associated with rotation 1. Green foxtail, wild oat and redroot

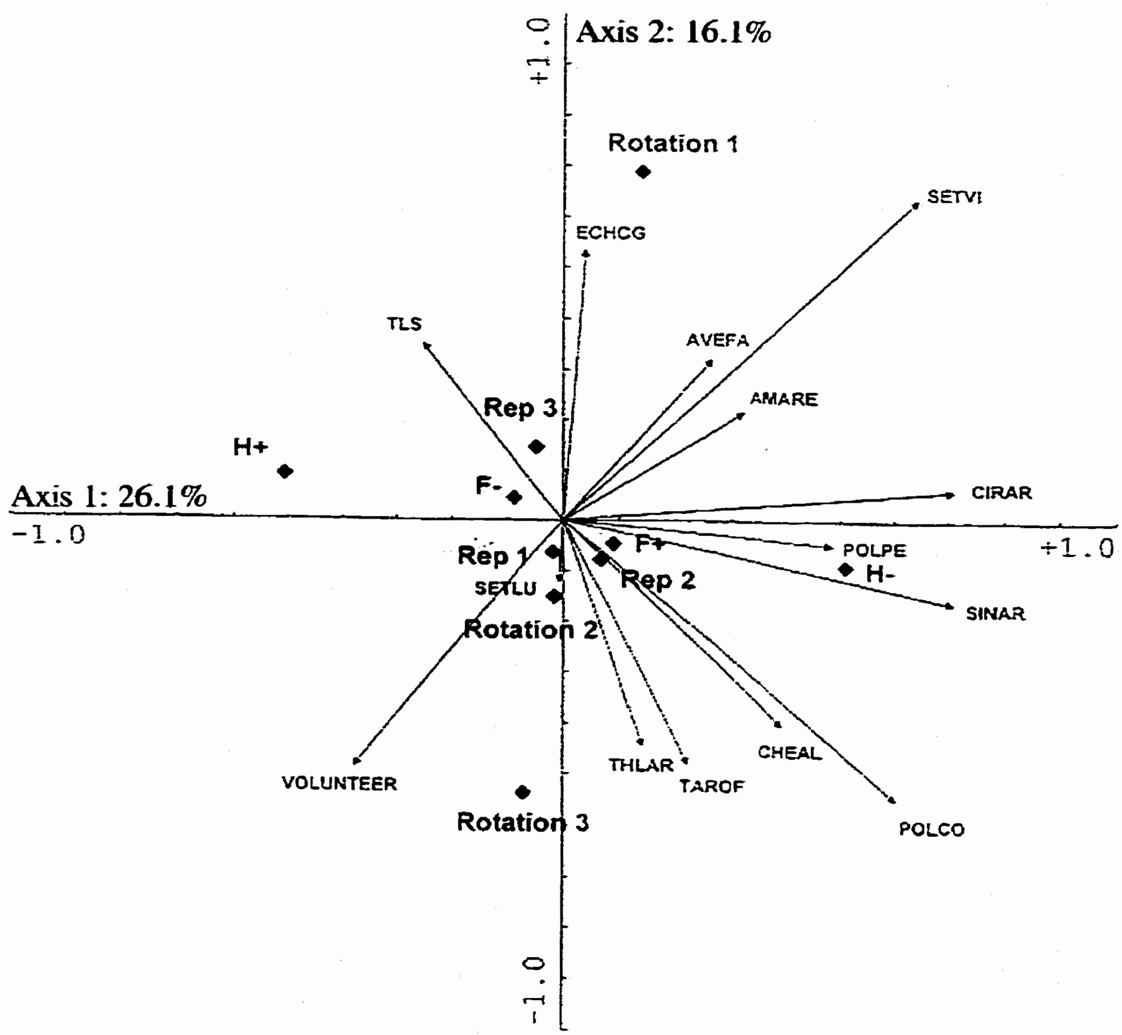

Figure 4.12 Redundancy analysis ordination diagram for weed community composition at the Glenlea long-term cropping systems study, 1999. The first and second axes are presented and account for 42.2% of the total variation.

pigweed vectors lay between rotation 1 and h-, indicating these species may be selected for in a low input annual grains cropping system. Table 4.8 confirms this hypothesis for green foxtail, however is less convincing for wild oat and redroot pigweed. Volunteer alfalfa was strongly associated with rotation 3, while rotation 2 was associated with yellow foxtail. Stinkweed, dandelion, lamb's quarter and wild buckwheat were all associated with rotations 2 and 3.

Thymeleaf spurge was the only weed species to be associated with the use of herbicide. Wild mustard, Canada thistle and lady's thumb were strongly associated with no herbicide use.

4.3.3.6 Summary of Weed Community Composition Results

The associations between weed species and cropping systems identified within the Glenlea long-term cropping systems study support work by several other researchers (Chancellor and Froud-Williams, 1986; Derksen, et al., 1998; Derksen et al., 1996; Derksen et al., 1993; Swanton and Murphy, 1996) who concluded that weed floras reflect agricultural practice. For example, in the present study green foxtail was associated with rotation 1, Canada thistle and stinkweed were associated with rotation 2, and dandelion was associated with rotation 3. Wild buckwheat, lady's thumb, redroot pigweed, green foxtail, wild mustard, lamb's quarter and Canada thistle were associated with either the h- or the combined h- and f+ environmental variables. Therefore, both crop rotation and crop input management played an important role in determining weed specie community.

Rotation 1 likely selected for grassy weeds, such as green foxtail, by providing a similar habitat and plant life cycle in each rotation phase. Work by Hume et al. (1991) indicated that green foxtail becomes a problem on land that is continually cropped with spring seeded annual crops. The inclusion of forages in rotation has been found to suppress green foxtail for 1, 2, or more years (Entz et al., 1995) thereby reducing green foxtail association with rotations 2 and 3 in the present study.

Rotation 2 selected for stinkweed for the following reasons: 1) No tillage in the sweet clover establishment year, thus this winter annual weed was able to establish in the sweet clover year. 2) In the second 4-year phase of the rotation cycle (i.e., 1996-1999), green manuring action took place during the second week of July, at the time when stinkweed plants would be expected to have flowered (Best and McIntyre, 1975) and set seed. 3) Klebesadel (1969) found that the larger the stinkweed seedling was at the onset of winter, the greater the number of seed pods were produced the following year. Stinkweed plants in sweet clover establishment year would be able increase in size without tillage disturbance. As well, following green manure the stinkweed would have time to mature and accumulate size before winter. 4) N released from green manured sweet clover may have encouraged additional germination and growth of stinkweed within the same cropping season.

The following reasons are suggested for the association of rotation 2 with Canada thistle: 1) no fall tillage in sweet clover establishment year allowed Canada thistle establishment. 2) Canada thistle root systems were fragmented by tillage and green manure, and vegetatively propagated. These factors can contribute to increase in the area of infestation (Moore, 1975; Ross et al., 1985).

Rotation 3 selected for dandelion likely because dandelion's prostate growth form was able to avoid defoliation during mechanical hay harvest of alfalfa in the second and third years of the rotation 3 cycle (Ominski, 1998). Dandelion does not experience germination periodicity (Chepil, 1946) thus could have germinated on exposed soil following hay harvest. Dandelion seedlings would have also benefited from N released by alfalfa. Plants would have matured before the end of the cropping season thereby increasing weed seed return resulting in increased populations in succeeding years.

The f+h- crop input system selected for wild buckwheat likely because of wild buckwheat's competitive ability for limited nutrient resources (Hume et al., 1983). The occurrence of wild buckwheat in the f+h- systems was therefore not surprising as added fertilizer contributed to increased DM through increased competition for resources. The absence of chemical control allowed increased interspecific plant competition; a situation that may have favoured wild buckwheat increase.

The f+h- crop input system significantly increased densities of lady's thumb and redroot pigweed, while the f-h- system had lower lady's thumb and redroot pigweed densities. This observation suggests that, in the absence of herbicide, the amount of nutrients made available to lady's thumb and redroot pigweed determined the abundance of these weed species within the cropping systems. Although no literature was available on the response of lady's thumb to fertilizer, preliminary results from greenhouse studies on weed response to fertilizer indicates a considerable increase in green smartweed (a close relative of lady's thumb) biomass to increased N and P (Blackshaw, 2001, Personal Communication). Literature indicating redroot pigweed is not significantly influenced by fertilizer (Hume, 1980), contradicted findings in the present study.

The h- variable selected for Canada thistle. This was attributed to Canada thistle's superior competition for essential resources in the absence of control. Canada thistle uses nutrients needed by the crop (Hodgson, 1968b) thus when no fertilizer was used, competition increased for the limited resource. The abundance of Canada thistle in the f-h- subplots increased relative to f-h+ subplots. Similar scenarios were observed for green foxtail, wild mustard, and lamb's quarter.

Hempnettle and thymeleaf spurge were associated with rotation 1 and the use of herbicide. Hempnettle and thymeleaf spurge are not common species in agricultural fields, occurring in 13.9% and 8.0%, respectively, of Manitoba oilseed or cereal fields (Van Acker et al., 2000). It was hypothesized that the control of important weed species, such as wild mustard, created niche space in the cropping system, allowing secondary weed species (those suppressed by more economically important weed species), such as hempnettle and thymeleaf spurge, to establish. Similar findings by Hay (1968) indicated that when wild mustard was controlled chemically, cow cockle seed production increased causing significant build up of the weed.

The separation of rotations 1 and 3 by the first axis in each year of the RDA analysis was of interest. In 1999 (Figure 4.12), rotations 1, 2 and 3 appeared to lie along a continuum with rotation 1 and 3 being at opposite ends of that continuum. This observation suggests that the grain and alfalfa based rotations contained distinctly different weed communities when both systems were seeded to a flax test crop.

Another point of interest was the shift over time, from rotation as the dominant determinant in weed community composition, to herbicide use being a dominant contribution to weed community composition. Few studies have considered the long-term effect of herbicide use on weed communities. In 1995 (Figure 4.1), h- and h+ were positioned relatively close to the origin of the ordination, indicating a weak influence of herbicide use on weed community composition. In that year, rotations were placed farther from the origin than herbicides indicating a stronger effect of rotation than of herbicide on weed community composition. Over the next four years (1996-1999), rotation maintained an influence on weed community composition, with the relative strength depending on the crop grown. However, the herbicide use effect on weed community composition increased dramatically between 1996 and 1999. This dramatic increase can be attributed to short term dynamics of plant communities following disturbance greatly differing from the long term, equilibrium effects of the same disturbance (Tilman, 1986). Herbicide has been considered to have a higher efficacy in weed control than other weed control measures (Coble, 1996), such as rotation, thus herbicide management would be expected to have a strong influence on weed community composition.

Fertilizer, on the other hand, appeared to have minimal influence on weed community composition throughout the duration of the present study. The soil at the Glenlea long-term cropping systems study location was relatively fertile thus fertilizer effects may require 3 or more rotation cycles before the fertilizer impact on weed community composition becomes strong.

4.4 Ground Beetles as Influenced by Crop Rotation Type and Crop Input Management

4.4.1 Ground Beetle Activity Assessment

4.4.1.1 1995 Average Ground Beetle Capture

In 1995, ground beetle assessments were conducted on the average capture of four sampling periods. In 1995, three species of ground beetles where significantly influenced by a rotation X treatment interaction (Table 4.15). *Anisodactylus sanctaecrucis*, a weed and insect eater, was observed within the low input treatments, where many of the weeds (Table 4.4) could increase food supply or alter the microclimate more favorably for the species. *Anisodactylus sanctaecrucis* was not captured in either rotation 2 or 3. Other studies have indicated that increased weediness in biological systems provide nutrition for seed feeding ground beetle species (Cromar et al., 1999; Kromp, 1989). Clark et al. (1997) demonstrated that management practices could not be categorized as positive or negative, rather that some practices favour some species while others are deterred.

Bembidion spp. occurred in equal numbers among all subplots of rotations 2 and 3 but differed between crop input treatments in rotation 1, thereby causing the significant interaction. The most *Bembidion* spp. in rotation 1 were found in the f+h- subplot. Total DM was ample in this subplot (Table 4.2) thus possibly altering the habitat in a favourable manner for *Bembidion* spp.

Harpalus herbivagus was present in relatively equal numbers in rotations 1 and 2. In rotation 3, it only appeared in low input subplots, the most occurring in the h+ subplots. The

Table 4.15 Average ground beetle capture for 4 sampling dates at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

	Rotation 1				Rotation 2				Rotation 3				Prairie	Prairie vs.				
	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-		Rotations	Rotation (R)	Treatment (T)	R X T	SEM
AMAR_APR	0.3	1.0	0.7	1.3	0.3	0.3	0.3	0.3	0.0	0.7	0.3	0.3	0.7	0.572	0.2139	0.1095	0.5082	0.24
AMAR_AVI	0.7	2.7	0.3	2.0	0.0	0.3	0.3	0.7	0.3	0.7	0.7	0.3	0.3	0.2853	0.072	0.0898	0.193	0.47
AMAR_CAR	0.3	1.0	0.3	1.0	1.0	0.3	1.0	1.0	0.0	0.7	0.3	0.7	0.7	0.0701	0.5169	0.2333	0.1119	0.25
AMAR_CUP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.†	.	.	.	0.00
AMAR_FAR	0.3	0.7	0.0	0.0	0.3	0.7	0.0	0.0	0.0	0.3	0.0	0.3	0.3	0.8022	0.6593	0.1609	0.8522	0.30
AMAR_LIT	0.7	0.7	0.0	0.0	0.7	0.7	0.0	0.7	0.0	0.3	0.7	0.0	0.3	0.4547	0.2844	0.3095	0.0982	0.25
AMAR_OBE	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	.	0.4444	0.5834	0.3665	0.14
ANIS_SAN	0.0	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4547	0.0123	0.0013	0.0003	0.10
BEMB_SPP	0.3	1.3	0.7	0.0	0.7	1.0	0.7	1.0	1.0	1.0	1.0	2.0	0.0	0.4547	0.4342	0.2378	0.0458	0.25
BRAD_CON	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
CALO_CAL	0.7	0.7	1.0	0.7	0.7	1.0	1.0	1.0	1.3	1.0	2.0	1.3	1.3	0.4547	0.4632	0.5533	0.9791	0.39
CHLAE_SE	0.7	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0701	0.25	0.2673	0.1081	0.21
HARP_AMP	0.0	0.0	0.0	0.0	0.7	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.1788	0.2844	0.1501	0.1975	0.16
HARP_ERR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
HARP_HER	0.7	0.7	0.3	1.7	1.0	1.0	0.3	1.0	0.0	1.0	1.3	0.0	1.3	0.0219	0.269	0.4759	0.0221	0.36
HARP_PEN	1.0	1.0	0.0	1.3	0.7	0.3	1.0	1.0	0.3	0.7	0.7	0.3	3.7	0.0076	0.4275	0.8348	0.1817	0.36
PTER_COR	8.7	8.0	7.7	3.7	7.7	6.0	4.0	7.7	7.0	8.3	5.3	5.7	5.3	0.7508	0.9807	0.3933	0.3593	1.87
PTER_FEM	1.0	0.7	0.7	0.3	1.0	0.3	0.0	0.7	0.0	1.0	0.3	0.7	0.7	0.2853	0.7254	0.6369	0.1864	0.33
PTER_LUC	0.7	0.7	0.7	0.0	1.0	0.3	0.0	0.7	0.7	1.3	0.3	0.7	0.0	0.0501	0.5527	0.161	0.1307	0.27
PTER_MEL	0.7	1.3	0.7	1.0	0.0	0.3	0.3	0.7	0.7	0.3	0.3	0.7	0.7	0.0701	0.0103	0.5271	0.7951	0.33
STEN_COM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
TRIC_COG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_CUP	1.3	3.7	0.3	1.0	1.0	1.0	0.7	0.7	0.3	1.0	1.0	1.3	1.0	0.4547	0.603	0.274	0.1887	0.81
AGON_DEC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_PLA	1.3	5.0	1.0	4.0	2.0	3.0	0.3	1.3	1.3	2.7	2.3	4.0	1.3	0.73	0.7646	0.0227	0.3846	1.22
AGON_PUN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_TRIG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
LORI_FOV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
DICA_SCU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	.	0.4444	0.4155	0.4552	0.10
HARP_FUL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
Total	19.3	30.0	14.7	18.7	18.7	17.3	10.3	18.7	12.7	21.7	16.7	17.7	18.7	0.3763	0.3997	0.014	0.1401	2.88

† Values of 0 for all analysed variables yielded no statistical probability

dense vegetation imposed by alfalfa in rotation 3 of the previous years may have impeded movement of *H. herbivagus*, deterring it from this system. Reduced activity would likely reduce the number of eggs layed thereby reducing catches in the succeeding year. The use of herbicide without fertilizer would reduce plant density in the subplot, providing a more favourable environment.

Two ground beetle species, *A. sanctaecrucis* and *P. melanarius*, were significantly influenced by the rotation system (Table 4.15). *Anisodactylus sanctaecrucis* was found in rotation 1 only (Table 4.16). The weed DM was greatest in rotation 1. Seed production of weeds is positively correlated to plant size (Jornsgard et al., 1996). The increased weed seed food source may have attracted *Anisodactylus sanctaecrucis* species to rotation 1.

When averaged over the sampling period, *P. melanarius* was found evenly distributed between the three rotations. Fisher's protected LSD tests indicated rotation 1 to be significantly higher than rotation 2, with rotation 3 not differing from either rotation. Research has been inconsistent in findings of the influence of agricultural practices on *P. melanarius*. Clark et al. (1997) found an increased number of this species in alfalfa, however Carcamo et al. (1995) found no difference in activity between barley and legume treatments receiving synthetic fertilizer and herbicides.

Anisodactylus sanctaecrucis was significantly influenced by crop input treatment in 1995 (Table 4.15). *Anisodactylus sanctaecrucis* was identified in low input systems only, but was greater in f+h- subplots (Table 4.16). The only other species of ground beetle to be significantly influenced by crop inputs in 1995 was *A. placidum*, which had the greatest activity where herbicide was not used. *Agonum placidum* appeared to have an affinity for accumulated biomass in the absence of herbicide with a preference for nutrient rich sites.

Table 4.16 Average ground beetle capture for 4 sampling dates at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means with the same letter are not significant different LSD (p<0.05).

		ANIS_SAN	PTER_MEL	AGON_PLA	Total
Rotation					
	Rotation 1	1 a	1 a	3	21
	Rotation 2	0 b	1 b	2	17
	Rotation 3	0 b	1 ab	3	18
SEM		0.05	0.08	1.13	1.94
Inputs					
	f+h+	0 b	1	2 bc	17 b
	f+h-	1 a	1	4 a	23 a
	f-h+	1 b	1	2 c	14 c
	f-h-	0 b	1	4 ab	19 ab
SEM		0.06	0.19	0.71	1.66

Clark et al. (1997) also who found greater activity of *A. placidum* in systems not receiving herbicides or fertilizers, with conventional tillage.

In 1995, the total ground beetle capture was significantly influenced by crop inputs (Table 4.15). Ground beetles were greatest in h- subplots (Table 4.16) as ground cover and food sources increased in the absence of herbicide due to increased biomass from weeds (Table 4.3) and increased food source from weed seeds. A favourable microhabitat would attract both ground beetles and prey insects. Purvis et al. (1984) found the highest capture numbers of Coleoptera to occur in plots where no herbicide was applied.

4.4.1.2 1999 Average Ground Beetle Capture

In 1999, analysis for ground beetle assessments were conducted on the average capture of five sampling periods. *Harpalus pensylvanicus* was significantly influenced by a rotation X treatment interaction (Table 4.17). Within rotation 1, the most beetles were found in the f+h- subplot, followed by f-h-, f+h+ and f-h+. This followed the decreasing order of total weed count in the pre in-crop spraying weed assessment (Table 4.8). There was an abundance of green foxtail seed within rotation 1. *Harpalus pensylvanicus* adults feed on weed seeds, including green foxtail (Ellsbury et al., 1998; Tonhasca, 1993), thus this species was likely responding to the available food sources. Ellsbury et al. (1998) found the proportion of *H. pensylvanicus* and diversity of ground beetles was greatest in low input plots, which they attributed to habitat preference for a weedier environment. Other research indicated increased weediness in the biological system provided nutrition for seed feeding ground beetle species, such as *Amara* and *Harpalus* (Cromar et al., 1999; Kromp, 1989). In rotation 2, the greatest capture of *H. pensylvanicus* occurred in h- subplots, where the greatest abundance of weeds also occurred. Rotation 3 had a stable capture of *H. pensylvanicus* between subplots in 1999, reflective of the lower weed abundance within this rotation compared with rotation 1.

Amara apricaria, *H. pensylvanicus*, *P. corvus* and *Agonum cupreum* were significantly influenced by the rotation system (Table 4.17). *Harpalus pensylvanicus* and *P.*

Table 4.17 Average ground beetle capture for 5 sampling dates at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when p<0.05.

	Rotation 1				Rotation 2				Rotation 3				Prairie	Prairie vs.				
	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-		Rotations	Rotation (R)	Treatment (T)	R X T	SEM
AMAR_APR	0.7	1.3	0.7	0.7	0.7	4.3	1.0	1.3	1.0	3.7	1.0	1.3	0.3	0.572	0.0538	0.0001	0.3202	0.47
AMAR_AVI	0.3	1.0	0.3	0.3	0.7	1.3	0.0	1.0	0.3	1.7	1.0	1.0	0.0	0.2853	0.1928	0.0056	0.1715	0.28
AMAR_CAR	1.0	1.0	0.7	1.0	1.0	0.7	1.0	1.3	1.0	1.0	1.0	1.0	0.3	0.0701	0.6593	0.3583	0.292	0.16
AMAR_CUP	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.[‡]	0.4444	0.4155	0.4552	0.10
AMAR_FAR	0.0	0.0	0.0	0.3	0.0	0.3	0.0	0.3	0.7	0.3	0.3	0.0	0.0	0.0701	0.5878	0.8603	0.1667	0.19
AMAR_LIT	1.0	1.0	0.3	1.0	0.3	2.0	1.0	4.0	0.7	1.3	0.7	1.0	0.3	0.6128	0.4833	0.0635	0.4796	0.84
AMAR_OBE	0.0	0.0	0.3	0.3	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.4547	0.9403	0.7401	0.7424	0.24
ANIS_SAN	7.3	6.3	10.3	2.0	0.7	1.3	1.0	1.0	0.3	1.0	1.0	1.0	0.3	0.0478	0.0867	0.2795	0.1431	2.04
BEMB_SPP	1.0	0.3	0.7	0.7	0.7	0.7	0.7	1.0	1.0	0.7	0.3	1.0	0.0	0.0161	0.8711	0.2642	0.7268	0.28
BRAD_CON	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	0.4444	0.4155	0.4552	0.10
CALO_CAL	0.0	1.0	0.0	1.0	0.3	0.3	0.3	0.3	0.7	0.7	0.3	0.7	0.3	0.572	0.4444	0.1677	0.3404	0.29
CHLAE_SE	1.0	1.3	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.5376	0.6304	0.7191	0.6342	0.23
HARP_AMP	1.0	1.3	0.7	1.7	1.3	3.0	1.3	2.7	1.0	1.3	1.0	1.0	0.3	0.1377	0.1195	0.0212	0.4843	0.38
HARP_ERR	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4547	0.1111	0.641	0.7479	0.15
HARP_HER	0.7	0.7	1.0	0.7	0.7	1.0	0.0	0.7	0.0	0.3	0.0	0.3	0.7	0.3486	0.0609	0.3901	0.4732	0.28
HARP_PEN	7.3	21.3	2.3	11.3	1.7	8.0	5.0	9.3	2.3	3.0	2.3	3.7	1.3	0.0332	0.0543	0.0005	0.0111	2.67
PTER_COR	32.3	54.7	19.0	31.3	15.0	27.3	14.3	29.7	14.3	17.3	13.3	14.3	2.0	0.0093	0.0259	0.0009	0.1179	6.13
PTER_FEM	0.3	0.3	0.3	0.0	1.0	1.0	0.3	0.7	1.0	1.0	0.7	0.7	1.0	0.0701	0.0803	0.1501	0.8002	0.24
PTER_LUC	0.7	1.3	0.7	1.0	0.3	1.0	0.7	1.0	0.7	1.0	1.0	1.0	1.0	0.572	0.5373	0.0512	0.8929	0.24
PTER_MEL	1.0	2.3	0.7	1.7	1.0	2.7	1.3	2.0	1.7	4.3	2.3	1.7	2.0	0.3617	0.1103	0.0005	0.3898	0.52
STEN_COM	0.7	0.0	0.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0701	0.3705	0.4125	0.365	0.21
TRIC_COG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_CUP	0.3	1.3	0.0	1.3	0.3	1.0	0.0	1.0	0.3	0.3	0.0	0.0	1.3	0.1829	0.0449	0.0018	0.1365	0.28
AGON_DEC	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.0	0.7	0.0701	0.4444	0.5834	0.3665	0.14
AGON_PLA	4.7	22.7	2.0	18.0	4.7	24.7	3.3	15.3	4.3	6.7	5.7	5.7	0.7	0.3927	0.3177	0.0007	0.3176	5.53
AGON_PUN	0.3	0.7	0.0	0.7	0.0	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.6542	0.223	0.3586	0.4982	0.21
AGON_TRIG	1.0	1.0	0.0	0.0	0.3	0.7	0.3	1.0	0.3	0.3	0.3	0.3	1.3	0.4547	0.2844	0.243	0.0794	0.27
LORI_FOV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
DICA_SCU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4547	.	.	.	0.00
HARP_FUL	0.0	0.3	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4547	0.64	0.735	0.3127	0.15
Total	63.0	122.0	42.0	76.3	32.0	83.3	33.3	75.3	33.0	47.3	34.0	37.0	15.0	0.002	0.0327	0.0001	0.0087	11.67

[‡] Values of 0 for all analysed variables yielded no statistical probability

corvus had the greatest activity in rotation 1 > rotation 2 > rotation 3 (Table 4.18). Rotation 1 had the greatest abundance of weeds, providing food source for *H. pensylvanicus*. The increased humidity from the ground cover by weeds would attract both species and prey insects for *P. corvus*. Fewer beetles in rotation 2 may be attributed to disturbance caused by green manuring, off setting captures for succeeding years. In rotation 3, dense architecture of the alfalfa plant may have impeded movement, deterring ground beetles from inhabiting this system. Reduced weed densities in rotation 3 would also reduce the food source available to *H. pensylvanicus*.

