EVALUATION OF SITE-SPECIFIC WEED MANAGEMENT AND IMPLICATIONS FOR SPATIAL BIOLOGY OF WEEDS

A Thesis
Presented to
The Faculty of Graduate Studies
of
The University of Guelph

by
HEATHER JAYNE GOUDY

In partial fulfilment of requirements
for the degree of
Master of Science
March, 2000

National Library of Canada
Acquisitions and Bibliographic Services
395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale du Canada
Acquisitions et services bibliographiques
395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

0-612-51068-9

Abstract

Evaluation of Site-Specific Weed Management and Implications for Spatial Biology of Weeds

Heather Goudy
University of Guelph, 2000

Advisor:
Professor F. J. Tardif

Site-specific herbicide applications only target areas of the field with weed infestations, and therefore have the potential to reduce operator costs and herbicide inputs into the environment. An experiment was initiated in a no-till corn – soybean rotational field in Woodstock, Ontario, Canada, in 1998 and 1999. Weeds were intensively scouted in a 4 ha area and weed distribution maps were generated for both years. Efficacy of weed control and yield were compared between conventional broadcast treatments and site-specific application treatments. Herbicide treatments were applied using a direct injection sprayer. There was no difference in the level of weed control or crop yield between treatments in both years. Percent area sprayed in the site-specific treatments was reduced as much as 26 to 59% in some treatments. Weed maps were found to be very accurate, yet herbicide applications based on prescription maps tended to over-apply and under-apply with respect to targeting herbicide.

Acknowledgements

I would like to begin by thanking François Tardif, my advisor, for taking a chance on an unknown and making me his first graduate student. It was a privilege and an honour to work with him on this project. He has given me the encouragement and freedoms to take this project were I wanted. His support of my decisions - good or bad, and his creative and logical input when I was lost have been unfailing. I have learned a great deal from François and I greatly appreciate his guidance and friendship.

I would like to thank Ralph Brown, my co-advisor, the only professor I know that is willing to sit on a rickety tractor for 10 hours straight (more than once) and spray all night come hell or high water! It is truly a testament to a professor's dedication and enthusiasm for this project. As well I would like to thank Ken Bennett, the only person I have ever seen asleep on a sprayer (while it was spraying) in full spray gear. Without Ken's persistence and ingenuity designing the direct injection sprayer, without him this project would not have existed.

My gratitude also goes to Clarence Swanton my remaining committee member. He was always able to give me the encouragement and time that I needed.

I would also like to thank all those that are part of the weeds lab, particularly Pete Smith. Pete was always willing to help out whenever you were in trouble. A thanks also goes to Kevin Chandler for keeping me on my toes with his intense intellect... There were many summer students that assisted with this project, Mary-anne, Vanessa, Johanna, Tara, Nathan, Sylvie, Karen, and Brian: many thanks to them for putting a little of their

sweat into my project. Of course the weeds lab would not be quite as interesting without my fellow students and I also appreciate their friendship, company and counting abilities. In particular those that joined me in the field, Shane, Kevin, Nancy, Kris, Rob and Christophe. I would also like to thank Mike Cowbrough for his assistance and input into this project, it was great to be able to talk to someone that was as excited (or not somedays) about site-specific applications as I was. A thank-you also needs to be sent out to Gabe Ferguson who listened and kept me going.

I would like thank members of the Weed Ecology Lab at the University of Lincoln Nebraska, in particular Dr. David Mortensen and Marty Williams II, for their insight into the project, and Dr. Anita Dieleman of Kansas State University for her guidance. Also without the help of Peter Von Bertoldi and Gary Parkin of the Land Resource Science Department at the University of Guelph in the area of geostats and mapping, I would still be sitting in the dark.

I would like to sincerely thank my family and friends (who mostly overlap) for all their support and understanding. Without you I think that I may have forgotten that there was a real world out there. Thank-you for listening and making me feel that I can accomplish anything.

To my husband, Jason Griffiths, I would like to say that I could not have done this without you and your support and love are immeasurable. Thank-you for truly understanding me and always knowing how to help.

Table of Contents

Literature Review

Chapter 1. Evaluation of Site-specific Weed Management Using a Direct Injection Sprayer.

Chapter 2: Evaluation of Site-Specific Procedures for Research Purposes

General Discussion

List of Tables

List of Figures

Introduction

Spatial variability has long been recognised in agricultural field situations; however, this variability has been considered bothersome and often was ignored. Management practices have been uniformly applied to whole fields with little regard for spatial differences. With the advent of new technological tools such as GPS (Global Positioning Systems) and GIS (Geographic Information Systems) the door has opened to a Precision Agriculture, whole new era of crop management which accounts for field variation. Yet, while the technology is available to manage fields in a spatial sense, information on how to manage this variation is lacking.

Weed density across a field has been recognised to be heterogeneously distributed; however, in conventional agricultural weed management, herbicides are sprayed on entire fields with the assumption of random or uniform weed distribution. The opportunity exists to make herbicide applications more efficient. The concept of site-specific herbicide application offers the chance to reduce the environmental impacts of herbicide used in farming, reduce costs for the farmer while maintaining crop yield and profitability. In theory, site-specific herbicide applications would only target the areas in the field that have weed patches at densities that would impact on crop yield. Impressive estimates of possible reductions of herbicide usage have drawn considerable attention to spatially variable weed management, yet little attention has been paid to implementing site-specific applications in real-farm situations.

Although weeds are recognised to be patchy in distribution, little else is known about the distribution or the stability of weed patches (Cousens and Woolcock 1997).

Information on weed patch dynamics is crucial to spatial management of weed populations. Evaluation of the efficacy of site-specific applications in a scientific manner and the characterisation of weed patches under site-specific management was the focus of this research.

Literature Review

Introduction and Background

Since the early 1970's agricultural outputs have increased two-fold with the advent of such intensive agricultural technologies as cultivation and the use of chemical fertilisers and herbicides (Brown 1981; Zimdahl 1993). Herbicides have been relied upon heavily and they were regarded as the miracle cure for weed problems (Zimdahl 1993). Reliance on these chemicals is still high with 96% of corn fields and 99% of soybean fields treated with herbicides in the 1990's as compared to 57% and 49%, respectively, in the 1970's in north central United States (Swanson and Dahl 1989). For farmers, herbicides mean greater yields and better quality crops with less energy inputs (Zimdahl 1993); however, increasing concerns about pesticides and their potential effects on human health and the environment have