Amara apricaria appeared to prefer rotations 2 and 3 over rotation 1, likely an indirect result of the added N from previous green manure and alfalfa hay crops. The N would have stimulated an increase in plant growth and biomass thereby supporting a greater capture of ground beetles. Larsen et al. (1996) observed a higher capture and diversity of ground beetles in fertilized plots. Despite initial significance in ANOVA (Table 4.17), there was no significant differences in the number of *A. cupreum* observed between rotation when separated by rotation means (Table 4.18). When averaged over the sampling period, *Agonum cupreum* did not differ between rotations but was considered significant. The Fisher's protected LSD indicated rotations 1 and 2 had the greatest capture of this ground beetle species. Weiss et al. (1990) found other *Agonum* species to be more abundant in annual cropped conventionally tilled system versus a stable alfalfa cropping system. No reasons were given.

Two *Amara*, two *Harpalus*, three *Pterostichus* and two *Agonum* species were significantly influenced by crop input (Table 4.17). Both *A. apricaria* and *A. avida* where significantly greatest in the f+h- subplots. The largest amount of weeds occurred in the same

Table 4.18 ***Average ground beetle capture for 5 sampling dates at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data. Means with the same letter are not significant different LSD (p<0.05).***

		AMAR_APR	AMAR_AVI	HARP_AMP	HARP_PEN	PTER_COR	PTER_LUC	PTER_MEL	AGON_CUP	AGON_PLA	*Total*
Rotation											
	Rotation 1	0.8 b	1	2	10.6 a	34.3 a	1	2	1	12	75.8 a
	Rotation 2	1.8 a	1	3	6.0 b	21.6 b	1	2	1	12	56.0 b
	Rotation 3	1.8 a	1	2	2.8 c	14.8 c	1	3	1	6	37.8 c
SEM		0.23	0.14	0.31	1.99	5.09	0.10	0.23	0.08	3.69	7.76
Inputs											
	f+h+	0.8 b	0.4 b	1.1 bc	3.8 b	20.6 bc	0.6 b	1.2 b	0.3 bc	4.6 b	42.7 c
	f+h-	3.1 a	1.3 a	1.9 a	10.8 a	33.1 a	1.1 a	3.1 a	0.9 a	18.0 a	84.2 a
	f-h+	0.9 b	0.4 b	1.0 c	3.2 b	15.6 c	0.8 ab	1.4 b	0.0 c	3.7 b	36.4 c
	f-h-	1.1 b	0.8 ab	1.8 ab	8.1 a	25.1 ab	1.0 a	1.8 b	0.8 ab	13.0 a	62.9 b
SEM		0.27	0.16	0.22	1.48	3.54	0.14	0.30	0.16	3.19	6.74

subplot providing adequate nutrients for this weed seed feeding species (Cromar et al., 1999; Kromp, 1989).

When separated by their means, *H. amputatus* and *H. pensylvanicus* species demonstrated similar results (Table 4.18). The greatest occurrence of *H. amputatus* and *H. pensylvanicus* species was in h- subplots. Adults of the *Harpalus* species prefer to eat seeds, roots or weeds and other insects (Larochelle, 1990; Lindroth, 1961-1969;Tonhasca, 1993). Although a direct cause and effect cannot be determined from data available in this study, the density of weeds was greatest in unsprayed subplots (Table 4.9) thus likely increasing the food resources and favorably altering the microclimate in the cropping system.

Pterostichus melanarius, *P. lucublandus* and *P. corvus* were most abundant in the f+h- subplot, the subplot which tended to have the largest weed population and greatest total biomass (Table 4.3). *Pterostichus* species are typically carnivorous. If increased plant biomass increased the overall insect activity, this would increase the food source for *Pterostichus*.

When separated by means, the use of herbicide was clearly associated with a decreased number of *A. cupreum* and *A. placidum* found within subplots. Similar effects of crop inputs occurred for *Harpalus* species, and is in agreement with Clark et al. (1997), who found greater activity of *A. placidum* in systems not receiving herbicides or fertilizers.

Rotation, crop inputs and the interaction of the two systems had a significant influence on ground beetle total catches (Table 4.17). Within rotation 3, the f+h- subplot had the greatest activity of ground beetles, however all other subplots within rotation 3 had similar ($P>0.05$) captures. The results suggested that in a robust system, the use of crop inputs did not increase beneficial insects present within the cropping system. Rotation 2 had twice as many ground beetles in h-subplots than in the h+ subplots suggesting that an organic cropping system which included a green manure legume would support a strong activity of beneficial insects. Rotation 1 had the most variable total ground beetle activity between crop input management systems. This indicates that in a fragile rotation, the management of inputs will be a significant factor in determining the presence of beneficial organisms in the long term. In rotation 1, the system that had the highest ground beetle capture (Table 4.17) produced the second lowest grain yield (Table 4.2), while the systems that had the highest ground beetle capture in rotation 3 were capable of producing high grain yields.

When individual rotations were examined, the annual rotation was found to have the largest capture of ground beetles (Table 4.18). The large weed population found within rotation 1, would influence the microclimate and food source favorably. Although the ground beetle activity should be encouraged, a large weed population was not desired in a cropping system. The introduction of a relay or inter-crop forage may help to suppress the weeds, stabilize the system and encourage the ground beetle activity.

Lower ground beetle captures in rotation 2 versus rotation 1 may be attributed to the disturbance of the green manure action. The beetle life cycle can require up to one year of larval development in the soil (Luff and Rushton, 1988). The disturbance of the green manure may have disrupted the ground beetle activity for succeeding years. An even lower beetle capture in rotation 3 may be because the density of the alfalfa hay crop may have impeded beetle movement, deterring them from this type of system and resulting in a low ground beetle capture (Kielhorn et al., 1999). Also, the lower weed population in rotation 3 would only be able to provide a small food source.

A clear effect of crop input management on ground beetle capture was observed in 1999. When herbicides were used, there were few ground beetles, attributed to the reduced ground cover thus reduced humidity and soil moisture, which would deter many ground beetles (Brust, 1990; DeVries et al., 1996). In addition, the reduced weed population associated with herbicide inputs reduces the food source for weed seed eating ground beetles (Cromar et al., 1999; Kromp, 1989). When herbicides were absent from a cropping system, the greatest activity of ground beetles was found where there were increased nutrients from synthetic fertilizer. The added fertilizer increased the total biomass (Table 4.3) thus increasing humidity and attracting the ground beetles to the f+h- system. Work by Larsen et al. (1996) has confirmed these results. Although the largest total weed populations (Table 4.8) and beetle (Table 4.17) captures occurred in the f+h- subplots of both rotation 1 and 3, there was a large occurrence of beetles and weeds in rotation 1. The results agree with the previous hypothesis that a larger food supply and increased plant density increased the occurrence of ground beetles.

4.4.2 Diversity

In 1995 and 1999, Shannon's, and Simpson's indices and evenness were not significantly affected by rotation, crop inputs or rotation X treatment interaction (Tables 4.19 and 4.20). In 1995, Shannon's diversity index was significantly different between the prairie grass system and f+h+ subplots of rotations 1, 2 and 3 (Table 4.19). Rotation 3 had less diversity than the other crop rotations or the prairie grass system (Table 4.21). Although a dense vegetation can create a favourable ground beetle habitat, dense vegetation can impede ground beetle surface activity (Kielhorn et al., 1999). The dense vegetation of the alfalfa hay crop in the preceding year (i.e., 1994) may have impeded the number of species attracted to

Table 4.19 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for ground beetles at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Prairie statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means considered significant when p<0.05.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	1.90	0.23	0.63
	f+h-	2.16	0.17	0.65
	f-h+	1.58	0.33	0.57
	f-h-	2.06	0.17	0.72
Rotation 2	f+h+	2.00	0.21	0.59
	f+h-	1.97	0.21	0.67
	f-h+	1.77	0.22	0.76
	f-h-	1.96	0.22	0.62
Rotation 3	f+h+	1.41	0.34	0.66
	f+h-	2.07	0.19	0.64
	f-h+	1.90	0.22	0.70
	f-h-	1.88	0.20	0.76
Prairie		2.09	0.16	0.76
Prairie vs. Rotations		0.016	0.115	0.481
Rotation (R)		0.724	0.850	0.664
Treatment (T)		0.085	0.183	0.514
R X T		0.185	0.322	0.374
SEM		0.164	0.049	0.061

Table 4.20 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for ground beetles at the Glenlea long-term cropping systems study, 1999, as influenced by crop rotation type and crop input management. Prairie statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means considered significant when p<0.05.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	1.75	0.30	0.51
	f+h-	1.74	0.28	0.54
	f-h+	1.76	0.28	0.56
	f-h-	1.74	0.30	0.50
Rotation 2	f+h+	1.92	0.26	0.50
	f+h-	1.98	0.23	0.54
	f-h+	1.94	0.24	0.55
	f-h-	1.97	0.23	0.56
Rotation 3	f+h+	2.04	0.23	0.52
	f+h-	2.19	0.18	0.57
	f-h+	2.05	0.22	0.54
	f-h-	2.14	0.20	0.56
Prairie		2.32	0.12	0.90
Prairie vs. Rotations		0.149	0.020	0.000
Rotation (R)		0.102	0.060	0.870
Treatment (T)		0.785	0.559	0.547
R X T		0.971	0.971	0.936
SEM		0.089	0.024	0.038

Table 4.21 Shannon-Weiner diversity index for average ground beetle capture at the Glenlea long-term cropping systems study, 1995, as influenced by crop rotation type and crop input management. Prairie was statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means with the same letter are not significantly different LSD (p<0.05).

	Shannon's
Rotation 1	1.90 a
Rotation 2	2.00 a
Rotation 3	1.41 b
Prairie	2.09 a
SEM	0.108

the alfalfa system. The non-significance of Simpson's may indicate the occurrence of rare or unique species in the prairie grass system and rotations 1 and 2. Table 4.15 indicates that in the prairie grass system, rotation 1 and rotation 2 had captured 19, 20 and 19 ground beetles, respectively, versus 13 ground beetles in rotation 3.

In 1999, Simpson's and evenness were significantly different between the prairie grass system and cropping systems. When separated by means, diversity and evenness were greater in the prairie grass system than in the cropping systems (Table 4.22). Simpson's is biased for common species. Although f+h+ subplot had greater total numbers of ground beetles, *P. corvus*, occurred in greater proportions compared to the other species present within the cropping system (Table 4.17). In the prairie grass system, fewer total beetles occurred but species occurred in even numbers across the plots. The prairie grass system, rotations 1, 2 and

3 each had approximately 20 ground beetle species identified within their respective systems.

Table 4.22 Simpson's diversity index and Hill's evenness for average ground beetle capture, 1999, as influenced by crop rotation type and crop input management. Prairie was statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means with the same letter are not significantly different LSD ($p<0.05$).

	Simpson's	Evenness
Rotation 1	0.30 a	0.51 b
Rotation 2	0.26 a	0.50 b
Rotation 3	0.23 a	0.52 b
Prairie	0.12 b	0.90 a
SEM	0.028	0.021

4.4.3 RDA Biplots for Ground Beetle Community Composition

4.4.3.1 1995 Ground Beetle Community Composition (Flax Test Crop)

The average of four sampling periods were used in the RDA for 1995. Herbicide management (h+: -0.7088, h-: 0.7088) and rotation 3 (0.8252) had the strongest correlation with the first axis. The first two axes accounted for 16.9% of the total variation observed with the beetle community. The correlation indicated that herbicide and rotation 3 were largely accountable for variation observed. All four ordination axes accounted for 23.1% of the variation. The first and combined four axes were significant using the Monte Carlo test indicating structure within the data set. *Amara apricaria* (46.04%) was the only species with greater than 45% of its variation explained by the four ordination axes. The vector for this species was directly between the f- and h- in the ordination with a long vector towards rotation 1. *Amara apricaria* was most abundant f-h- subplot of rotation 1 (Table 4.15).

The influence of rotation and crop inputs were relatively equal in determining the ground beetle community composition (Figure 4.13). Rotation 1 separated from rotation 2 and 3 on the first and second axes indicating a distinct difference between the beetle communities found within those types of cropping systems. Herbicide use was separated from h- on the first and second axis, as was the use of fertilizer. Fertilizer use was placed in the same ordination space as h- suggesting similar effects of the two management strategies on ground beetle activity. It may also indicate that when used together, f+ and h-management strategies would have a greater influence on ground beetle community than when used individually with other management strategies. Weed biomass was greatest in the f+h- subplots (Table 4.3) which was previously suggested as a reason for increased ground beetle capture in the f+h- subplots.

There were larger numbers of ground beetle species associated with rotation 1. *Amara avida*, *P. melanarius* and *A. apricaria* were all strongly associated with rotation 1. *Harpalus pensylvanicus*, *P. femoralis* and *A. littoralis* were weakly associated with rotation 1. The weak associations were attributed to the presence of these species in both rotations 2 and 3 (Table 4.15). The vector for *A. cupreum* was between rotation 1 and the f+ and h-, indicating preference for an annual cropping system with abundant ground cover and food source. Rotation 2 and 3 appeared to have few associated species. *Calosoma calidum* was associated with both rotations 2 and 3. *Bembidion* spp. were strongly associated with rotation 3.

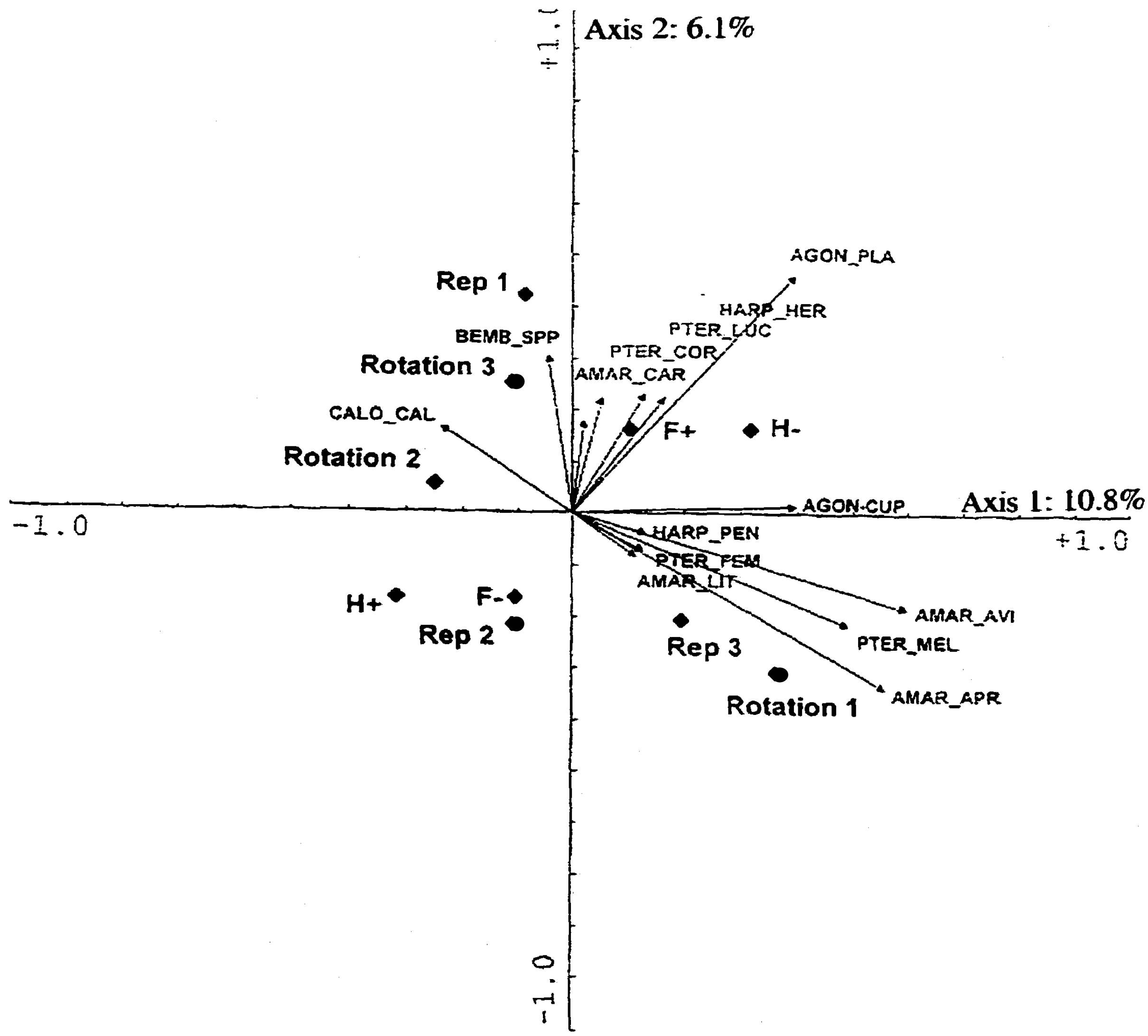

Figure 4.13 Redundancy analysis ordination diagram for ground beetle community composition at the Glenlea long-term cropping systems study, 1995. The first and second axes are presented and account for 16.8% of total variation.

There were no ground beetle species associated with h+ or f-, which was attributed to reduced biomass in the f-h+ systems (Table 4.3), which would reduce the humidity and soil moisture at ground level, creating an undesirable habitat for most ground beetle species. In addition, there would be less food source as other insects and weed species would also be deterred from the f-h+ system. In general, results from 1995 suggest that ground beetles appear to have an affinity for the use of fertilizer in the absence of herbicide. *Agonum placidum*, *H. herbivagus*, *P. lucublandus*, had a positive relation with the presence of fertilizer attributed to increased biomass and food source. Vectors for *A. carinata* and *P. corvus* species fall between rotation 3 and fertilizer use, indicating a preference for this type of cropping system.

4.4.3.2 1996 Ground Beetle Community Composition (Wheat Monoculture Underseeded to Sweet Clover and Alfalfa)

One sampling period was used in RDA for 1996, 1997 and 1998. Rotation 1 had the strongest correlation with the first axis (0.6577) while rotation 3, and herbicide management were correlated with the second axis (h+: -0.7073, h-: 0.7073, R3: 0.5763). The first two axes account for 27.1% of the variation observed within the beetle community. Due to their correlation with the first and second axis, rotation1 and 3, and herbicide management were accountable for most of the variation observed. All four ordination axes account for 30.3% of the variation. The first and combined axes of the ordination were considered significant under the Monte Carlo test.

Of the species identified, *H. pensylvanicus* (52.80%) and *A. avida* (45.17%) were the only 2 species to have greater than 45% of their variation explained by the 4 ordination axes. The ordination indicated *H. pensylvanicus* had a strong association with fertilizer and was present in rotations 1 and 3. The ground beetle catches indicated that within rotations 1 and 3, *H. pensylvanicus* had the greatest activity in the f+h- subplot (Table B.10). *Amara avida* had the greatest activity in f+h- subplots of fertilizer without herbicide use in rotation 1, thus its vector was strong in between the f+ and h- systems.

In 1996, rotation and herbicide management were strongly influenced the beetle community composition (Figure 4.14). Rotation 1 separated from rotations 2 and 3 on the first and second axis. Although rotations 2 and 3 did not separate from one another, rotation 2 was strongly associated with the first axis while rotation 3 was strongly associated with the second axis suggesting an increased difference between the two rotation systems attributed to the difference in disturbance levels in preceding years. The herbicide management techniques were separated on the first and second axis. Fertilizer management did not strongly influence the ground beetle community composition.

Amara avida and *H. amputatus* had strong associations with rotation 1. Rotation 2 had no species associations. The disturbance of the green manure in the previous rotation cycle may have deterred or damaged the ground beetle activity through disturbance in the life cycle of both spring and autumn breeders (Theile, 1977). Rotation 3 had the strongest associations with *P. corvus*, *A. carinata*, and *P. melanarius*. Clark et al. (1997) found *P. melanarius* to increase in alfalfa plots compared with annual cropping system, two years after treatments were initiated in the annual cropping systems.

As in the previous year, few ground beetle species were associated with the use of herbicide or the absence of fertilizer. The only species strongly associated with h- was *P.*

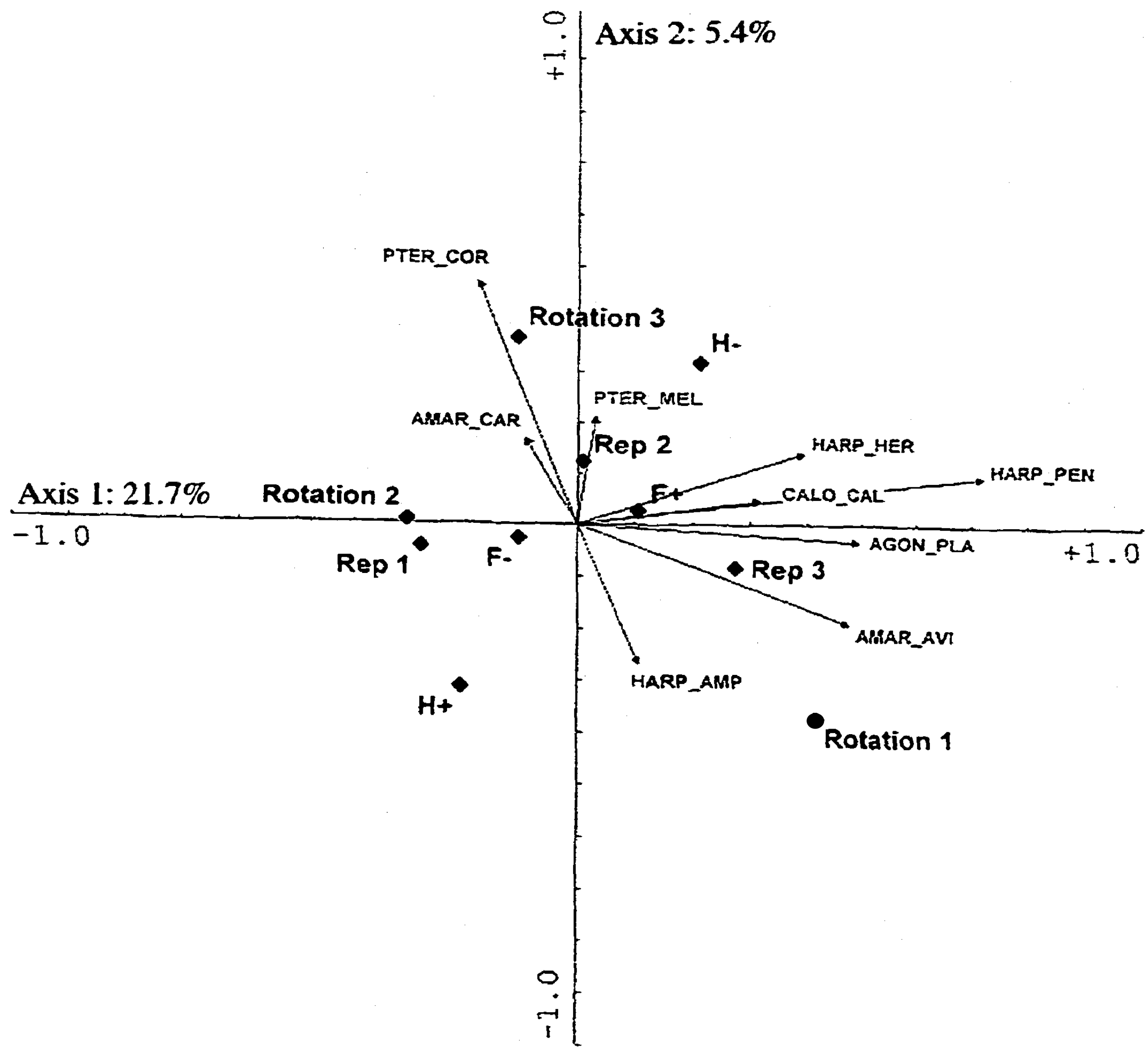

Figure 4.14 Redundancy analysis ordination diagram for ground beetle community composition at the Glenlea long-term cropping systems study, 1996. The first and second axes are presented and account for 26.1% of total variation.

melanarius. The use of fertilizer was strongly associated with *H. herbivagus*, *H. pensylvanicus*, and *C. calidum*.

4.4.3.3 1997 Ground Beetle Community Composition (Legume Year)

In 1997, rotations 2 and 3 had the strongest correlation with the first axis (0.8245 and -0.7556, respectively). Fertilizer was most strongly associated with the second axis (f+:0.6316, f-: -0.6316). Rotation 1 and herbicide management had their strongest associations with the fourth axis, however because rotations 2 and 3 was complimentary to rotation 1 it can be stated that rotation type was related to axis 1. The first two axes accounted for 19.4% of the total variation, with all four axes having explained 24.9% of the variation. The first ordination axes was not significant under a Monte Carlo test, indicating there was not enough structure within the data set to describe the community analysed. In addition, no species of ground beetles had greater than 45% of the variation explained by this ordination by the 1997 ordination, attributed to the above average precipitation in April followed by an extreme dry period throughout the month of May. The unstable extremes in the environment may have negatively affected emerging over wintering species and spring breeders.

Rotation had the strongest influence on community composition in 1997 (Figure 4.15). Rotations 2 and 3 were separated on the first axis and rotation 1 was separated from rotations 2 and 3 on the second axis, which suggested three distinct communities of ground beetles as a result of crop rotation. Fertilizer use was also an important factor in determining ground beetle community. The use and absence of both herbicide and fertilizer were separated

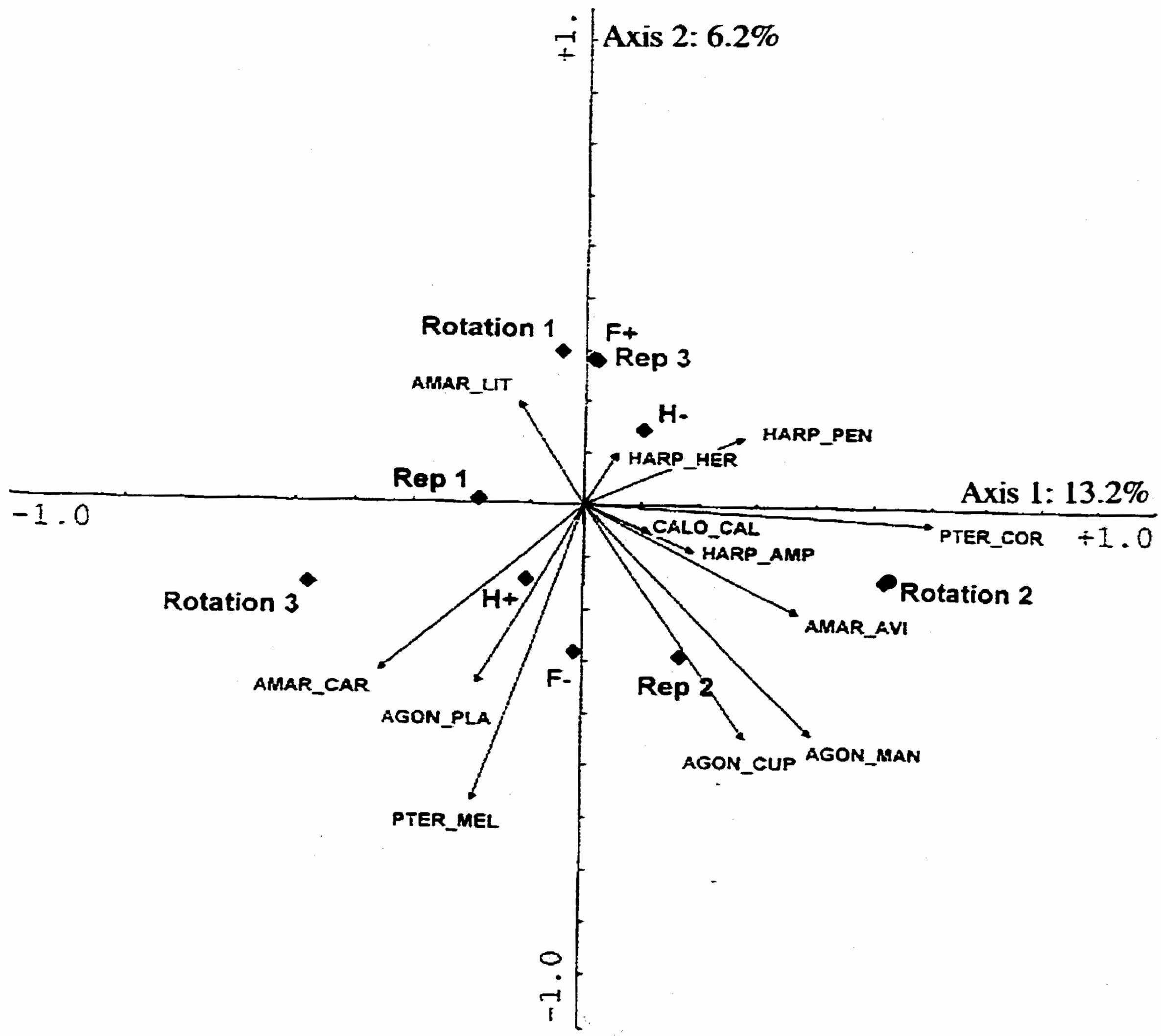

Figure 4.15 Redundancy analysis ordination diagram for ground beetle community composition at the Glenlea long-term cropping systems study, 1997. The first and second axes are presented and account for 19.4% of total variation.

by the second axis. Again, the f+ and the h- were placed in similar ordination space.

Amara littoralis was the only species to have demonstrated an association with rotation 1. Rotation 2 appeared to have the largest number of ground beetle species associated with it. The ground cover would have been different in rotation 2, compared with rotations 1 and 3, due to the green manure plowdown. Although there was plenty of ground cover, impediment of ground beetle movement would have been reduced (i.e. compared with rotations 1 and 2) thereby resulting in increased ground beetle captures. Strongest in association with rotation 2 were *P. corvus*, *C. calidum*, *H. amputatus* and *A. avida*. *Amara carinata* was associated with rotation 3. Vectors for *A. placidum*, *P. melanarius*, *A. cupreum* and *A. mannerheimi* were found between rotations 2 and 3. A point of interest was that all the *Agonum* species were separated from rotation 1, f+ and h- which was contrary to other studies which indicate a greater capture of *A. placidum* in annual cropped systems not receiving herbicides or fertilizers, with conventional tillage (Clark et al., 1997; Weiss et al., 1990). *Agonum placidum* is a spring breeder thus the above average precipitation in April followed by an unusually dry May in 1997 may have offset the community of *Agonum* species.

Amara carinata, *A. placidum* and *P. melanarius* were associated with h+ and f-. *Harpalus herbivagus* and *H. pensylvanicus* were associated with f+ and h- in a cropping system. The majority of identified ground beetle species had vectors between f- and h-. *Harpalus* and *Amara* species are weed seed eaters. In rotations 2 and 3, there would be a large abundance of weeds in f-h- subplots at the time of ground beetle sampling due to regrowth following plowdown and mechanical hay harvest. Increased weed seeds would result, improving the food source for the ground beetles.

4.4.3.4 1998 Ground Beetle Community Composition (Wheat, Wheat following Sweet Clover Plowdown and Alfalfa)

In 1998, rotation 1 (-0.6123) and 3 (0.9654) had the strongest correlation with the first axes. All other environmental variables were strongest in correlation with the third or fourth axes (h+: 0.3905, h-: -0.3905; f+: -0.3246, f-: 0.3246). The first two ordination axes accounted for 39.9% of the variation observed in ground beetle community, with all four axes having explained 44.2% of the variation observed. The first and combined axes of the ordination were significant, thus there was structure in the data set. Two ground beetle species had greater than 45% of their variation explained by the ordination; *A. carinata* (72.95%) and *H. pensylvanicus* (51.98%). The vector for *A. carinata* was strongly in the direction of rotation 3. The majority of *A. carinata* was found in rotation 3 (Table B.12) . *Harpalus pensylvanicus* was likely strongly explained by the ordination because of its large capture in rotation 1 in f+h- subplots (Table B.12).

In 1998, rotation had a strong influence on ground beetle community composition (Figure 4.16). Rotation 3 was strongly associated with the first axis and was separated from rotations 1 and 2 on the first axis. Rotations 1 and 2 separated on the second axis. The separation of the rotations on the first and second axes suggested distinct differences in ground beetle communities between rotations. The influence of herbicide management was minimal and fertilizer management had the least influence on ground beetle community description.

In 1998, the largest number of species was associated with rotation 3; likely a result of the stable alfalfa system. Species included *P. lucublandus*, *A. placidum*, *A. carinata* and.

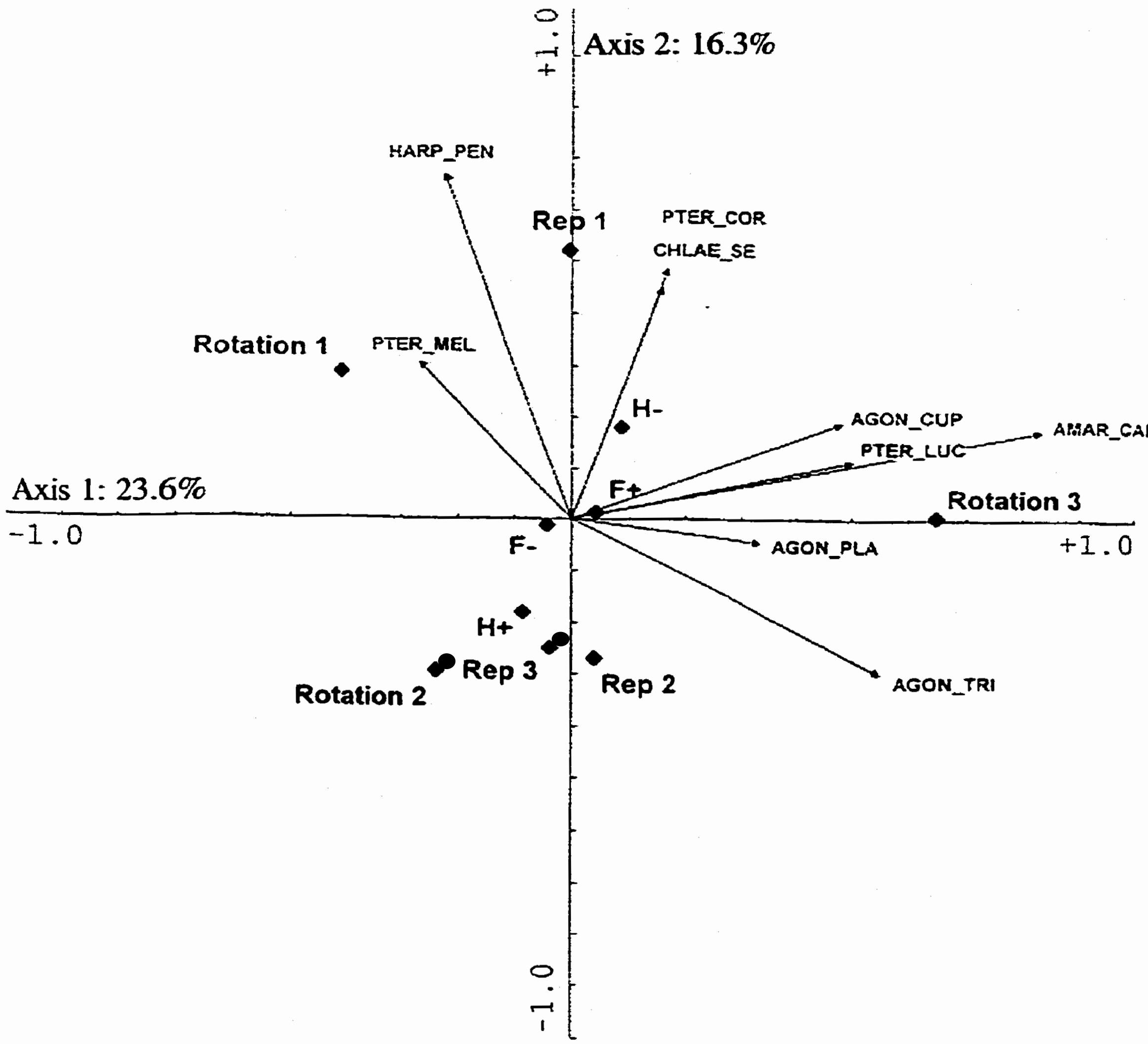

Figure 4.16 Redundancy analysis ordination diagram for ground beetle community composition at the Glenlea long-term cropping systems study, 1998. The first and second axes are presented and account for 39.9% of total variation.

A. cupreum. All the *Agonum* species identified were associated with rotation 3. By contrast, no ground beetle species were associated with rotation 2. The green manure in the preceding year may have disturbed the ground beetle activity in a significant manner. Also, the change in crop type (i.e., clover in 1997 to wheat in 1998) may have altered the habitat and deterred species that were associated with the previous crop from the rotation system. Rotation 3 had a more stable habitat across 1997 and 1998. Rotation 1 was associated with *P. melanarius* and *H. pensylvanicus*. *Harpalus pensylvanicus* was placed between h- and rotation 1 where there was increased weed biomass and food source.

The h+ and f- systems demonstrated no ground beetle associations. Species associated with f+ were also those associated with rotation 3. The added N by the alfalfa hay crop would increase biomass in a similar matter to synthetic fertilizer. Species associated h- included *P. corvus* and *C. sericeus*.

4.4.3.5 1999 Ground Beetle Community Composition (Flax Test Crop)

In 1999, the average of five sampling periods were used in the RDA. The correlation matrix indicated all environmental variables had their strongest correlation with the first two axes, excluding rotation 2 which had its strongest association with axis 4. Axis 4 does not account for much variation indicating rotation 2 was relatively unimportant in determining weed community composition. However, rotation 2 complimented rotations 1 and 3 so it was assumed to be associated with axis 1 and 2. Although it was correlated strongest with axis 2, fertilizer management was very weakly associated (f+: -0.191, f-: 0.191). The first two axes accounted for 38.9% of the variation observed within the beetle community, with all four axes having accounted for 44.3%. The percent of total variation had doubled since the 1995 test crop (23.1%) indicating that the rotation and crop input effects were having a stronger influence on community composition as time progressed. The first and combined axes of the ordination were significant under Monte Carlo testing.

Nine species had 45% or greater variation explained by the ordination axes: *A. apricaria*: 55.02%, *A. avida*: 44.41%, *H. pensylvanicus*: 54.76%, *A. sanctaecrucis*: 60.9%, *H. amputatus*: 54.32%, *P. corvus*: 85.54%, *P. femoralis*: 49.86%, *P. melanarius*: 52.31%, *A. cupreum*: 58.46%, and *A. placidum*: 63%. The first three species listed had variation explained in preceding RDA indicating the importance of time in the development of a ground beetle community with a cropping system.

Rotation and herbicide treatments were the strongest determinants of ground beetle community composition in 1999 (Figure 4.17). Rotation 1 separated from rotation 3 on the first axis, while rotations 2 and 3 separated from rotation 1 on the second axis. Herbicide use and the absence of fertilizer use were located within the same ordination space and were separated from absence of herbicide and use of fertilizer on the first and second axis. Fertilizer management had minimal influence on ground beetle community description.

Anisodactylus sanctaecrucis was the only beetle species to be strongly related to rotation 1. *Pterostichus melanarius* and *A. apricaria* were strongly associated with rotation 2. *Pterostichus femoralis* and *A. carinata* had a strong association with rotation 3. The majority of the species appeared to be more associated with h- and f+ than with individual rotations indicating that crop input management was becoming a more important than rotation in determining ground beetle community composition.

The f+ and h- systems ordinated along the same direction indicating a strong similarity

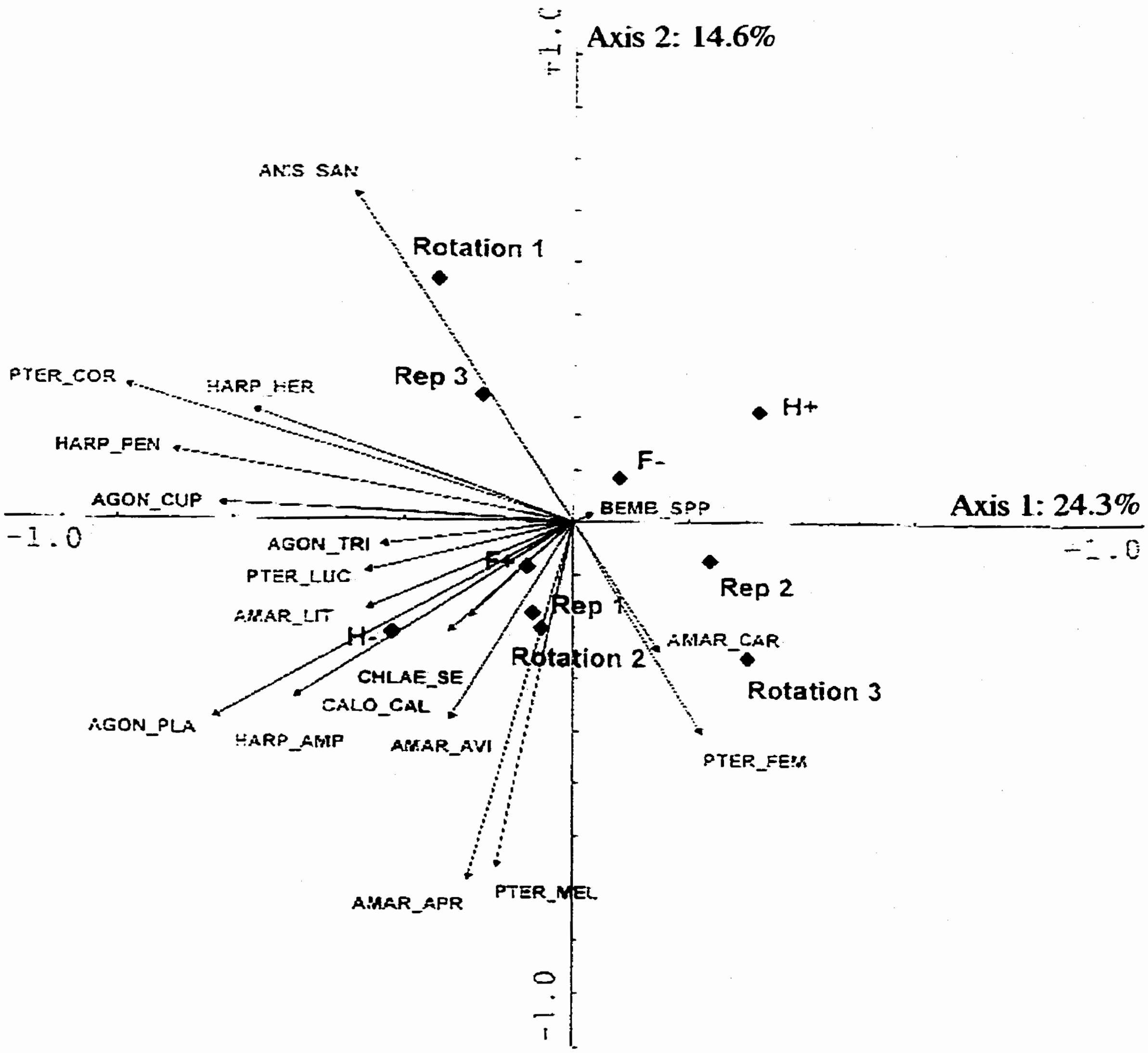

Figure 4.17 Redundancy analysis ordination diagram for ground beetle community composition at the Glenlea long-term cropping systems study, 1999. The first and second axes are presented and account for 38.9% of total variation.

in ground beetle assemblage response to these two environmental variables, however f+ had a vary weak association with axes 1 and 2. The combination of fertilizer use and the absence of herbicide favoured the majority of the ground beetle species, including the seed eating *Amara* and *Harpalus* species. The microhabitat in the f+h- systems would attract other insects and increase weed seeds shed, thus providing a larger food supply for ground beetles. The use of herbicide, especially when fertilizer was not used, was not associated with any ground beetle species. The change of crop type from 1998 to 1999 may be the reason fewer ground beetles were associated with rotation 3 in 1999 compared with 1998.

4.4.3.6 Summary of Ground Beetle Community Composition Results

Ground beetle community composition was influenced by crop rotation, however, the effect was not consistent. For example, *P. melanarius* was associated with rotation 1 in 1995 and 1998, rotation 2 in 1999 and rotation 3 in 1996 and 1997. *Pterostichus melanarius* is a larger species of ground beetle, and as such, it can move easily between smaller plots, especially prior to weed vegetation becoming dense (Scheller et al., 1984). Thus, the inconsistent rotational effect on this species may be attributed to the fact that those ground beetles may have moved to more suitable habitats in each year of the rotation. In another example, *Agonum* spp. appeared to have a preference for an alfalfa habitat in rotation 3 of the cropping system. Various *Amara* spp. and *Harpalus* spp. were associated with rotation 1, though the associations were not consistent across years. The general association of *Amara* spp. and *Harpalus* spp. with rotation 1 was attributed to the abundant food source provided by the largest total population of weeds (Tables 4.5 and 4.9) in rotation 1 to these known seed eaters (Hengeveld, 1980; Lindroth, 1961-1969).

The majority of ground beetle species were associated with the f+ and h- crop input systems. Ground beetles and the f+ and h- treatments occurred in the same ordination space or along the same continuum in all years from 1995 through 1999. The f+h- subplots also contained the greatest abundance of weeds and the highest weed and total biomass levels (Tables 4.3 and 4.9). The abundance of weeds and biomass would alter the climate favorably, attracting many ground beetles, in addition to other pests and prey (deVries et al., 1996; Theile, 1977). In addition, the weeds and prey would provide an abundant food source for both carnivorous and phytophagous ground beetle species (Ellsbury et al., 1998; Lindroth, 1961-1969; Pavuk et al., 1997). Therefore, the association of ground beetles with the f+h- systems was attributed to favourable habitat resulting from high levels of plant biomass and diversity of crop and weed biomass.

The capture of ground beetles in f-h+ subplots was minimal in 1995 and 1999 (Tables 4.16 and 4.18), thus ground beetles were not associated with the f- and h+ variables in RDA ordination. The f-h+ subplots contained the least weed and total biomass, and had lower weed densities than other systems (Table 4.3 and 4.9). Therefore, ground beetles were likely deterred from the f-h+ subplots because of exposed soil becoming dry quickly, reduced humidity and reduced food sources compared with the f+h- subplots. Therefore, the absence of beetles in the f-h+ crop input systems was attributed to unfavourable habitat conditions.

Rotation 1 and 3 had distinctively different ground beetle community composition, as indicated by the separation of rotation 1 from rotation 3 in each of the RDA analysis year. *Anisodactylus sanctaecrucis* was associated with rotation 1 and *A. obesa* associated with rotations 1 and 2, but not rotation 3. *Harpalus amputatus* was associated with rotations 2 and

3, but not in rotation 1. Within crop input systems, *A. obesa* associated with unfertilized subplots, while *H. amputatus* associated with fertilized subplots. Differences in community composition could likely be attributed to the difference in disturbance between the two systems, reduced capture attributed to impediment of movement through dense plant cover, microclimate and available food source. For the most part, beetle species were found in all systems but differed in density captured. The relative influence of rotation and crop inputs on ground beetle community remained relatively consistent between years.

4.4.4 Prairie Grass System versus Cropping Systems

4.4.4.1 Ground Beetle Assessment

In 1995, three ground beetle species were significantly influenced by the prairie grass system versus cropping systems (Table 4.15). *Harpalus herbivagus* did not occur in rotation 3. Although found in rotations 1 and 2, greater capture of *H. herbivagus* occurred in the prairie grass system attributed to the large amount of biomass in the prairie grass system creating a favourable microhabitat for the species. Similarly, the capture of *H. pensylvanicus* was greatest in the prairie grass system. *Pterostichus lucublandus* did not occur in the prairie grass system, but occurred in equal numbers across the cropping systems suggesting that *P. lucublandus* may be an agricultural species not likely to be found in unmanaged ecosystems.

The ground beetle activity in 1999 differed from that in 1995. For example, unlike results of 1995, in 1999, *H. pensylvanicus* was associated with rotation 1 and not the prairie grass system (Table 4.15 and Table 4.17). Greater activity of this species in rotation 1 in 1999 may be attributed to the increased food source provided by the abundance of weeds within rotation 1. Similar results occurred for *A. sanctaecrucis* and P. *corvus*, which had their greatest capture in rotation 1 and no significant difference between the prairie grass system and rotations 2 and 3. *Bembidion* spp. did not occur in the prairie grass system but occurred in equal numbers in the f+h+ subplots of all rotations indicating that *Bembidion* species would not likely occur in unmanaged systems.

The total number of ground beetles in the prairie grass system and the f+h+ subplots of the three rotations did not differ significantly in 1995 (Table 4.15), but did differ in 1999 (Table 4.17). In 1999, the greatest number of ground beetles occurred in rotation 1 which was likely a result of the abundant food source from weeds and prey insects and a favourable habitat from altered humidity by the increased biomass of weeds. Rotations 2 and 3 did not differ from one another but did have more ground beetles than the prairie grass system. This was likely due to the nutrient rich soil found in these rotation which would increase biomass within these cropping systems.

4.4.4.2 1995 RDA Biplot for Prairie Grass System and Cropping Systems

The prairie grass system was included in the RDA to determine the association of ground beetle species with the prairie grass system versus the cropping systems, and how the inclusion of the prairie grass system in the ordination would change the description of the ground beetle community.

The first 2 axes of the ordination accounted for 16.8% of the variation observed. All four axes accounted for 25.5% of the variability observed in the beetle community. The

Monte Carlo test indicated the first and all four combined axes to be significant implying a structured data set. Of the species identified, only one had approximately 45% or greater of the their variability explained by the four ordination axes. *Amara apricaria* (47.99%) was associated with rotation 1 because of its greater activity within the rotation. *Harpalus pensylvanicus* (44.24%) was associated with the prairie grass system and occurred in the largest numbers in the prairie grass system in 1995 attributed to the biomass and ground cover provided by the prairie grass system (Table 4.15).

The prairie grass system was most strongly associated with axis two and appeared to have the largest influence on describing the ground beetle community (Figure 4.18). It was separated on the second axis from all other environmental variables. The cropping system variables were clustered close to the biplot origin because of the overshadowing prairie grass system influence. The separation demonstrated the difference between ground beetle communities in cropping systems and prairie grass systems, and the importance community ecology had in determining community composition. The ordination appeared congested at the origin due to beetle associations with the cropping system variables. *Harpalus pensylvanicus* was strongly associated with the prairie grass system, which also observed in the ground beetle activity assessment (Table 4.15).

4.4.4.3 1996 RDA Biplot for Prairie Grass System and Cropping Systems

The first two axes of the ordination accounted for 25.9% of the variation in ground beetle communities. The important pattern in the ordination is the disposition of the points along the first axis because little variance is explained along the second axis. All four axes

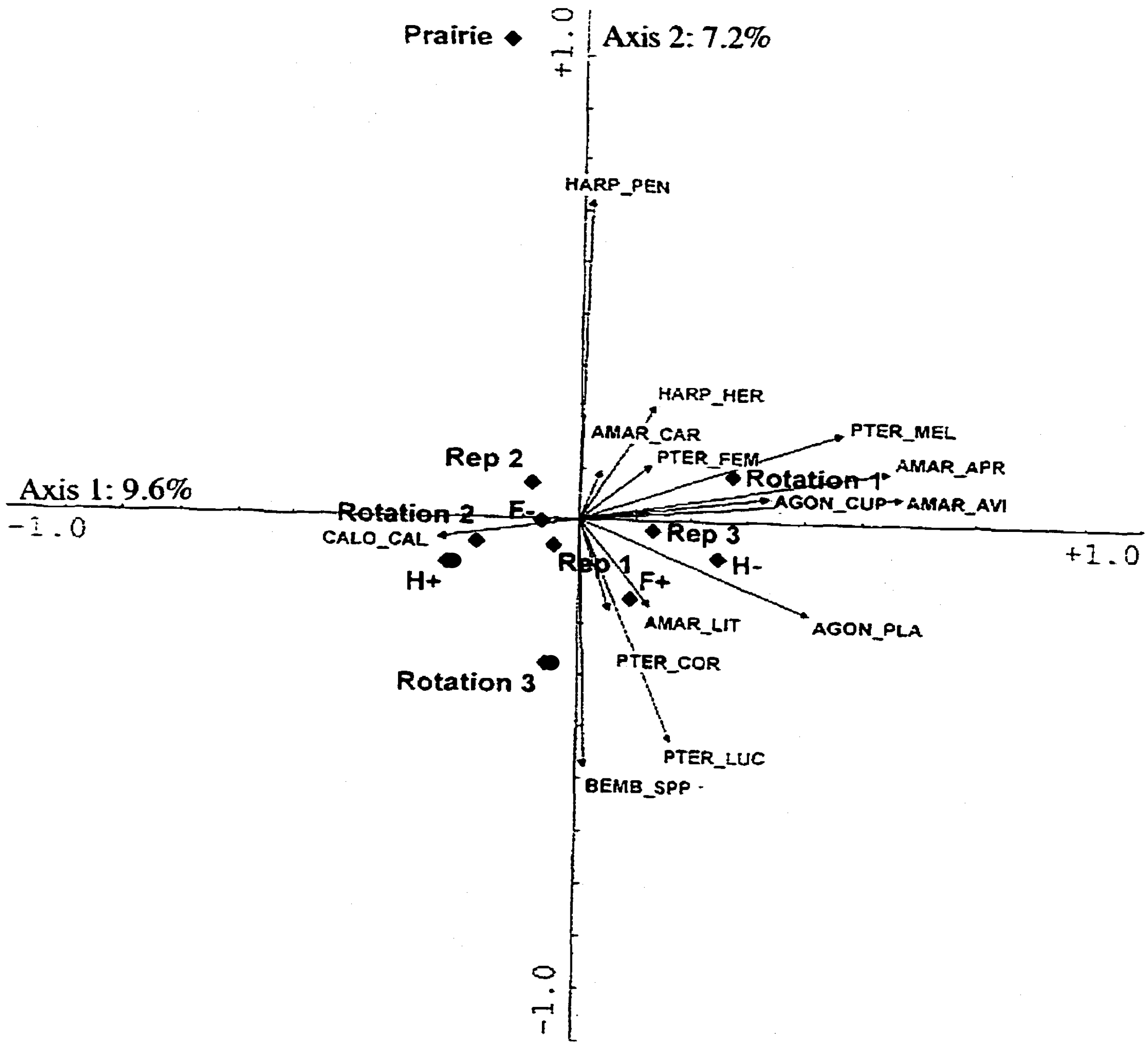

Figure 4.18 Redundancy analysis ordination diagram for ground beetle community composition in the prairie grass and cropping systems at the Glenlea long-term cropping systems study, 1995. The first and second axes are presented and account for 16.8% of total variation.

accounted for 31.2% of the variation observed within the ground beetle community. Both the first and combined axes remained significant under Monte Carlo testing. Four of the identified species had greater than 45% of their variability explained by the ordination. *Harpalus pensylvanicus* (54.12%) was strongly associated with f+ and h-, where the greatest ground beetle activity was observed (Table B.10). *Pterostichus lucublandus* (67.57%), *D. sculptills* (67.57%) and *H. ventralis* (67.57%) were found in the prairie grass system only, and in such few numbers that they were suppressed in the RDA biplot. *Dicaelus* spp. and certain members of *Pterostichus* spp are often found in similar habitats (Lindroth, 1961-1969).

The prairie grass system and cropping system variables had an equal influence on ground beetle community composition (Figure 4.19). The prairie grass system separated from all cropping system variables except h- and rotation 3 on the second axis suggesting the alfalfa-containing cropping system was similar to the prairie grass system. Rotation 3 may have provided similar resources and conditions to the prairie grass system. Species associated with rotation 3 and the prairie grass system included *P. corvus*, *P. melanarius* and *A. carinata*. Both *P. corvus* and *P. melanarius* had a strong presence in rotation 3 and the prairie grass system (Table B.10). When averaged over the sampling period, *A. carinata* was even across rotation, crop inputs and the prairie grass system, thus the strong association was not expected.

4.4.4.4 1997 RDA Biplot for Prairie Grass System and Cropping Systems

The first 2 ordination axes account for 19.2% of the variation observed in ground beetle communities. All four axes together account for 27.3% of the variation. The first axis

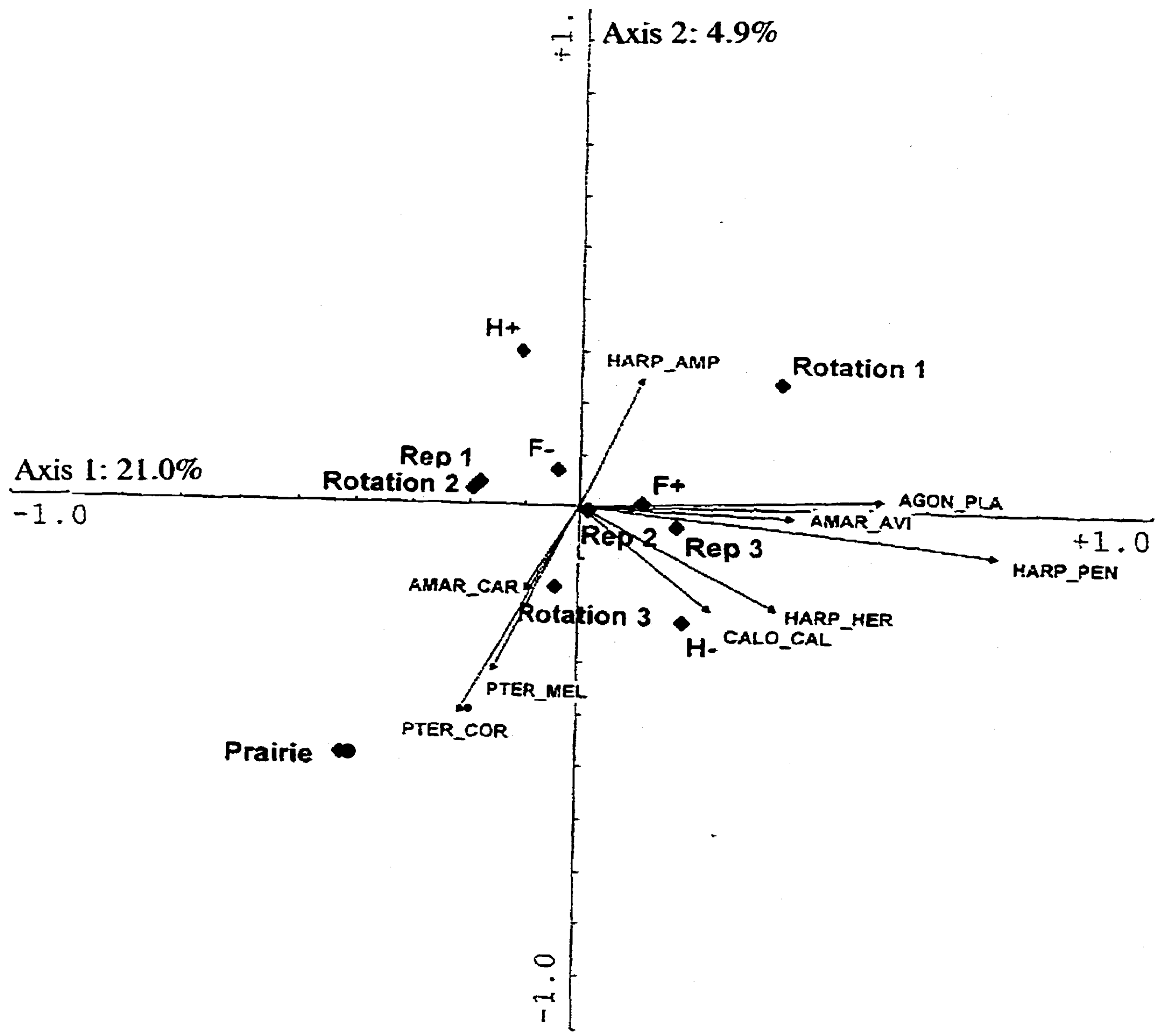

Figure 4.19 Redundancy analysis ordination diagram for ground beetle community composition in the prairie grass and cropping systems at the Glenlea long-term cropping systems study, 1996. The first and second axes are presented and account for 25.9% of total variation.

was not significant under Monte Carlo test indicating the data set was not structured. Reduced structure within the data set may be attributed to the above average precipitation in April and the dry month of May which may have interfered with ground beetle life cycles.

Three ground beetle species had greater than 45% explained variation. *Pterostichus lucublandus* (58.97%) had its greatest capture in the prairie grass system (Table B.11). *Dicaelus sculptilis* (94.97%) and *C. neglecta* (94.97%) were present in the prairie grass system only. These three species may likely prefer an undisturbed prairie grass system.

The prairie grass system had the strongest influence in ground beetle community composition of the environmental variables analysed (Figure 4.20). Rotation 3 and the prairie grass system had separated on the first axis. The prairie grass system separated from all remaining crop inputs and rotations on the second axis. Crop inputs and rotations were clustered to the origin indicating the prairie grass system was overshadowing the effects of other environmental variables on ground beetle community composition. The clustered variables also indicated little discriminating value of the cropping system in the presence of a prairie grass system. There were no ground beetle species strongly associated by the prairie grass system.

4.4.4.5 1998 RDA Biplot for Prairie Grass System and Cropping Systems

The amount of variation in ground beetle communities accounted for by the first two ordination axes was 37.9%, with all four axes accounting for 48.1% of the variation. Both the first and combined four axes of the ordination were significant under the Monte Carlo test. *Amara carinata*, *H. pensylvanicus*, *P. corvus* and *A. trigeminum* had greater than 45% of the

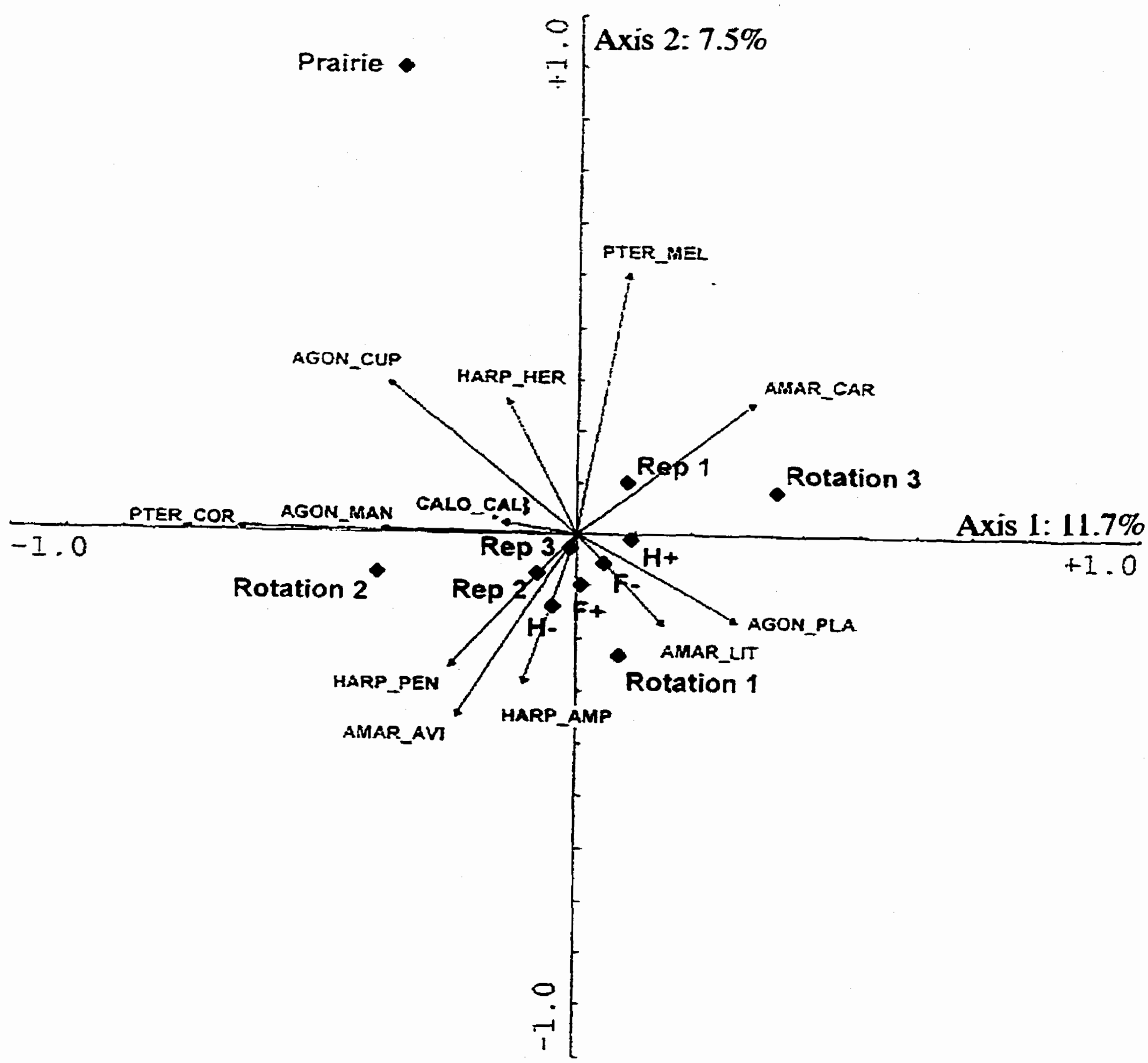

Figure 4.20 Redundancy analysis ordination diagram for ground beetle community composition in the prairie grass and cropping systems at the Glenlea long-term cropping systems study, 1997. The first and second axes are presented and account for 19.2% of total variation.

variation explained by the ordination axes. *Harpalus pensylvanicus* was strongly associated with rotation 1, where the greatest capture of this species was found (Table B.12). *Amara carinata* and *A. trigeminum* were found to have the greatest capture in rotation 3. *Pterostichus corvus* demonstrated a strong association with h-, where it was assessed to have its greatest activity.

The prairie grass and cropping systems rotation environmental variables appeared to have equivalent influences on determination of ground beetle community composition in 1998 (Figure 4.21). The prairie grass system separated from all environmental variables, excluding rotation 2 and h+, on the second axis. Rotation 2, as well as crop input management variables were clustered around the biplot origin indicating little discriminating power in the ground beetle community. There were no species associated with the prairie grass system indicating that if the ground beetle species found in the cropping systems, they occurred in low densities thus vectors point away from the prairie grass system. As well, species characteristic of the prairie grass system may occur in low numbers thereby having little influence on the overall ordination.

4.4.4.6 1999 RDA Biplot for Prairie Grass System and Cropping Systems

The first two ordination axes accounted for 42.3% with all four axes accounting for 50.1% of the variation. The difference in the variation explained 1999 compared to 1995 demonstrated the importance of long-term studies in assessing the influence of cropping systems on ground beetle communities. The first and combined four axes were significant under the Monte Carlo testing.

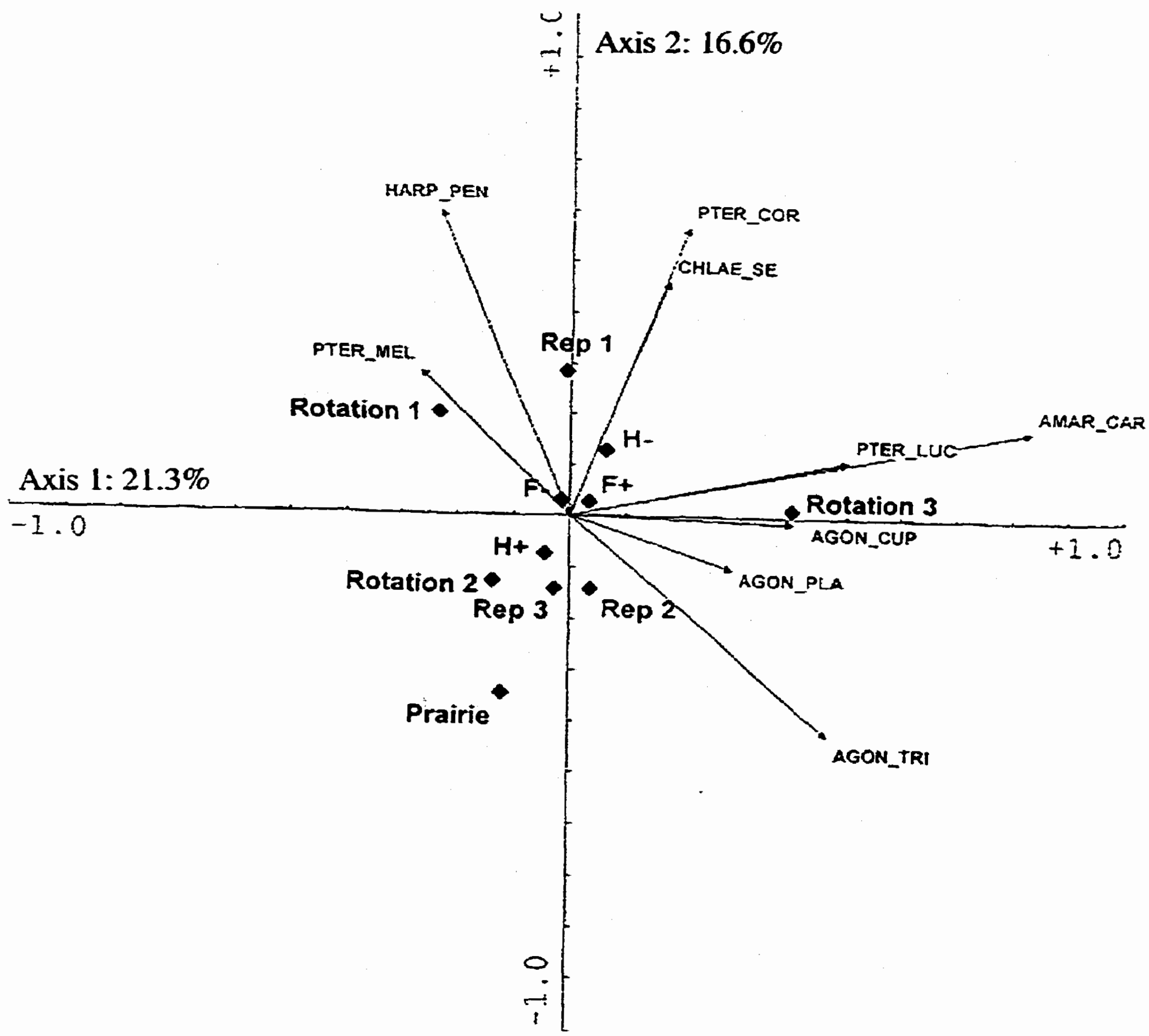

Figure 4.21 Redundancy analysis ordination diagram for ground beetle community composition in the prairie grass and cropping systems at the Glenlea long-term cropping systems study, 1998. The first and second axes are presented and account for 37.9% of total variation.

Species which had greater than 45% of their variation explained included: *A. apricaria* (55.07%), *A. avida* (49.89%), *A. sanctaecrucis* (60.9%), *H. amputatus* (54.32%) , *H. pensylvanicus* (60.18%), *P. corvus* (85.54%), *P. femoralis* (49.86%), *P. melanarius* (58.46%), *A. cupreum* (58.46%) and *A. placidum* (63%). These were previously discussed in section 4.4.3.5.

In 1999, the influence of the prairie grass system on ground beetle community composition was not important in differing the prairie grass system from the cropping system ground beetle community because the removal of the prairie from the RDA did not change the ordination (Figure 4.22 and Figure 4.17). Crop input management treatments were close to the origin, having little influence on community description when a prairie grass system was included in the RDA. The prairie grass system separated from all rotations and crop inputs within the first 2 axes, excluding h+. Similarly to h+, there were no ground beetle species associated with prairie grass system which was attributed to the density of ground cover impeding movement in the prairie grass system. Reduced food resource in h+ subplots may also have influenced activity and capture. It was concluded that the cropping systems did not mimic or reflect the prairie grass system.

4.5 Associations between Cropping Systems, Weeds and Ground Beetles

4.5.1 1995 RDA Biplot for Weeds and Ground Beetles

Weed and ground beetle data was combined for test crop years and subjected to RDA to identify associations existing between weed and ground beetle communities. The

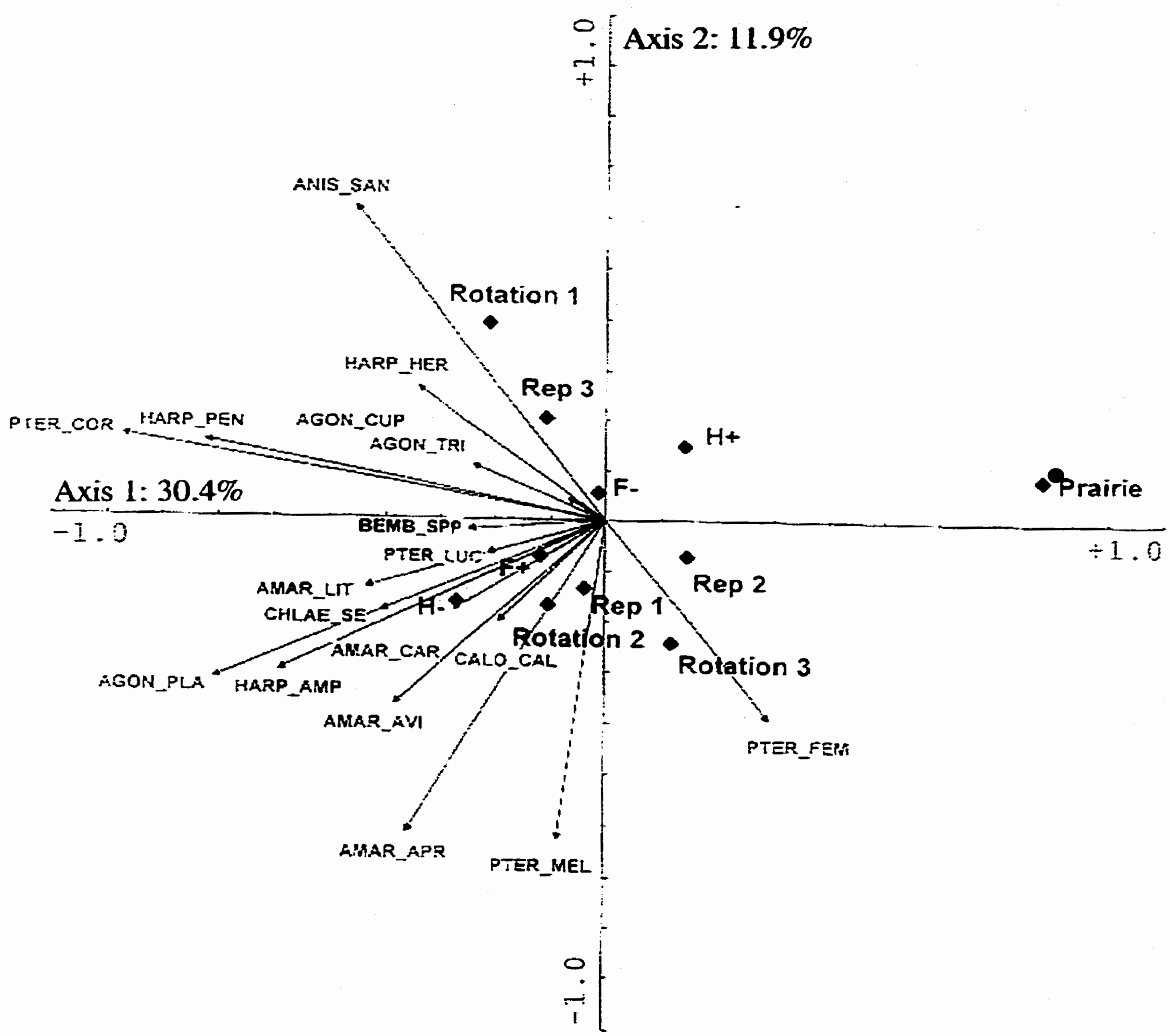

Figure 4.22 Redundancy analysis ordination diagram for ground beetle community composition in the prairie grass and cropping systems at the Glenlea long-term cropping systems study, 1999. The first and second axes are presented and account for 42.3% of total variation.

correlation matrix indicates that all environmental variables, excluding fertilizer, had their strongest correlation with either the first or second axis, accounting for 29.9% of the variation observed in the species communities. All four axes account for 40.2% of the variation. The first and combined axes were significant under Monte Carlo testing indicating structure within in the data set.

Rotation had the greatest effect on community description for both weeds and ground beetles in 1995 (Figure 4.23). Rotation 2 and 3 were separated from each other on the first axis, while rotation 1 separated from rotations 2 and 3 on the second axes. The ground beetle/weed communities and associations were distinctly different between rotation types. The crop inputs were oriented close to the origin indicating minimal influence on the weed and beetle community. The f+ and h+ were separated from f- and h- on the first and second axis. Rotation 3 was in the same ordination space as f- and h- suggesting that a robust organic system and a robust rotation would demonstrate similar ground beetle and weed communities.

Rotation 2 had distinctive weed and beetle associations. *Amara carinata* and *A. littoralis*, and stinkweed were both positively associated with rotation 2. *Amara* species are known weed seed feeders (Cromar et al., 1999; Kromp, 1989), so it was not surprising for some of these ground beetle species to be associated with a weed species. The other *Amara* species identified within the cropping system study, *A. apricaria* and *A. avida*, had negative associations with stinkweed suggesting differences in feeding preferences between the species. Rotation 3 had four beetle species and three weed species grouped together. The only strong association between beetle and weed was dandelion and *A. placidum*. Weed and beetle species within rotation 1's ordination space included *A. cupreum*, *A. apricaria*, *P. melanarius*, *A. avida*, hempnettle, and barnyard. However, rotation 1 showed no strong association

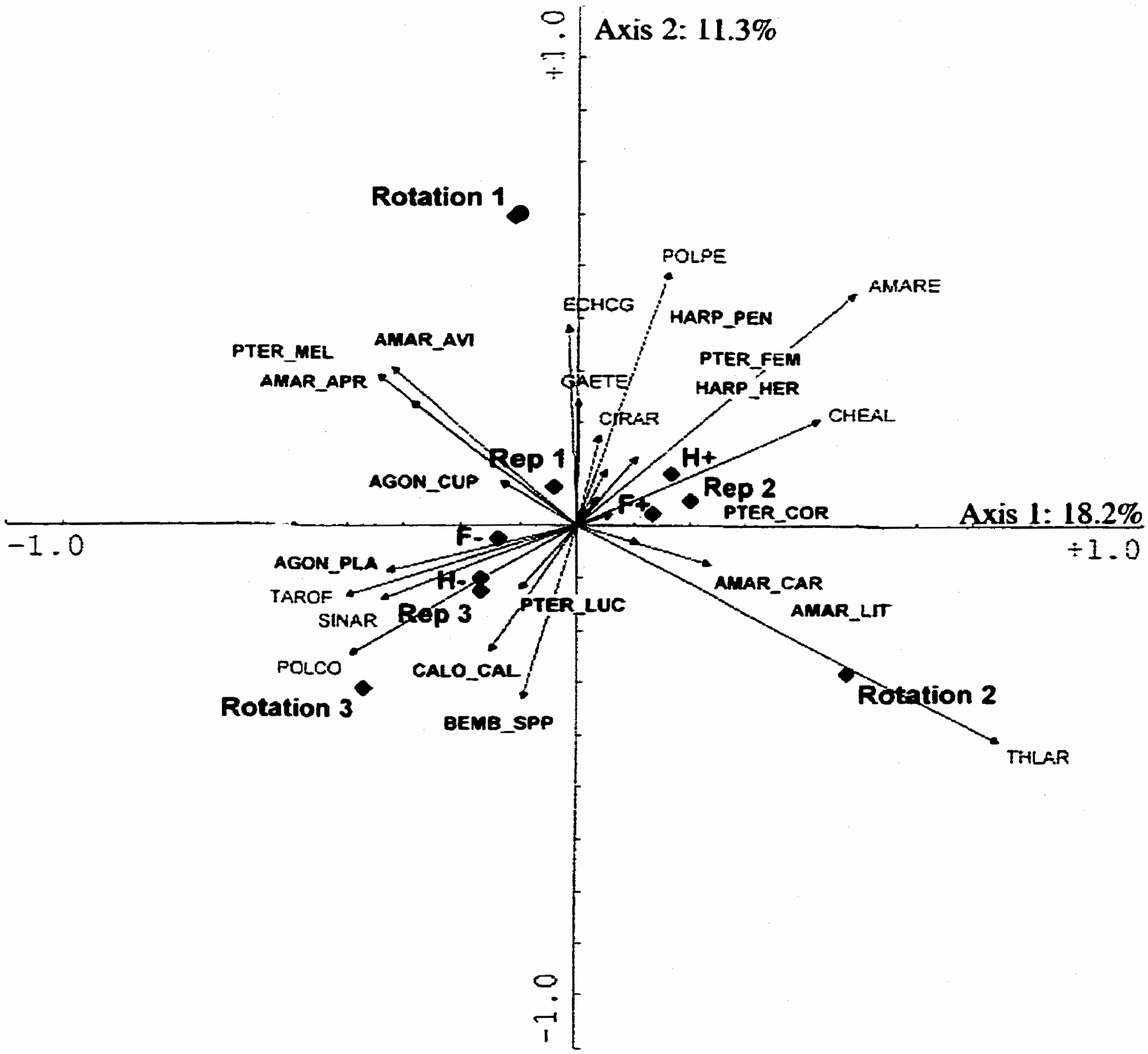

Figure 4.23 Redundancy analysis ordination diagram for the combined data set for weed and ground beetle population at the Glenlea long-term cropping systems study, 1995. The first and second axes are presented and account for 29.5% of total variation.

between weed and ground beetle species.

The use of fertilizer and herbicide were associated with beetle species *H. pensylvanicus*, *P. femoralis*, *H. herbivagus*, and weed species lamb's quarter, redroot pigweed, lady's thumb and Canada thistle. Vectors for the ground beetle species were short, indicating they may have been present in other rotations and crop inputs thus were held central to environmental variables. The ground beetle assessment data for 1995 confirmed these findings (Table 4.15). No strong associations existed between weeds and ground beetles.

4.5.2 1999 RDA Biplot for Weeds and Ground Beetles

Rotations 1 and 3, and herbicide management had their strongest correlation with the first 2 ordination axes thus having accounted for the majority of the variation observed. The amount of variation accounted for by the first two axes was 42.1%, with all four axes accounting for 52.7% of the variation occurring in the weed and ground beetle community. The increased variation explained from 1995 indicated the importance of long-term study in accurately describing ecological communities.

In 1999, rotation and herbicide input management had the strongest influence on the weed and ground beetle communities (Figure 4.24). Rotation 1 separated from rotations 2 and 3 on the second axis. Rotations 2 and 3 did not separate, although rotation 3 demonstrated a stronger influence on community description. The placement of rotation 2 close to the origin indicated it had little discriminating value in the weed and ground beetle communities thus ground beetle/weed communities within the system where determined by

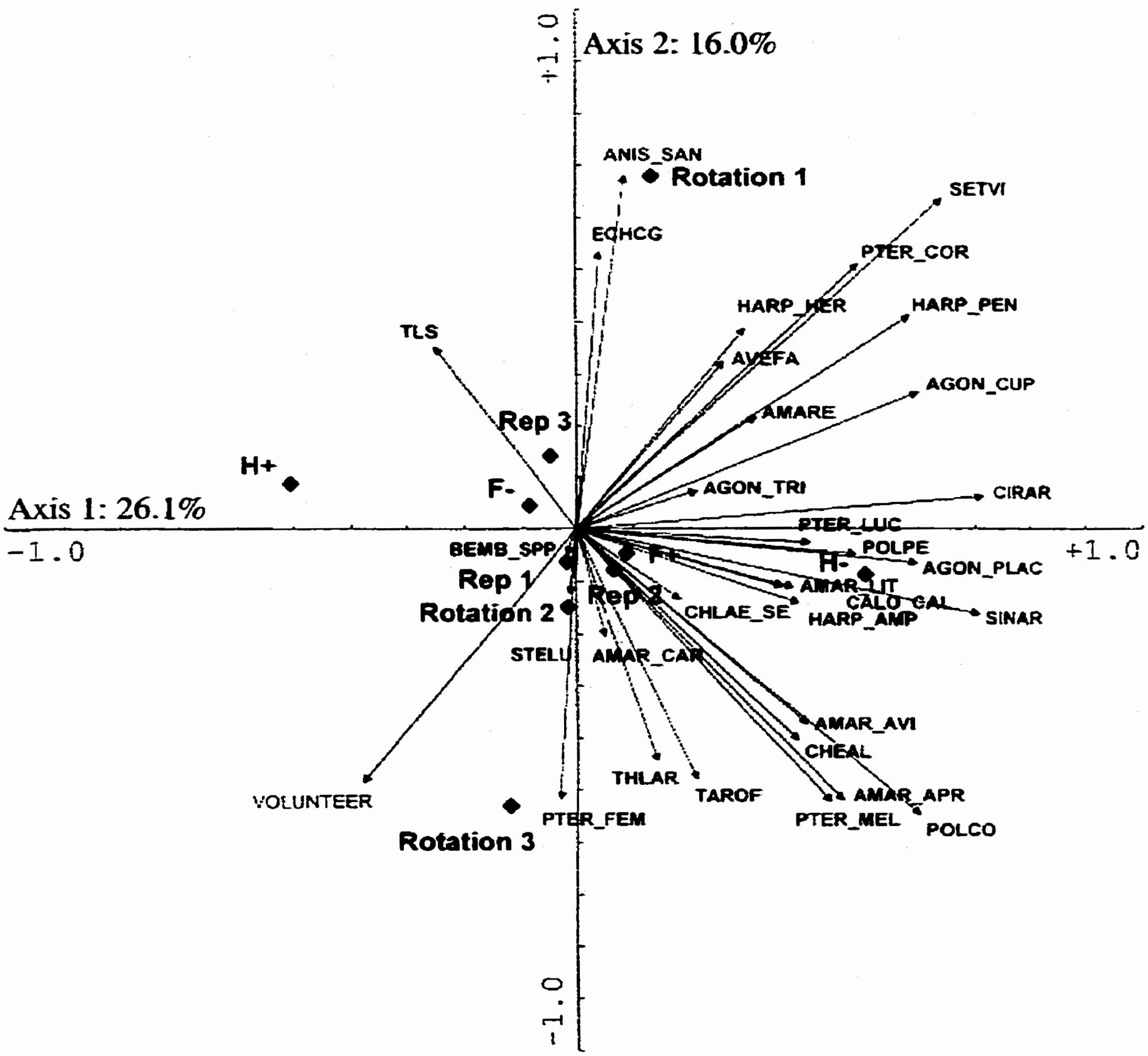

Figure 4.24 Redundancy analysis ordination diagram for the combined data set for weed and ground beetle population at the Glenlea long-term cropping systems study, 1999. The first and second axes are presented and account for 42.1% of total variation.

crop inputs. Rotation 1 had a strong association with *A. sanctaecrucis* and barnyard grass. Rotation 2 had an association with yellow foxtail and *P. femoralis*. Yellow foxtail was most abundant in rotation 2 (Table 4.8), however P. femoralis was equally present among rotations and crop input treatments (Table 4.17).

The majority of weeds and beetles appeared to be associated with the management of crop inputs. Herbicide use was in the same ordination space as f-, while h- was placed in the same ordination space as f+. When herbicide was used and fertilize was not, there were no ground beetles associated, and only thymeleaf spurge observed for weed species.

Although the majority of weed and beetle species occurred together in a large grouping, some strong positive associations occurred between beetle and weed species. For example, *H. herbivagus* and wild oat were associated with one another. *Harpalus* and *Amara*, seed eaters (Cromar et al., 1999; Kromp, 1989), are medium sized ground beetles and may prefer larger seeds, such as wild oat. Redroot pigweed and *H. pensylvanicus* were positively associated. Wild mustard appeared to be associated with *C. calidum*, *A. littoralis* and *H. amputatus*. *Amara carinata* was associated with both stinkweed and dandelion. *Amara avida* was associated with wild buckwheat.

Pterostichus corvus and green foxtail were strongly associated. *Pterostichus corvus* feeds on grasshopper eggs and other soil dwelling insects. Green foxtail supports populations of grasshoppers (Douglas et al., 1985) thus green foxtail may indirectly be benefiting the *P. corvus* by providing a food source. *Pterostichus melanarius* and *A. apricaria* were both strongly associated with lamb's quarter. *Pterostichus lucublandus* and *A. placidum* were strongly associated with lady's thumb.

4.5.3 Summary of Associations between Cropping Systems, Weeds and Ground Beetles Results

In 1995, crop inputs had little influence on community composition while rotations were clearly separated from one another by the first and second axes. Despite the strength of rotation in determining community composition, the majority of weed and beetle species appeared to have been associated with the crop input variables. The variables f+ and h+ were placed in similar ordination space, while f- and h- were also placed in similar ordination space.

In 1999, rotation strongly influenced weed community composition. Rotations appeared to lie along a continuum suggesting that the grain and alfalfa based rotations contained distinctly different weed communities when both systems were seeded to a flax test crop. However, herbicide use was the strongest determinant of both weed and ground beetle communities in 1999. Neither ground beetles or weeds were associated with the h+ system, suggesting that as weeds were controlled, ground beetle activity generally declined.

It was interesting to note that, in 1999, all weed and ground beetle vectors fell between rotation 1 and 3, somewhat associating with f+h-. Coincidently, the greatest density of weeds occurred in the f+h- subplots (Table 4.8). The attraction of ground beetles to the f+h- treatment, therefore, was likely an indirect result of the h+ and f- variables. Increased weed presence would increase humidity (deVries et al., 1996; Theile, 1977; Work et al., 1998), thereby favorably altering the microclimate for ground beetles (Carcamo and Spence, 1994). In addition, an abundant and diverse weed population would provide an abundant food supply either through weed seeds or through attraction of ground beetle prey (Altieri and Liebman, 1988; Clements et al., 1994; Cussans, 1996; Norris, 1992; Work et al., 1998).

Four consistent associations existed between weed and beetle species in 1995 and 1999. These included *H. pensylvanicus* and redroot pigweed; *A. carinata* and stinkweed; and *A. placidum* and *C. calidum*, and wild mustard. A weak association between *H. pensylvanicus* and redroot pigweed existed in 1995, and had developed into a strong association by 1999. *Harpalus* spp. are known weed seed eaters (Ellsbury et al., 1998; Hengeveld, 1980; Larochelle, 1990; Lindroth, 1961-1969). In a laboratory study in Indiana, *H. pensylvanicus* was offered seeds of 16 weed species from Indiana corn fields (Lund and Turpin, 1977). Of the 250 redroot pigweed seeds offered, *H. pensylvanicus* damaged all 250 seeds. Seeds were crushed and both the endosperm and some of the seed coat was eaten. The authors suggested that redroot pigweed, among other common weed seeds, was part of the natural field diet of *H. pensylvanicus*.

Amara carinata was associated with stinkweed in 1995, as well as 1999. Similar to *Harpalus* spp., *Amara* spp. also feed on weed seeds (Hengeveld, 1980; Lindroth, 1961-1969). No literature was available on seed species preference of *Amara* spp.; thus further studies would be required to determine the basis of the association between *A. carinata* and stinkweed.

The association between *A. placidum* and *C. calidum*, and wild mustard strengthened between 1995 and 1999. *Agonum placidum* and *C. calidum* are known to feed on Lepidoptera and their eggs (Larochelle, 1990). Wild mustard is a host for several Lepidoptera species (Warwick et al., 2000). If future studies could identify the cause of the association between *A. placidum* or *C. calidum* and wild mustard as the presence of Lepidoptera species on wild mustard, there may be potential to develop *A. placidum* or *C. calidum* as a bio-control agent. In addition, if a correlation could be drawn between densities of *A. placidum* or *C. calidum*, and Lepidoptera, then *A. placidum* or *C. calidum* could be used as bioindicators for economic thresholds of some Lepidoptera species.

5.0 SUMMARY AND CONCLUSIONS

5.1 General Summary

Within the Glenlea long-term cropping systems study, the following major findings were made on the influence of crop rotation type and crop input management on weeds and ground beetles:

- Weed DM was significantly affected by rotation, crop input and a rotation X crop input treatment interaction with the greatest weed DM in f+h- treatments and lowest in f-h+ for all rotations, with greatest overall weed DM occurring in the f+h- subplot of rotation 1.
- In 1995, grain yield was greatest ($p<0.05$) in f+h+ system. In 1999, grain yield was greatest in the f+h+ and f+h- systems. Grain yield had a rotational trend ($p<0.1$) in 1995 and 1999. The magnitude of difference between the grain yields of rotations 1, 2 and 3 appeared to increase after the second rotation cycle. Rotations 2 and 3 appeared to have a greater grain yield than rotation 1 in 1999 ($p<0.10$).
- In 1995, total weed population density was significantly different between rotations, with the largest densities occurring in rotations 1 and 2. In 1999, total weed total population was significantly influenced by crop inputs at all 3 weed populations assessment times, but influenced by rotation only at the pre in-crop spraying assessment with the largest densities occurring in rotation1. The greatest weed densities occurred in the f+h- subplots at each weed population assessment.
- In 1995, weed diversity differences between rotations and crop inputs were non-

significant. In 1999, weed diversity was significantly different at the pre- seeding and pre in-crop spraying weed population assessments with the greatest diversity in rotations 1 and 3, and 2 and 3, respectively. Weed diversity was significantly influenced by crop inputs at the pre-harvest weed population assessment with greatest diversity in h- systems.

- The RDA for weeds indicated rotation 1 was associated with green foxtail, rotation 2 was associated with stinkweed and Canada thistle and rotation 3 was associated with dandelion. Wild buckwheat, lady's thumb, redroot pigweed, green foxtail, wild mustard, lamb's quarter and Canada thistle were associated with either the h- or the combined h- and f+ systems.
- In 1999, ground beetle capture was greatest in rotation1 > rotation 2 > rotation 3. For crop input system, ground beetle capture was greatest in the f+h- > f-h- > f+h+ and f-h+.
- In 1995 and 1999, ground beetle diversity and evenness were not affected by crop rotation type or crop input management.
- The RDA for ground beetles indicated that although ground beetle community composition was influenced by crop rotation, the effect was not consistent. The majority of beetle species were associated with the f+ and h- systems.
- Four consistent associations were observed between weed and beetle species in 1995 and 1999. These were *H. pensylvanicus* and redroot pigweed; *A. carinata* and stinkweed; *A. placidum* and *C. calidum*, and wild mustard.
- As the robustness of the cropping system increased (rotation 3 > rotation 2 > rotation1), the cropping system was less reliant (i.e., the absence of crop inputs did

not create large variation in DM, yield, weed populations or ground beetle activity) on external crop inputs, of herbicide and fertilizer.

5.2 Robust versus Fragile Cropping Systems

Rotation 3 was found to be the most robust rotation based on the following observations: The added nitrogen from alfalfa hay crops reduced the need for synthetic fertilizer over time. Weed populations were suppressed, thus reducing the need for herbicides. Grassy weeds were not associated with rotation 3, thus the concerns of herbicide resistant green foxtail or wild oat was reduced. Crop DM, total DM, yield and ground beetle capture demonstrated the least variability between crop input treatments in rotation 3.

Rotation 1 was most representative of a fragile cropping system because it could only do well under a narrow range of conditions. Herbicide was required to manage weed densities, otherwise the density of weeds dramatically reduced yields. The monoculture of small grains, that is rotation 1, selected for grassy weed species with similar life cycles. Although not observed, use of similar herbicides between years would likely select for resistant weed species in as little as 3 years (Morrison and Devine, 1993). Fertilizer was annually required to maintain soil fertility, however fertilizer increased weed DM. Crop, weed and total DM, yield and weed density had greatest variability between the different crop inputs in rotation 1.

Rotation 2, which included a sweet clover green manure crop, demonstrated characteristics of both robust and fragile systems. Rotation 2 realized N benefits from the sweet clover green manure and grain yields in flax test crop years were less variable between crop input systems than the grain yields between crop input systems in rotation 1. Rotation 2 was strongly associated with stinkweed and Canada thistle, with increased densities of Canada thistle in the f-h- subplot. Therefore, 1 year of sweet clover in 4 was not enough to provide good weed control. Perhaps if sweet clover was followed by rye, as in many commercial organic systems (Entz et al., 2001b), it would be more efficient for weed control than in the present study.

5.3 Rotation Type and Crop Input Effects on Ground Beetles

Stability of the ground beetle population within rotations may be a better bioindicator than capture *per se* because observation of stable ground beetle populations would imply that the cropping system is stable enough to provide a consistent habitat for the bioindicators. Rotation 3, the most robust rotation, had the most stable beetle population between treatments indicating the use or absence of crop inputs did not deter ground beetles from the rotation system. As a result the benefits associated with ground beetles, such as predation, could be maintained even when the rotation system required herbicide. Rotation 1, the most fragile rotation, had the greatest differences in ground beetle populations between treatments, indicating instability. For example, the ample weed population in a fragile system, like rotation 1, would require the use of herbicide. However, herbicide use would have negative influence on ground beetles, deterring them from the system, thereby losing the beneficial predatory insect.

Throughout the second rotation cycle, ground beetle activity and weed growth was greatest in the f+h- subplots. It was concluded that these weedy subplots (i.e., f+h-) provided a superior habitat for beetles through increased humidity and abundant food supply. Unfortunately, this superior habitat includes weed competition. Intercropping two or more grain crops may be a means of maintaining plant diversity and microclimate humidity while suppressing detrimental weed populations, and at the same time, increasing yield.

5.4 Utilizing Knowledge about Weed and Ground Beetle Associations

The association of *Amara* and *Harpalus* with the f+h- subplots, which also contained the greatest abundance of weeds, and highest weed and total biomass, suggests that these ground beetle species may be used to sustainably manage the weed population through seed predation. Cromar et al. (1999) estimated 82% of produced seeds would be consumed by seed predators, most of which would be ground beetles. This was considered a conservative estimate as it did not account for pre- or post dispersal seed predation outside of measurement times, or weed mortality. Cardina et al. (1996) indicated that ground beetles could account for half of the post-dispersal seed predation occurring in old fields, resulting in reduced weed seed supply and seedling emergence. However, weed densities in the present study remained high in the f+h- systems despite the high capture of ground beetles in the f+h- systems, suggesting predation was not enough to provide economic weed control in the present study. The abundance of weeds may have been too great for the affect of weed seed predation to be clearly observed after two rotation cycles. Ground beetles may be more effective in an IPM system, where some herbicide is used to keep weed densities at levels lower than in the present study. Another consideration is whether enough time had elapsed to clearly demonstrate weed seed predation. Weed and ground beetle associations had strengthened between the first and second rotation cycles, thus data from an additional rotation cycle may provide even stronger evidence.

5.5 Long-term Studies

One of the concerns with long-term rotation studies regards the optimum or minimum number of rotation cycles required to stabilize the cropping system function. Liebman et al. (1996) suggested that weed dynamics may require four years or more to stabilize following a change in management practice. In the present study, rotational and herbicide effects on weeds were clearly evident following two rotation cycles. However, fertilizer *per se* did not demonstrate a large influence on weed community composition after two rotation cycles. The nutrient rich soil at Glenlea may have masked fertilizer effects on weeds. More rotation cycles may be required to uncover fertilizer effects on weed dynamics.

Clark et al. (1997) found ground beetle abundance and community structure to manifest itself slowly over time. In the present study, no clear effect of rotation on ground beetle activity occurred. Additional rotation cycles may be required to identify what associations, if any, would develop or be strengthened. The impact of crop inputs on beetles was evident, however, following two rotation cycles.

5.6 Implementing Results

Cropping systems diversity is key to managing weeds and stabilizing ground beetle population in an organic system. A robust rotation (e.g., rotation 3) is less dependent on external inputs. It would be recommended that organic producers include legumes in their system to suppress weeds and to realize the N benefits. The sweet clover system in the present study did not perform well in the absence of crop inputs, especially herbicides. Based on these results, an alfalfa hay crop would be a better legume choice than sweet clover in an organic system.

Cropping systems diversity is also key to stabilizing yields and managing pests in a reduced input conventional system. For producers looking to reduce expenses, adopting more robust rotations (such as rotation 3) would provide the opportunity to reduce external crop inputs in certain years and not sacrifice yield potential

Based on information in this study, it can be concluded that the use of crop inputs cannot be reduced in fragile systems (such as rotation 1) without risking reduced yields and increased risk of weed problems.

6.0 FUTURE RESEARCH QUESTIONS

The study raised more questions than it answered. For example, how would the results from the present study differ if zero-tillage, intercrop, or organic fertilizer in the form of farmyard manure had been utilized in the cropping system? What weed community shifts would be expected if current dominant weed species were continuously controlled? How would weed and ground beetle processes are affected by landscape features such as topography (which affects weeds) or adjacent woodland or grassland (which can affect insect populations)?

- Disturbance during breeding could reduce ground beetle populations for the next generation. In addition, the reduced ground cover associated with tillage may deter ground beetles from habitating within the cropping system due to decreased micro habitat humidity. Systems with reduced disturbance such as zero tillage or reduced tillage may benefit the ground beetle population. Tillage practices are also known to affect arthropods indirectly through changes in weed populations (Carcamo, 1995). Fields under reduced tillage have increased plant diversity and greater structural heterogeneity. Soils under zero tillage are also wetter than those under conventional tillage management. Therefore, questions around how the absence of tillage affects beetles would be of interest.
- Ground beetles should be encouraged in cropping systems without the additional presence of detrimental weed species. Intercropping may be a beneficial addition to a cropping system as it would suppress weeds and increase biomass to create a favourable microclimate for ground beetles. In addition, Clements et al. (1994)

indicated an increase in cropping system diversity, through such methods as inter-cropping, could be used to assist weed management. Therefore, future research should question how diversifying the plant community through intercropping would reduce weed density and affect ground beetles.

- The use of synthetic fertilizer benefited the ground beetle community indirectly by contributing to a thicker crop and weed canopy. On a mixed farm, an alternative to fertilizer is farmyard manure. Farmyard manure has been found to increase ground beetle activity, due to a favorable micro climate and alternate food source (Purvis et al., 1984). Therefore, more research is required to understand how different organic fertilizers, such as cattle or liquid hog manure, would affect ground beetles.
- Often large sections of farmland will contain tree clusters, hedgerows, or islands of mixed trees and bushes. Both complex and simple field borders are known to support abundant, diverse populations of ground beetles (Varchola and Dunn, 2001). The weed and ground beetle communities of these field borders would likely differ in composition from those of the cropping system as border species of weeds and beetles would co-habitat with those of the cropping system (Ogilvy et al., 1996). Ground beetles would be provided with an alternative habitat during disturbances, which could also be used for overwintering thus encouraging ground beetles to remain in the cropping system rather than be deterred from it. Therefore, research emphasis on the use of landscape diversity on weeds and ground beetles is warranted.
- In the present study, hempnettle and thymeleaf spurge were selected for in the f+h+ system. This observation raises the question as to whether zero tolerance for weeds actually created more weed species. When do weed shifts stop resulting in the

creation of new weed problems? Ecological theory suggests never. Therefore, is there a need to design control methods for all new weed species? Of particular interest will be the control of herbicide resistant volunteer crops, which are quickly becoming weed species in many production fields in Manitoba.

7.0 REFERENCES

Altieri, M. A. 1994. Biodiversity and Pest Management in Agroecosystems. Food Products Press. New York. P. 1-16, 39, 131-138.

Altieri, M. A. and Liebman, M. 1988. CRC Weed Management in Agroecosystems: Ecological Approaches. CRC Press, Inc. Florida. P. 2-6, 220-227.

Baars, M. A. 1979. Catches in Pitfall Traps in Relation to Mean Densities of Carabid Beetles. Oceologia **41**(1): 25-46.

Ball, D. A. 1992. Weed seedbank response to tillage, herbicides and crop rotation sequence. Weed Science **40**: 654-659.

Banting, J. D. 1974. Growth habit and control of wild oats. Agriculture Canada Publication 531. 34 pp.

Barden, J. A., Halfacre, R. G. and Parrish, D. J. 1987. Plant Science. McGraw-Hill, Inc. New York. P. 255.

Begon, M., Harper, J. L. and Townsend, C. R. 1990. Ecology: Individuals, Populations and Communities Second Edition. Blackwell Scientific Publications. P. 273-278, 792.

Bell, A. R. and Nalewaja, J. D. 1968a. Competitive effects of wild oat in flax. Weed Science **16**: 501-504.

Bell, A. R. and Nalewaja, J. D. 1968b. Competition of Wild Oat in Wheat and Barley. Weed Science **16**: 505-508.

Bell, C. E. 1993. Weed Management in Seedling Alfalfa (*Medicago sativa* L.); Long Term Effects. 8th EWRS Symposium "Quantitative approaches in weed and herbicide research and their practical application". P. 761-768.

Benoit, D. L., Derksen, D. A. and Panneton, B. 1992. Innovative approaches to seedbank studies. Weed Science **40**: 660-669.

Best, K. F. and McIntyre, G. I. 1975. The biology of Canadian Weeds. 9. *Thlaspi arvense* L. Canadian Journal of Plant Science **55**: 279-292.

Bischoff, A. and Mahn, E. G. 2000. The effects of nitrogen and diaspore availability on the regeneration of weed communities following extensification. Agriculture, Ecosystems and Environment **77**: 237-246.

Blackman, G. E. and Templeman, W. G. 1938. The nature of competition between cereal crops and annual weeds. Journal of Agricultural Science **28**: 247-271.

Blackshaw, R. E., Larney, F. O., Lindwall, C. W. and Kozub, G. C. 1994. Crop rotation and tillage effects on weed populations on the semi arid Canadian Prairies. Weed Technology **8**: 231-237.

Bommarco, R. 1998. Reproduction and energy reserves of a predatory carabid beetle relative to agroecosystem complexity. Ecological Applications **8**: 846-853.

Borror, D. J., Triplehorn, C. A. and Johnson, N. F. 1992. An Introduction to the Study of Insects Sixth Edition. Harcourt Brace College Publishers. P. 409.

Bowden, B. A. and Friesen, G. 1967. Competition of wild oats (*Avena fatua* L.) in wheat and flax. Weed Research **7**: 349-359.

Brust, G. E. 1990. Direct and indirect effects of four herbicides on the activity of carabid beetles (Coleoptera: Carabidae). Pesticide Science **30**: 309-320.

CANOCO 4 for Windows. Microcomputer Power. Ithaca, New York. USA.

Carcamo, H. A. 1995. Effect of tillage on ground beetles (Coleoptera: Carabidae): A farm-scale study in central Alberta. Canadian Entomologist **127**: 631-639.

Carcamo, H. A. and Spence, J. R. 1994. Crop type effects on the activity and distribution of ground beetles (Coleoptera: Carabidae). Environmental Entomology **23**: 684-692.

Carcamo, H. A., Niemela, J. K. and Spence, J. R. 1995. Farming and ground beetles: effects of agronomic practices on populations and community structure. Canadian Entomologist **127**: 123-140.

Cardina, J., Norquay, H. M., Stinner, B. R. and McCartney, D. A. 1996. Postdispersal Predation of Velvetleaf (*Abutilon theophrasti*) Seeds. Weed Science **44**: 534-539.

Chancellor, R. J. 1979. The long term effects of herbicides on weed populations. Annals of Applied Biology **91**: 141-144.

Chancellor, R. J. and Froud-Williams, J. R. 1986. Weed problems of the next decade in Britain. Crop Protection **5**: 66-72.

Chepil, W. S. 1946. Germination of weed seeds: I. Longevity, periodicity of germination, and vitality of seeds in cultivated soil. Sci. Agric. **26**: 307-346.

Chiverton, P. A. and Sotherton, N. W. 1991. The effects on beneficial arthropods of the exclusion of herbicides from cereal crop edges. Journal of Applied Ecology **28**: 1027-1039.

Clark, M. S. 1999. Ground beetle abundance and community composition in conventional and organic tomato systems of California's Central Valley. Applied Soil Ecology **11**: 199-206.

Clark, M. S., Gage, S. H. and Spence, J. R. 1997. Habitats and Management Associated with Common Ground Beetles (Coleoptera: Carabidae) in a Michigan Agricultural Landscape. Environmental Entomology **26**: 521-527.

Clements, D. R., Weise, S. F. and Swanton, C. J. 1994. Integrated weed management and weed species diversity. Phytoprotection **75**: 1-18.

Coble, H. D. 1996. Weed management tools and their impact on the agroecosystem. Second International Weed Control Congress. P. 1143-1146.

Cousens, R. and Mortimer, M. 1995. Weed population dynamics: synthesis and prognosis. *In* Dynamics of Weed populations. Cambridge University Press. Cambridge, UK. P 283-294.

Cromar, H. E., Murphy, S. D. and Swanton, C. J. 1999. Influence of tillage and crop residue on postdispersal predation of weed seeds. Weed Science **47**: 184-194.

Cussans, G. W. 1996. Which weed management strategies are appropriate? Second International Weed Control Congress. P. 1159-1166.

Dale, J. E. and Chandler, J. M. 1979. Herbicide-crop rotation for johnsongrass (*Sorghum balepense)* control. Weed Science **27**: 479-485.

Dekker, J. 1997. Weed diversity and weed management. Weed Science **45**: 357-363.

Derksen, D. A., Lafond, G. P., Thomas, A. G., Loeppky, H. A. and Swanton, C. J. 1993. Impact of Agronomic Practices on Weed Communities: Tillage Systems. Weed Science **41**: 409-417.

Derksen, D. A., Blackshaw, R. E. and Boyetchko, S. M. 1996. Sustainability, conservation tillage and weeds in Canada. Canadian Journal of Plant Science **76**: 651-659.

Derksen, D. A., Watson, P. R. and Loeppky, H. A. 1998. Weed community composition in seedbanks, seedling, and mature plant communities in a multi-year trial in western Canada. Aspects of Applied Biology **51**: 43-50.

deVries, H. H., denBoer, P. J. and VanDijk, T. S. 1996. Ground beetle species in heathland fragments in relation to survival, dispersal, and habitat preference. Oceologia **107**: 332-342.

Dietz, J. 1993. Using alfalfa to choke weeds out. Farm Light & Power. P13.

Di Tomaso, J. M. 1995. Approaches for Improving Crop Competitiveness through the Manipulation of Fertilization Strategies. Weed Science **43**: 491-497.

Dole, U. 1991. Beneficial insects of British Columbia cranberry bogs. British Columbia Cranberry Growers Association. Available On-line. World. Wide Web. @ http://www.corp.direct.ca/pestpage/ben3.html

Doucet, C., Weaver, S. E., Hamill, A. S. and Zhang, J. 1999. Separating the effects of crop rotation from weed management on weed density and diversity. Weed Science **47**: 729-735.

Douglas, B. J., Thomas, A. G., Morrison, I. N. and Maw, M. G. 1985. The biology of Canadian weeds. 70. *Setaria viridis* (L.) Beauv. Canadian Journal of Plant Science **65**: 669-690.

Dritschilo, W. and Wanner, D. 1980. Ground Beetle Abundance In Organic and Conventional Corn Fields. Environmental Entomology **9**: 629-631.

Dyck, E. and Liebman, M. 1995. Crop-weed interference as influenced by a leguminous or synthetic fertilizer nitrogen source: II. Rotation experiment with crimson clover, field corn and lamb's quarter. Agriculture Ecosystems and Environment **56**: 109-120.

Edwards, C. A. and Regnier, E. E. 1989. Designing integrated low-input farming systems to achieve effective weed control. Brighton Crop Protection Conference. P. 585-590.

Ellsbury, M. M., Powell, J. E., Forcella, F., Woodson, W. D., Clay, S. A. and Riedell, W. E. 1998. Diversity and Dominant Species of Ground Beetle Assemblages (Coleoptera Carabidae) in Crop Rotation and Chemical Input Systems for the Northern Great Plains. Annals of the Entomological Society of America **91**: 619-625.

Entz, M. H., Bullied, W. J. and Katepa-Mupondwa, F. 1995. Rotational Benefits of Forage Crops in Canadian Prairie Cropping Systems. Journal of Production Agriculture **8**: 521-529.

Entz, M. H., Baron, V. S., Carr, P. M., Meyer, D. M., Smith, S. R. Jr. and McCaughey, W. P. 2001a. Potential of Forages to Diversify Northern Great Plains Cropping Systems. Agronomy Journal (in press).

Entz, M. H., Guilford, R. and Gulden, R. 2001b. Crop yield and soil nutrient status on 14 organic farms in the eastern portion of the northern Great Plains. Canadian Journal of Plant Science **81**: 000-000 (in press).

Ewel, J. J., Mazzarino, M. J. and Berish, C. W. 1991. Tropical soil fertility changes under monocultures and successional communities of different structure. Ecological Applications **1**: 289-302.

Fawcett, R. S. and Slife, F. W. 1978. Effects of field applications of nitrate on weed seed germination and dormancy. Weed Science **26**: 594-596.

Fernandez-Quintanilla, C. 1988. Studying the population dynamics of weeds. Weed Research **28**: 443-447.

Fisher, R. A., Corbet, A. S. and Williams, C. B. 1943. The relation between the number of species and the number of individuals in a random sample of an animal population. Journal of Animal Ecology **12**: 42-58.

Forcella, F., Eradat-Oskoui, K. and Wagner, S. W. 1993. Application of weed seedbank ecology to low-input crop management. Ecological Applications **3**: 74-83.

Foster, R. K. and Austenson, H. M. 1990. Management of Sweetclover and Alfalfa in Cereal Rotations. *In* Transition to Organic Agriculture Conference. P. 32-47.

Frank, J. H. 1971. Carabidae (Coleoptera) as predators of the red-backed cutworm (Lepidoptera: Noctuidae) in central Alberta. Canadian Entomologist **103**: 1039-1044.

Friesen, G., Shebeski, L. H. and Robinson, A. D. 1960. Economic losses caused by weed competition in Manitoba grain fields II. Effect of weed competition on the protein content of cereal crops. Canadian Journal of Plant Science **40**: 652-658.

Gardner, S. M. 1991. Ground beetle (Coleoptera: Carabidae) communities on upland heath and their association with heathland flora. Journal of Biogeography **18**: 281-289.

Ghersa, C. M., Martinez-Ghersa, M. A. and Suarez, S. 1996. Spatial and temporal patterns of weed invasions: Implications for weed management and crop yield. Second International Weed Control Congress. P. 41-47.

Greenslade, P. J. M. 1964. Pitfall trapping as a method for studying populations of carabidae (Coleoptera). Journal of Animal Ecology **33**: 301-310.

Hallgren, E. 1996. Do the weed flora and effect of herbicide change with time? Second International Weed Control Congress. P. 1355-1368.

Hay, J. R. 1968. The changing weed problem on the prairies. Agriculture Institute Review. P. 17-19.

Hengeveld, R. 1980. Polyphagy, oligophagy and food specialization in ground beetles (Coleoptera, Carabidae). Netherlands Journal of Zoology **30**: 564-584.

Hodgson, J. M. 1968a. The nature, ecology and control of Canada thistle. U.S. Department of Agriculture. Technical Bulletin 1386. 32pp.

Hodgson, J. M. 1968b. Canada thistle and its control. U. S. Department of Agriculture leaflet No. 523. 8pp.

Hume, L. 1982. The long term effects of fertilizer application and 3 rotations on weed communities in wheat (after 21-22 years at Indianhead, Saskatchewan). Canadian Journal of Plant Science **62**: 741-750.

Hume, L., Martinez, J. and Best, K. 1983. The biology of Canadian weeds. 60. *Polygonum convolvulus* L. Canadian Journal of Plant Science **63**: 959-971.

Hume, L., Tessier, S. and Dyck, F.B. 1991. Tillage and rotation influences on weed community composition in wheat (*Tritticum aestivum* L.) in southwestern Saskatchewan. Canadian Journal of Plant Science **71**: 783-789.

Johnson, W. C. and Coble, H. D. 1986. Crop Rotation and Herbicide Effects on the Population Dynamics of Two Annual Grasses. Weed Science **34**: 452-456.

Jongman, R. H. G., Ter Braak, C. J. F. and Van Tongeren, O. F. R., Editors. 1995. Data Analysis in Community and Landscape Ecology. Cambridge University Press. P. 144-147.

Jordan, N. R. and Jannink, J. L. 1996. Evolution in weed populations: when should it concern weed managers?. Second International Weed control Congress. P. 27-34.

Jornsgard, B., Rasmussen, K., Hill, J. and Christiansen, J. L. 1996. Influence of nitrogen on competition between cereals and their natural weed populations. Weed Research **36**: 461-470.

Kareiva, P. 1985. Finding and losing host plants by *Phyllotreta*: patch size and surrounding habitat. Ecology **66**:1809-1816.

Kelner, D. J., Vessey, J. K. and Entz, M. H. 1997. The nitrogen dynamics of 1-,2- and 3-years stands of alfalfa in a cropping system. Agriculture Ecosystems & Environment **64**: 1-10.

Kielhorn, K. H., Keplin, B. and Hüttl, R. F. 1999. Ground beetle communities on reclaimed mine spoil: Effects of organic matter application and revegetation. Plant and Soil **213**: 117-125.

Klebesadel, L. J. 1969. Life cycles of field pennycress in the subarctic as influenced by time of germination. Weed Science **17**: 563-566.

Krebs, C. J. 1989. Ecological Methodology. Harper Collins Publishers. P. 342-346, 357-362.

Kromp, B. 1989. Carabid Beetle Communities (Carabidae, Coleoptera) in Biologically and Conventionally Farmed Agroecosystems. Agriculture, Ecosystems and Environment **27**: 241-251.

Larochelle, A. 1990. The food of carabid beetles (Coleoptera: Carabidae, including cicindelinae) Fabreries Supplement 5. Association des Entomologistes Amateurs du Québec. 132 pp.

Larsen, K. J., Purrington, F. F., Brewer, S. R. and Taylor, D. H. 1996. Influence of sewage sludge and fertilizer on the ground beetle (Coleoptera: Carabidae) fauna of an old field community. Environmental Entomology **25**: 452-459.

Legérè, A., Schreiber, M. M., Hickman, M. V. and Samson, N. 1996. Residual weed populations: innocent bystanders or potential time bombs ? Second International Weed Control Congress. P. 1261-1266.

Liebman, M., Drummond, F. A., Corson, S. and Zhang, J. 1996. Tillage and Rotation Crop Effects on Weed Dynamics in Potato Production Systems. Agronomy Journal **88**: 18-26.

Lindroth, C. H. 1961-1969. The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Opusaula Entomological Supplement. Lund. Sweden. 1192 pp.

Luff, M. L. and Rushton, S. P. 1988. The effects of pasture improvement on the ground beetle and spider fauna of upland grasslands. Aspects of Applied Biology. P. 67-74.

Lund, R. D. and Turpin, F. T. 1977. Carabid damage to weed seeds found in Indiana corn fields. Environmental Entomology **6**: 695-698.

Lys, J., Zimmermann, M. and Nentwig, W. 1994. Increase in activity, density and species number of carabid beetles in cereals as a result of strip management. Entomologia Experimentalis et Applicata **73**: 1-9.

Macey, A. *Editor*. 1992. Weed Management. *In* Organic Field Crop Handbook: A project of Canadian Organic Growers Inc. P 58-68.

Magurran, A. E. 1988. Ecological Diversity and Its Measurement. Princeton University Press. P. 34-40, 61, 71- 78.

Manitoba Agriculture. 2001. 2001 Crop Production Costs: Seed&Treatment / Fertilizer / Chemicals. Manitoba Agriculture and Agrifood: Business & Economics. Available On-line. World. Wide. Web. @
http://www.gov.mb.ca/agriculture/financial/farm/cac40s01.html

Manly, B. F. J. 1991. Randomization and Monte Carlo Methods in Biology. Chapman and Hall. P. 21-23.

Milliken, G. A. and Johnson, D. A. 1992. Analysis of Messy Data, Volume 1: Designed Experiments. Chapman and Hall/CRC. P. 17-28.

Moore, R. J. 1975. The biology of Canadian weeds. 13. *Cirsium arvense* (L.) Scop. Canadian Journal of Plant Science **55**: 1033-1048.

Morrison, I. N. and Devine, M. D. 1994. Herbicide resistance in the Canadian prairie provinces: Five years after the fact. Phytoprotection **75(Suppl.)**: 5-16.

Norris, R. F. 1992. Multidisciplinary IPM: A Challenge for the Future. Proceedings of the California Weed Conference. P. 55-63.

O'Donovan, J. T. and Sharma, M. P. 1987. The biology of Canadian weeds. 78. *Galeopsis tetrahit* L. Canadian Journal of Plant Science **67**: 787-796.

Ogilvy, S. E., Green, M. R. and Mills, A. R. 1996. SCARAB - the effects of reduced herbicide inputs on floral density in two arable rotations. Rotations and Cropping Systems. 16-18 December 1996. Churchill College, Cambridge/ Wellesbourne, Warwick, UK. P. 211-214.

Ominski, P. 1998. Weed Population Dynamics as Influenced by Alfalfa and Alfalfa Termination Method. M.Sc. Thesis. University of Manitoba. Winnipeg, Manitoba.

Ominski, P. D., Entz, M. H. and Kenkel, N. 1999. Weed suppression by *Medicago sativa* in subsequent cereal crops: a comparative survey. Weed Science **47**: 282-290.

Paoletti, M. G., Stinner, B. R. and Lorenzoni, G. 1989. Agriculture Ecosystems and Environment **27**: 1-4.

Pavuk, D. M., Purrington, F. F., Williams, C. E. and Stinner, B. R. 1997. Ground Beetle (Coleoptera: Carabidae) Activity Density and Community Composition in Vegetationally Diverse Corn Agroecosystems. American Midland Naturalist **138**:14-28.

Potts, G. R. and Vickerman, G. P. 1974. Studies of the cereal ecosystem. Advances in Ecological Research. **8**: 107-197.

Powles, S. B., Preston, C., Bryan, I. B. and Jutsum, A. R. 1997. Herbicide Resistance: Impact and Management. Advances in Agronomy **58**: 57-92.

Purvis, G. and Curry, J. P. 1984. Influence of weeds and farmyard manure on the activity of carabids and other ground dwelling arthropods in a sugar beet crop. Journal of Applied Ecology **21**: 271-283.

Pyšek, P. and Lepš, J. 1991. Response of a weed community to nitrogen fertilizer: a multivariate analysis. Journal of Vegetation Science **2**: 237-244.

Rivard, I. 1966. Ground Beetles (Coleoptera: Carabidae) in relation to agricultural crops. Canadian Entomologist **98**: 189-195.

Rojas-Garciduenas, M. and Kommedahl, T. 1960. The effect of 2,4-D on germination of pigweed seed. Journal of the Weed Society of America **8**: 1-5.

Ross, D. M. 2001. Effect of Nitrogen Rate and Weed Density on Spring Wheat Yield at Two Landscape Positions. M.Sc. Thesis. University of Manitoba. Winnipeg, Manitoba.

Ross, M. A. and Lembi, C. A. 1985. Applied Weed Science. MacMillan Publishing Company. New York. P. 1, 214-215.

SAS version 6.12 for Windows. SAS Institute Inc. Cary, North Carolina. USA.

Sauerborn, J. 1996. Underrated methods of weed control and their use in the agriculture of developing countries. Second International Weed Control Congress. P.611-621.

Scheller, H. V. 1984. Pitfall trapping as the basis for studying ground beetle (Carabidae) predation in spring barley. Tidsskr-Plant-Dan-J-Plat-Soil-Sci. **88**: 317-324.

Schoofs, A. and Entz, M. H. 2000. Influence of annual forages on weed dynamics in a cropping system. Canadian Journal of Plant Science **80**: 187-198.

Schreiber, M. M. and Orwick, P. L. 1978. Influences of nitrogen fertility on the growth of foxtail (*Setaria*) taxa. Weed Science **26**: 347-350.

Shannon, C. E. and Weaver, W. 1949. The mathematical theory of communication. University of Illinois Press, Urbana.

Sharma, M. P. and Vanden Born, W. H. 1978. The biology of Canadian weeds. 27. *Avena fatua* L. Canadian journal of Plant Science **58**: 141-157.

Shaw, W. C. 1982. Integrated Weed Management Systems Technology for Pest Management. Weed Science **30(suppl.1)**: 2-12 .

Sheaffer, C. C., Barnes, D. K. and Heichel, G. H. 1989. "Annual" Alfalfa in Crop Rotations. Station Bulletin 588. Minnesota Agricultural Experiment Station. University of Minnesota.

Sibuga, K. P. and Bandeen, J. D. 1980. Effects of green foxtail and lamb's-quarters interference in field corn. Canadian Journal of Plant Science **60**: 1419-1425.

Siemens, L. B. 1963. Cropping systems: an evaluative review of literature. Faculty of Agriculture, University of Manitoba. Technical Bulletin No.1.

Simpson, E. H. 1949. Measurement of diversity. Nature (London) **163**: 688.

Skorda, E. A., Adamidis, T. H. and Efthimiadis, P. G. 1995. Long-term effects of reduced herbicide use on weed populations and crop yield in wheat. Brighton Crop Protection Conference. P. 695-700.

Snodgrass, G. L. and Stadelbacher, E. A. 1989. Effect of Different Grass and Legume Combination on Spider (Araneae) and Ground Beetle (Coleoptera: Carabidae) Populations in Roadside Habitats in the Mississippi Delta. Environmental Entomology **18**: 575-581.

Southwood, T. R. E., Brown, V. K. and Reader, P. M. 1979. The relationships of plant and insect diversities in succession. Biol. J. Linn. Soc. **12**: 327.

Stupnicka-Rodzynkiewicz, E. 1996. Changes in population sizes of weeds in cereals grown in a five-year rotation. Second International Weed Control Conference. P. 185-190.

Swanton, C. J., Harker, K. N. and Anderson, R. L. 1993. Crop Losses Due to Weeds in Canada. Weed Technology **7**: 537-542.

Swanton, C. J. and Murphy, S. D. 1996. Integrated weed management (IWM) promotes increased energy efficiency and biodiversity. Second International Weed Control Congress. P. 1369-1374.

Swanton, C. J. and Weise, S. F. 1991. Integrated Weed Management: The Rationale and Approach. Weed Technology **5**: 657-663.

Taylor, L. R. 1978. Bates, Williams and Hutchinson - a variety of diversities. *In* Diversity of Insect Faunas: 9th Symposium of the Royal Entomological Society. Blackwell. Oxford. P. 1-18.

Tereshchuk, V. S. 1996. Occurrence of weeds in barley depending on the preceding crop. Second International Weed Congress. Copenhagen. P. 259-264.

Terrell-Nield, C. 1990. Is it possible to age woodlands on the basis of their carabid diversity? The Entomologist **109**: 136-145.

Theile, H. U. 1977. Carabid Beetles in Their Environments: A Study on Habitat Selection by Adaptations in Physiology and Behaviour. Springer-Verlag Berlin Heidelberg. Germany. 369 pp.

Thomas, A. G., Frick, B., Derksen, D. A., Brandt, S. A. and Zentner, R. P. 1996. Crop rotations and weed community dynamics on the Canadian prairies. Second International Weed Control Congress. P. 227-232.

Thomas, A.G., Frick, B. L., Van Acker, R. and Joosse, D. 1998. Weed Survey of Manitoba Cereal and Oilseed Crops 1997. Weed Survey Series Publication 98-1. Agriculture and Agri-Food Canada, Saskatoon.

Thomas, A. G. and Leeson, J. Y. 1999. Residual Weed Populations in Canola Associated with Farm Management Practices. Expert Committee on Weeds 1999 National Meeting. Poster.

Thomas, C. F. G. and Marshall, E. J. P. 1999. Arthropod abundance and diversity in differently vegetated margins of arable fields. Agriculture, Ecosystems and Environment **72**: 131-144.

Thompson, R. G. 1977. A synoptic list of the described ground beetle larvae of North America (Coleoptera: Carabidae). Proceedings of the Biological Society of Washington **90**: 99-107.

Tilman, D. 1986. Resources, Competition and the Dynamics of Plant Communities *In* Plant Ecology. Blackwell Scientific Publications. P. 51-75.

Tilman, D. 1987. Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. Ecological Monographs **57**: 189-214.

Tilman, D. and Downing, J. A. 1994. Biodiversity and stability in grasslands. Nature **367**: 363-365.

Tonhasca, A. Jr. 1993. Carabid beetle assemblage under diversified agroecosystems. Entomol. Exp. Appl. **68**: 279-285.

Van Acker, R. C., Derksen, D. A., Entz, M. H., Martens, G., Andrews, T and Nazarko, O. 2001. Pesticide-Free Production: A reason to implement integrated weed management. Integrated Weed Management (Monograph). Expert Committee on Weeds. Ottawa, Canada. P. 61-73.

Van Acker, R. C. and Oree, R. 1999. Wild oat (*Avena fatua* L.) And wild mustard (*Brassica kaber* (D.C.) L.C. Wheeler interference in canola (*Brassica napus*). Weed Science Society of America **39**: 10.

Van Acker, R. C., Thomas, A. G., Leeson, J. Y., Knezevic, S. Z. and Frick, B. L. 2000. Comparison of weed communities in Manitoba ecoregions and crops. Canadian Journal of Plant Science **80**: 963-972.

Vandermeer, J. 1995. The ecological basis of alternative agriculture. Annual Reviews of Ecological Systems **26**: 210-224.

Varchola, J. M. and Dunn, J. P. 2001. Influence of hedgerow and grassy field borders on ground beetle (Coleoptera: Carabidae) activity in fields of corn. Agriculture, Ecosystems and Environment **83**: 153-163.

Warwick, S. I., Beckie, H. J., Thomas, A. G. and Macdonald, T. 2000. The biology of Canadian weeds. 8. *Sinapis arvensis* L. (updated). Canadian journal of Plant Science **80**: 939-961.

Weaver, S. E. and McWilliams, E. L. 1980. The biology of Canadian weeds. 44. *Amaranthus retroflexus* L., *A. powellii* S. Wats. and *A. hybridus* L. Canadian Journal of Plant Science **60**: 1215-1234.

Weiss, M., Balsbaugh, E., French, E. and B. Hoag. 1990. Influence of tillage management and cropping system on ground beetle (Coleoptera: Carabidae) fauna in the Northern Great Plains. Environmental Entomology **19**: 1388-1391.

Weston, L.A. 1996. Utilization of Allelopathy for Weed Management in Agroecosystems. Agronomy Journal **88**: 860-866.

Whitson, T. D., Burrill, L. C., Dewey, S. A., Cudney, D. W., Nelson, B. E., Lee, R. D. and Parker, R. 1996. Weeds of the West 5th Edition. The Western Society of Weed Science in cooperation with the Western United States Land Grant Universities Cooperative Extension Services. Jackson, Wyoming. 630 pp.

Work, T. T., McCullough, D. G. and Mattson, W. J. 1998. Moth and Carabid Beetle Species Associated with Two Ecological Landtype Phases in Northern Michigan. USDA Forest Service North Central Research Station General Technical Report NC-201.

Young, J. A. and Evans, R. A. 1976. Responses of Weed Populations to Human Manipulations of the Natural Environment. Weed Science **24**: 186-190.

Appendix A

Table A.1 Summary of the % variance of species data, % variance of species-environment relation and Monte Carlo test for significance for weed population at the Glenlea long-term cropping systems study, 1995 to 1999.

	Summary of RDA Biplot								Summary of Monte Carlo Test			
	% Variance of Species Data				% Variance of Species-Environment Relation				First Canonical Axis		All Canonical Axes	
Year	Axis 1	Axis 2	Axis 3	Axis 4	Axis 1	Axis 2	Axis 3	Axis 4	F-ratio	P-value	F-ratio	P-value
1995	18.5	11.4	6.7	4.4	42.6	26.1	15.4	10.0	6.362	0.005	3.081	0.005
1996	24.8	15.0	5.3	1.8	50.7	30.7	10.9	3.6	9.240	0.005	3.830	0.005
1997	44.6	19.6	2.5	1.1	64.4	28.5	3.6	1.5	22.501	0.005	8.959	0.005
1998	33.9	24.0	2.2	1.6	54.5	38.4	3.6	2.6	9.243	0.005	5.949	0.005
1999	26.1	16.1	7.8	3.0	45.9	28.4	13.7	5.3	9.888	0.005	5.259	0.005

Table A.2 Summary of the % variance of species data, % variance of species-environment relation and Monte Carlo test for significance for ground beetles at the Glenlea long-term cropping systems study, 1995 to 1999.

	Summary of RDA Biplot								Summary of Monte Carlo Test			
	% Variance of Species Data				% Variance of Species-Environment Relation				First Canonical Axis		All Canonical Axes	
Year	Axis 1	Axis 2	Axis 3	Axis 4	Axis 1	Axis 2	Axis 3	Axis 4	F-ratio	P-value	F-ratio	P-value
1995	10.8	6.1	3.7	2.5	42.9	24.0	14.5	9.8	3.529	0.010	1.635	0.005
1996	21.7	5.4	2.4	0.8	69.4	17.2	7.7	2.3	8.057	0.010	2.204	0.010
1997	13.2	6.2	3.6	1.9	48.4	22.5	13.4	6.8	4.414	0.120	1.817	0.015
1998	23.6	16.3	3.3	1.0	52.5	36.3	7.3	2.3	8.971	0.005	3.950	0.050
1999	24.3	14.6	3.5	1.9	52.0	31.3	7.6	4.0	9.288	0.005	4.230	0.005

Table A.3 Summary of the % variance of species data, % variance of species-environment relation and Monte Carlo test for significance for ground beetles in the prairie grass and cropping systems at the Glenlea long-term cropping systems study, 1995 to 1999.

	Summary of RDA Biplot								Summary of Monte Carlo Test			
	% Variance of Species Data				% Variance of Species-Environment Relation				First Canonical Axis		All Canonical Axes	
Year	Axis 1	Axis 2	Axis 3	Axis 4	Axis 1	Axis 2	Axis 3	Axis 4	F-ratio	P-value	F-ratio	P-value
1995	9.6	7.2	5.9	2.8	33.2	24.9	20.4	9.9	3.289	0.020	1.797	0.005
1996	21.0	4.9	3.6	1.7	63.8	14.9	11.0	5.2	8.222	0.010	2.169	0.010
1997	11.7	7.5	5.3	2.8	38.2	24.2	17.3	9.2	4.124	0.240	1.968	0.005
1998	21.3	16.6	7.3	2.9	43.2	33.8	14.7	6.0	8.377	0.005	4.303	0.005
1999	30.4	11.9	5.1	2.8	57.1	22.3	9.6	5.0	13.567	0.005	5.054	0.005

Table A.4 Summary of the % variance of species data, % variance of species-environment relation and Monte Carlo test for significance for weed and ground beetle combined dataset at the Glenlea long-term cropping systems study, 1995 and 1999.

	Summary of RDA Biplot								Summary of Monte Carlo Test			
	% Variance of Species Data				% Variance of Species-Environment Relation				First Canonical Axis		All Canonical Axes	
Year	Axis 1	Axis 2	Axis 3	Axis 4	Axis 1	Axis 2	Axis 3	Axis 4	F-ratio	P-value	F-ratio	P-value
1995	18.2	11.3	6.4	4.3	43.0	26.7	14.9	10.3	6.472	0.005	3.557	0.005
1999	26.1	16.0	7.8	2.8	46.5	28.7	13.9	5.0	10.219	0.005	6.158	0.005

Appendix B

Table B.1 Dry matter (g m^{-2}) and grain yield (kg ha^{-1}) at the Glenlea long-term cropping systems study, 1996. Statistical analysis for dry matter and yield performed on log transformed data. Means considered significant when $p<0.05$.

			Dry Matter				
Rotation	Inputs	Crop	Crop	Legume	Weed	Total	Yield
Rotation 1	f+h+	Wheat	683.8	.	57.9	741.7	3275.9
	f+h-	Wheat	477.7	.	216.8	694.5	2325.2
	f-h+	Wheat	331.3	.	13.7	345.0	1493.5
	f-h-	Wheat	261.3	.	81.0	342.3	1259.7
Rotation 2 [z]	f+h+	Wheat	500.7	48.2	81.3	630.2	2400.1
	f+h-	Wheat	510.5	10.0	96.0	616.4	2450.9
	f-h+	Wheat	263.5	111.2	51.7	426.4	1076.0
	f-h-	Wheat	266.7	36.7	60.9	364.3	1240.0
Rotation 3 [y]	f+h+	Wheat	752.8	9.8	17.9	780.6	3513.6
	f+h-	Wheat	535.0	1.7	146.1	682.8	2899.9
	f-h+	Wheat	506.3	22.9	27.0	556.3	2540.2
	f-h-	Wheat	405.5	13.8	74.7	494.1	2088.1
Rotation (R)			0.0360	0.0147	0.2599	0.0690	0.0218
Treatment (T)			0.0001	0.0048	0.0001	0.0001	0.0001
R X T			0.0070	0.0023	0.0043	0.0064	0.0312
SEM			30.76	8.21	19.95	25.45	176.15

[z] Wheat undersown to sweet clover

[y] Wheat undersown to alfalfa

Table B.2 Dry matter ($g\ m^{-2}$) and grain and legume yield ($kg\ ha^{-1}$) at the Glenlea long-term cropping systems study, 1997. Statistical analysis for dry matter and yield performed on log transformed data. Means considered significant when $p<0.05$.

Rotation	Inputs	Crop	Dry Matter			
			Crop	Weed	Total	Yield
Rotation 1	f+h+	Pea	454.0	10.9	464.8	2261.0
	f+h-	Pea	174.9	141.8	316.7	1311.0
	f-h+	Pea	457.2	6.4	463.5	3833.3
	f-h-	Pea	212.5	179.5	392.1	1554.3
Rotation 2	f+h+	Sweet Clover	265.8	20.2	286.0	2860.1
	f+h-	Sweet Clover	133.1	85.3	218.4	2183.7
	f-h+	Sweet Clover	287.6	16.8	304.3	2831.3
	f-h-	Sweet Clover	348.6	37.3	385.9	3859.1
Rotation 3	f+h+	Alfalfa	736.2	11.4	747.5	7475.3
	f+h-	Alfalfa	581.3	37.9	619.2	6191.9
	f-h+	Alfalfa	801.4	3.9	805.3	8053.1
	f-h-	Alfalfa	652.3	11.5	663.8	6638.1
Rotation (R)			0.0983	0.0484	0.0441	0.0991
Treatment (T)			0.0008	0.0001	0.0037	0.0361
R X T			0.0265	0.0430	0.2269	0.0426
SEM			41.46	17.70	39.01	442.69

Table B.3 Dry matter (g m^{-2}) and grain and legume yield (kg ha^{-1}) at the Glenlea long-term cropping systems study, 1998. Statistical analysis for dry matter and yield performed on log transformed data. Means considered significant when $p<0.05$.

			Dry Matter			
Rotation	Inputs	Crop	Crop	Weed	Total	Yield
Rotation 1	f+h+	Wheat	640.0	53.0	693.0	2105.9
	f+h-	Wheat	225.3	236.7	462.1	887.2
	f-h+	Wheat	495.5	39.0	534.5	1394.0
	f-h-	Wheat	198.0	99.0	297.1	476.0
Rotation 2	f+h+	Wheat	885.1	0.1	885.2	2610.4
	f+h-	Wheat	609.2	135.7	744.9	1704.1
	f-h+	Wheat	717.9	2.8	720.7	2173.9
	f-h-	Wheat	455.1	124.5	579.6	1658.4
Rotation 3	f+h+	Alfalfa	788.9	8.6	797.5	7986.7
	f+h-	Alfalfa	784.4	27.7	812.1	8121.4
	f-h+	Alfalfa	683.7	2.7	686.4	6863.6
	f-h-	Alfalfa	611.1	20.0	631.0	6310.4
Rotation (R)			0.0231	0.059	0.101	0.0015
Treatment (T)			0.0001	0.0001	0.0017	0.0006
R X T			0.0298	0.0365	0.4186	0.0187
SEM			80.17	21.41	75.84	443.18

Table B.4 Weed population density (plants m^{-2}) at the Glenlea long-term cropping systems study, 1996, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie was statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	KCHSC	Volunteer	Total
Rotation 1	f+h+	176	2	5	1	0	10	0	0	23	0	0	216
	f+h-	218	90	16	5	0	6	1	1	18	9	0	366
	f-h+	48	2	3	3	2	5	0	0	27	0	1	91
	f-h-	200	66	16	8	0	4	1	0	1	8	0	303
Rotation 2	f+h+	118	1	33	2	0	16	4	0	54	0	0	228
	f+h-	88	24	43	7	0	1	6	1	6	0	1	177
	f-h+	104	0	53	3	0	23	0	0	14	0	1	199
	f-h-	83	33	58	7	1	3	1	0	0	0	0	186
Rotation 3	f+h+	13	2	4	1	1	1	0	4	0	0	1	26
	f+h-	133	43	21	5	0	1	1	2	0	0	0	206
	f-h+	13	2	2	1	0	0	1	3	2	0	1	24
	f-h-	187	25	13	4	0	1	0	1	1	0	1	233
Prairie		0	0	0	0	0	0	0	0	0	0	0	0
Prairie vs. Rotations		0.0650	0.1565	0.0711	0.4547	0.4547	0.2140	0.1170	0.1170	0.0594	.[z]	.	0.0347
Rotation (R)		0.1190	0.6010	0.1251	0.2105	0.3325	0.1480	0.2674	0.3942	0.1926	0.4444	0.0871	0.0074
Treatment (T)		0.0014	0.0001	0.0259	0.0014	0.4452	0.4364	0.0008	0.6385	0.0030	0.5118	0.3273	0.0016
R X T		0.0047	0.7713	0.5918	0.8691	0.0494	0.0029	0.0046	0.6102	0.0440	0.3991	0.6300	0.0206
SEM		50.2	18.5	11.8	1.3	0.5	3.7	0.7	1.2	9.1	2.9	0.5	68.3

[z] Values of 0 for all analysed variables yielded no statistical probability

Table B.5 Weed population density (plants m^{-2}) at the Glenlea long-term cropping systems study, 1997, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie was statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	TLS	KCHSC	Total
Rotation 1	f+h+	2592	9	1	1	0	4	0	0	60	9	0	2676
	f+h-	1512	547	13	4	1	1	7	0	89	1	0	2177
	f-h+	1351	15	1	0	1	2	0	0	36	19	0	1424
	f-h-	1473	198	11	4	1	2	6	0	13	0	0	1709
Rotation 2	f+h+	771	14	188	4	1	3	1	3	6	0	0	991
	f+h-	783	251	284	31	1	1	6	11	1	0	0	1368
	f-h+	432	18	400	4	1	0	1	4	2	0	0	861
	f-h-	611	58	259	11	0	4	4	6	0	0	0	952
Rotation 3	f+h+	32	123	458	2	1	0	0	10	0	0	0	627
	f+h-	884	379	368	30	0	1	3	6	0	0	0	1670
	f-h+	75	8	402	3	0	0	0	8	0	0	0	497
	f-h-	1041	357	464	6	0	0	1	4	0	0	0	1874
Prairie		0	0	0	0	0	0	0	0	0	0	0	0
Prairie vs. Rotations		0.0003	0.1826	0.0117	0.3279	0.3776	0.3584	0.1170	0.0572	0.0608	0.0752	.[z]	0.0060
Rotation (R)		0.0020	0.8914	0.0015	0.0088	0.5069	0.2707	0.1010	0.0033	0.0485	0.0092	.	0.0415
Treatment (T)		0.0001	0.0001	0.0099	0.0001	0.8170	0.8213	0.0001	0.4119	0.1059	0.0001	.	0.0164
R X T		0.0001	0.1327	0.0013	0.3878	0.3527	0.7565	0.7897	0.3637	0.5842	0.0001	.	0.0917
SEM		277.3	105.6	49.0	4.1	0.7	1.5	1.4	2.1	19.8	2.2	0.0	348.5

[z] Values of 0 for all analysed variables yielded no statistical probability

Table B.6 Weed population density (plants m^{-2}) at the Glenlea long-term cropping systems study, 1998, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie was statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

Rotation	Input	SETVI	SINAR	THLAR	POLCO	POLPE	CHEAL	CIRAR	TAROF	AMARE	TLS	AVEFA	KCHSC	Total
Rotation 1	f+h+	491	3	6	9	2	2	1	0	0	10	0	0	525
	f+h-	756	214	46	32	8	5	6	0	0	3	4	0	1075
	f-h+	286	3	3	11	1	0	0	0	0	10	0	0	316
	f-h-	792	168	17	23	5	3	15	0	0	0	1	0	1025
Rotation 2	f+h+	32	5	42	10	2	1	8	0	0	1	0	0	100
	f+h-	31	29	78	13	3	3	14	0	0	1	1	0	173
	f-h+	29	4	30	15	3	1	1	0	0	3	0	0	86
	f-h-	39	17	18	10	2	0	13	0	0	2	0	0	101
Rotation 3 [z]	f+h+	.	.	.	.	.	.	.	.	.	.	.	.	.
	f+h-	.	.	.	.	.	.	.	.	.	.	.	.	.
	f-h+	.	.	.	.	.	.	.	.	.	.	.	.	.
	f-h-	.	.	.	.	.	.	.	.	.	.	.	.	.
Prairie		0	0	0	0	0	0	0	0	0	0	0	0	0
Prairie vs. Rotations		0.0001	0.3460	0.0193	0.1964	0.3859	0.0331	0.1469	. [y]	0.4444	0.0010	.	.	0.0001
Rotation (R)		0.0056	0.1858	0.0294	0.7537	0.8111	0.2400	0.0961	0.1835	0.4226	0.1144	0.2639	.	0.0008
Treatment (T)		0.2172	0.0002	0.0516	0.5532	0.0534	0.0383	0.0011	0.6445	0.4262	0.0087	0.1806	.	0.0538
R X T		0.5134	0.0824	0.2007	0.5042	0.2664	0.5512	0.5140	0.6445	0.4262	0.0968	0.7360	.	0.4244
SEM		132.8	46.9	21.0	8.3	1.5	1.2	4.4	0.2	0.1	1.3	1.5	0.0	142.3

[z] Weed populations were not assessed in the alfalfa hay crop in 1998

[y] Values of 0 for all analysed variables yielded no statistical probability

Table B.7 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for weed population at the Glenlea long-term cropping systems study, 1996, as influenced by crop rotation type and crop input management. Statistical analysis preformed on log transformed data. Means considered significant when p<0.05.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	0.64	0.69	0.52
	f+h-	1.11	0.42	0.69
	f-h+	0.97	0.52	0.59
	f-h-	1.03	0.46	0.69
Rotation 2	f+h+	1.17	0.41	0.69
	f+h-	1.31	0.36	0.67
	f-h+	1.07	0.46	0.67
	f-h-	1.20	0.37	0.73
Rotation 3	f+h+	1.41	0.32	0.70
	f+h-	1.01	0.47	0.66
	f-h+	1.31	0.35	0.70
	f-h-	0.66	0.66	0.55
Rotation (R)		0.4241	0.4500	0.5128
Treatment (T)		0.5681	0.7196	0.9120
R X T		0.0002	0.0107	0.5300
SEM		0.097	0.065	0.082

Table B.8 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for weed population at the Glenlea long-term cropping systems study, 1997, as influenced by crop rotation type and crop input management. Statistical analysis preformed on log transformed data. Means considered significant when $p<0.05$.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	0.17	0.94	0.36
	f+h-	0.76	0.56	0.70
	f-h+	0.27	0.90	0.36
	f-h-	0.51	0.74	0.53
Rotation 2	f+h+	0.66	0.63	0.61
	f+h-	1.02	0.46	0.68
	f-h+	0.83	0.49	0.82
	f-h-	0.91	0.50	0.70
Rotation 3	f+h+	0.72	0.60	0.64
	f+h-	0.99	0.43	0.82
	f-h+	0.67	0.64	0.62
	f-h-	0.94	0.43	0.84
Rotation (R)		0.0547	0.0589	0.0145
Treatment (T)		0.0003	0.0010	0.0223
R X T		0.3772	0.3441	0.0328
SEM		0.103	0.063	0.064

Table B.9 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for weed population at the Glenlea long-term cropping systems study, 1998, as influenced by crop rotation type and crop input management. Means considered significant when $p<0.05$.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	0.33	0.88	0.35
	f+h-	0.94	0.52	0.60
	f-h+	0.55	0.76	0.41
	f-h-	0.70	0.65	0.54
Rotation 2	f+h+	1.43	0.30	0.78
	f+h-	1.49	0.31	0.73
	f-h+	1.28	0.38	0.65
	f-h-	1.51	0.28	0.76
Rotation 3	f+h+	.	.	.
	f+h-	.	.	..
	f-h+	.	.	.
	f-h-	.	.	.
Rotation (R)		0.0626	0.0627	0.1101
Treatment (T)		0.0378	0.0204	0.1635
R X T		0.1726	0.0398	0.1865
SEM		0.115	0.054	0.065

Table B.10 Ground beetle capture for 1 sampling date at the Glenlea long-term cropping systems study, August, 1996, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when p<0.05.

	Rotation 1				Rotation 2				Rotation 3					Prairie vs.				
	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	Prairie	Rotations	Rotation (R)	Treatment (T)	R X T	SEM
AMAR_APR	0	0.66	0	0	0	0.33	0	0	0	0	0.33	0.33	0	.[†]	0.6944	0.2584	0.2467	0.20
AMAR_AVI	0.66	1.66	0.33	1.33	1	0.66	0.33	0.66	0	0.66	0.33	0	0.66	0.0501	0.0123	0.5274	0.4137	0.45
AMAR_CAR	0.33	0.66	0.33	0.66	0.33	0.66	1	0.66	0.66	1	0.33	0.66	0.66	0.6542	0.4444	0.8354	0.8713	0.43
AMAR_CUP	0	0	0	0	0	0	0.33	0	0	0	0	0	0	.	0.4444	0.4155	0.4552	0.10
AMAR_FAR	0	0	0	0	0	0	0	0	0.33	0.33	0	0	0	0.4547	0.4444	0.4155	0.4552	0.11
AMAR_LIT	0	0.33	0	0	0	0	0	0	0	0	0	0	0	.	0.4444	0.4155	0.4552	0.10
AMAR_OBE	0	0	0	0.33	0	0	0	0	0	0	0	0	0.33	0.4547	0.4444	0.4155	0.4552	0.10
ANIS_SAN	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
BEMB_SPP	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
BRAD_CON	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
CALO_CAL	0.66	0.66	0	0.33	0	0.33	0	0.66	0	0	0.33	0.66	0.66	0.1788	0.7516	0.4798	0.4169	0.32
CHLAE_SE	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0.4547	0.4444	0.4155	0.4552	0.10
CHLAE_TRI	0.33	0	0	0	0	0	0	0	0	0.33	0	0	0	0.4547	0.6944	0.5834	0.3665	0.14
HARP_AMP	0.66	1	0.33	1	1.66	0.33	0.66	0	0	0.33	0.66	0	0.33	0.0997	0.4283	0.7676	0.1582	0.40
HARP_ERR	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
HARP_HER	0.66	0.33	0	0.66	0	0.33	0	0	0	0.66	0	0.33	0.33	0.1889	0.6537	0.1370	0.3785	0.24
HARP_PEN	11.66	82	11	56.33	9.66	8.33	6.33	8.33	8	19	8.66	11.33	4.33	0.0774	0.1014	0.0055	0.0506	14.70
PTER_COR	0.66	5	1	4.66	5.33	3	4.33	4.33	4	7.66	5	3.33	5.66	0.0780	0.1074	0.3209	0.0945	1.61
PTER_FEM	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
PTER_LUC	0	0	0	0	0	0	0	0	0	0	0	0	0.66	0.0701	.	.	.	0.00
PTER_MEL	0.33	0.33	0.66	0.33	0.33	1	0	1.33	1	0.66	0.66	0.33	2	0.3609	0.8199	0.8536	0.1313	0.32
STEN_COM	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
TRIC_COG	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
AGON_CUP	0	0	0	0	0	0	0	0	0	0.33	0	0	0	.	0.4444	0.4155	0.4552	0.10
AGON_DEC	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
AGON_HAR	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
AGON_PLA	1	1.33	1	1.33	0.33	0.33	0.33	0	0.66	1	0.33	1	0.33	0.4547	0.0277	0.8459	0.8933	0.49
AGON_PUN	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
AGON_TRIG	0	0	0	0	0	0.33	0	0	0	0	0	0	0	.	0.4444	0.4155	0.4552	0.10
LORI_FOV	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
DICA_SCU	0	0	0	0	0	0	0	0	0	0	0	0	0.66	0.0701	.	.	.	0.00
CYM_NEG	0	0	0	0	0	0	0	0	0.33	0	0	0	0	0.4547	0.4444	0.4155	0.4552	0.10
HARP_FUL	0	0	0	0	0	0	0	0	0	0	0	0	0	.	.	.	.	0.00
HARP_VEN	0	0	0	0	0	0	0	0	0	0	0	0	0.66	0.0701	.	.	.	0.00
TOTAL	17.33	94	14.66	67	18.66	15.66	13.33	16	15	32	16.66	18	17.33	0.7685	0.1961	0.0180	0.0791	16.23

[†] Values of 0 for all analysed variables yielded no statistical probability

Table B.11 Ground beetle capture for 1 sampling date at the Glenlea long-term cropping systems study, August, 1997, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

	Rotation 1				Rotation 2				Rotation 3					Prairie vs.				
	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	Prairie	Rotations	Rotation (R)	Treatment (T)	R X T	SEM
AMAR_TOR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4547	.[†]	.	.	0.00
AMAR_APR	0.0	0.0	0.3	0.0	0.7	0.0	0.3	0.3	0.5	0.0	0.0	0.3	0.0	0.1889	0.6056	0.1895	0.3685	0.19
AMAR_AVI	1.3	0.7	4.7	0.7	2.0	2.7	1.3	3.3	0.3	1.1	1.3	2.3	0.0	0.1342	0.5758	0.7303	0.1828	1.20
AMAR_CAR	1.0	1.0	1.7	0.3	1.3	0.7	1.0	0.3	1.1	0.9	1.7	1.3	1.0	0.8195	0.5123	0.0930	0.5964	0.40
AMAR_CUP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AMAR_FAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AMAR_LIT	0.0	3.0	0.3	0.7	0.3	0.0	0.0	0.0	0.1	1.3	0.0	0.3	0.0	0.4547	0.3571	0.4418	0.7815	0.98
AMAR_OBE	0.0	0.3	0.7	0.3	0.3	0.0	0.0	0.0	0.1	0.1	0.3	0.7	0.3	0.6542	0.2708	0.6090	0.4055	0.28
ANIS_SAN	0.3	0.0	0.0	0.0	0.0	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.4547	0.2732	0.7942	0.5444	0.25
BEMB_SPP	0.0	0.3	0.0	0.3	0.3	0.0	0.3	0.3	0.1	0.0	0.0	0.3	0.0	0.4547	0.7385	0.5348	0.7383	0.22
BRAD_CON	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
CALO_CAL	0.7	2.3	1.0	0.7	0.7	1.3	1.3	1.3	1.2	0.4	1.0	1.7	1.3	0.1889	0.9956	0.9154	0.2941	0.57
CHLAE_IM	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	0.4412	0.4034	0.4457	0.10
CHLAE_SE	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	.	0.7162	0.5162	0.3598	0.14
HARP_AMP	0.3	1.3	0.7	0.7	1.0	0.3	1.0	0.3	0.1	0.2	0.7	0.3	0.0	0.1416	0.2252	0.6942	0.5170	0.45
HARP_ERR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
HARP_HER	0.0	0.3	0.0	0.0	1.0	1.3	0.7	0.3	0.9	5.2	0.3	1.3	1.3	0.0342	0.3829	0.1226	0.4072	1.59
HARP_PEN	28.0	55.3	18.0	14.0	14.7	18.0	13.0	27.3	1.4	19.0	13.7	20.7	9.7	0.0547	0.1660	0.4410	0.0976	8.59
PTER_COR	6.0	15.7	3.7	11.0	15.7	9.3	20.0	27.0	0.5	4.2	1.7	6.7	18.0	0.2759	0.0674	0.4831	0.1433	5.10
PTER_FEM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3	0.4547	0.4461	0.4175	0.4558	0.10
PTER_LUC	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.0	0.0	0.0	0.0	0.3	1.3	0.0129	0.1458	0.2855	0.0224	0.16
PTER_MEL	0.0	0.3	0.7	0.0	0.3	0.0	1.0	1.3	0.4	0.8	3.0	2.0	4.0	0.3029	0.1519	0.0952	0.7066	0.81
STEN_COM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
TRIC_COG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_CUP	0.0	0.0	0.0	0.0	0.7	0.0	1.3	1.3	0.1	0.0	0.3	0.3	0.7	0.3776	0.1669	0.0382	0.1970	0.27
AGON_DEC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_HAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_MAN	0.0	0.0	0.0	0.0	2.7	0.0	1.7	1.7	0.0	0.0	0.3	0.0	0.3	0.5017	0.4423	0.3753	0.4865	0.65
AGON_PLA	2.0	5.3	2.7	3.3	1.3	0.7	4.3	2.3	1.2	3.7	6.7	8.7	0.3	0.4963	0.4197	0.2956	0.7048	2.38
AGON_PUN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_TRIG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
LORI_FOV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
DICA_SCU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0029	.	.	.	0.00
HARP_FUL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.4547	.	.	.	0.00
HARP_OPA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.4547	.	.	.	0.00
HARP_VEN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.4547	.	.	.	0.00
CYNI_NEG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0029	.	.	.	0.00
Total	39.7	86.7	34.3	32.0	43.7	34.7	48.7	67.7	1.8	36.8	31.0	47.7	44.0	0.2648	0.2406	0.4656	0.1423	15.72

[†] Values of 0 for all analysed variables yielded no statistical probability

Table B.12 Ground beetle capture for 1 sampling date at the Glenlea long-term cropping systems study, August, 1998, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2, and 3. Means considered significant when $p<0.05$.

	Rotation 1				Rotation 2				Rotation 3					Prairie vs.				
	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	f+h+	f+h-	f-h+	f-h-	Prairie	Rotations	Rotation (R)	Treatment (T)	R X T	SEM
AMAR_APR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	. [z]	.	.	0.00
AMAR_AVI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AMAR_CAR	0.7	0.7	0.3	0.3	0.3	0.7	0.0	1.0	10.0	15.0	2.7	20.7	0.7	0.0049	.	.	.	3.17
AMAR_CUP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AMAR_FAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	.	0.4444	0.4155	0.4552	0.19
AMAR_LIT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AMAR_OBE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
ANIS_SAN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
BEMB_SPP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	.	0.4444	0.4155	0.4552	0.10
BRAD_CON	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
CALO_CAL	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.4547	0.4444	0.8250	0.5161	0.18
CHLAE_SE	0.0	1.7	0.0	0.3	0.3	0.7	0.0	0.7	0.3	0.7	0.0	0.7	0.0	0.4547	0.8561	0.0530	0.9662	0.51
HARP_AMP	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	.	0.4444	0.4155	0.4552	0.10
HARP_ERR	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	0.4444	0.4155	0.4552	0.10
HARP_HER	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4547	0.4444	0.4332	0.4552	0.10
HARP_PEN	10.0	44.0	17.0	3.0	2.7	1.3	2.0	4.0	2.3	2.7	1.3	2.7	6.3	0.5075	0.0747	0.1929	0.0577	6.35
PTER_COR	25.0	73.3	41.0	41.3	16.3	29.3	8.7	41.7	48.7	30.0	25.7	49.0	2.0	0.1568	0.3889	0.2698	0.4179	13.84
PTER_FEM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
PTER_LUC	1.0	6.3	0.3	1.0	1.3	2.3	0.7	2.7	7.0	3.7	3.0	5.7	1.3	0.3062	0.2594	0.4093	0.7453	2.38
PTER_MEL	1.7	9.3	3.0	2.0	2.0	3.3	3.0	7.7	1.0	1.0	1.0	3.3	7.7	0.4368	0.0148	0.5234	0.6615	2.55
STEN_COM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
TRIC_COG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_CUP	0.3	2.0	0.0	0.7	1.0	0.0	0.0	0.7	3.0	1.3	1.3	3.0	3.0	0.2408	0.1653	0.1574	0.8209	0.91
AGON_DEC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_HAR	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4547	0.4444	0.4155	0.4552	0.10
AGON_PLA	0.0	0.7	0.0	0.0	0.3	0.3	0.0	0.0	0.7	0.3	0.7	0.3	0.7	0.4547	0.2566	0.5833	0.7016	0.31
AGON_PUN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
AGON_TRIG	0.3	0.0	0.3	0.0	2.0	2.0	0.0	4.3	5.0	1.3	3.7	3.0	5.0	0.1281	0.0058	0.3088	0.1154	1.07
LORI_FOV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
DICA_SCU	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.6542	0.4444	0.4155	0.4552	0.10
HARP_FUL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	.	.	.	.	0.00
Total	39.7	138.3	62.3	48.7	26.7	40.0	14.3	62.7	78.3	56.0	39.3	90.0	27.0	0.3102	0.2759	0.3006	0.3210	25.27

[z] Values of 0 for all analysed variables yielded no statistical probability

Table B.13 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for ground beetles at the Glenlea long-term cropping systems study, 1996, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	Shannon's	Simpson's	Evenness
Rotation 1	f+h+	1.17	0.49	0.52
	f+h-	0.60	0.75	0.41
	f-h+	0.96	0.49	0.69
	f-h-	0.87	0.61	0.47
Rotation 2	f+h+	1.15	0.40	0.71
	f+h-	1.34	0.34	0.71
	f-h+	1.19	0.36	0.82
	f-h-	1.18	0.37	0.77
Rotation 3	f+h+	1.19	0.38	0.73
	f+h-	1.16	0.44	0.58
	f-h+	1.17	0.40	0.72
	f-h-	1.11	0.45	0.63
Prairie		1.81	0.21	0.72
Prairie vs. Rotations		0.0477	0.0533	0.0223
Rotation (R)		0.1711	0.0688	0.0045
Treatment (T)		0.6522	0.2656	0.0119
R X T		0.3271	0.3227	0.5094
SEM		0.152	0.063	0.056

Table B.14 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for ground beetles at the Glenlea long-term cropping systems study, 1997, as influenced by crop rotation type and crop input management. Statistical analysis performed on log transformed data, excluding prairie. Prairie statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means considered significant when $p<0.05$.

Rotation	Inputs	Shannon's	Simpson	Evenness
Rotation 1	f+h+	0.96	0.52	0.58
	f+h-	1.10	0.47	0.57
	f-h+	1.42	0.32	0.69
	f-h-	0.86	0.24	0.47
Rotation 2	f+h+	1.72	0.25	0.67
	f+h-	1.39	0.33	0.71
	f-h+	1.72	0.26	0.61
	f-h-	1.34	0.35	0.67
Rotation 3	f+h+	1.70	0.20	0.95
	f+h-	0.94	0.56	0.53
	f-h+	1.60	0.29	0.63
	f-h-	1.84	0.24	0.66
Prairie		1.82	0.26	0.58
Prairie vs. Rotations		0.1250	0.1200	0.6144
Rotation (R)		0.0418	0.1943	0.1538
Treatment (T)		0.2087	0.0350	0.2819
R X T		0.2763	0.0452	0.2610
SEM		0.202	0.067	0.090

Table B.15 Shannon-Weiner and Simpson's diversity indices and Hill's evenness for ground beetles at the Glenlea long-term cropping systems study, 1998, as influenced by crop rotation type and crop input management. Prairie statistically compared with f+h+ subplots of rotations 1, 2 and 3. Means considered significant when p<0.05.

Rotation	Inputs	Shannon's	Simpson	Evenness
Rotation 1	f+h+	0.81	0.55	0.71
	f+h-	1.04	0.44	0.72
	f-h+	0.81	0.54	0.70
	f-h-	0.57	0.70	0.59
Rotation 2	f+h+	1.19	0.42	0.62
	f+h-	1.10	0.47	0.60
	f-h+	0.70	0.59	0.73
	f-h-	1.10	0.48	0.56
Rotation 3	f+h+	1.22	0.43	0.58
	f+h-	1.13	0.45	0.62
	f-h+	1.26	0.42	0.58
	f-h-	1.34	0.39	0.58
Prairie		1.65	0.25	0.75
Prairie vs. Rotations		0.0008	0.0066	0.5307
Rotation (R)		0.0153	0.1846	0.6843
Treatment (T)		0.4484	0.4857	0.4873
R X T		0.1162	0.1973	0.8668
SEM		0.135	0.065	0.076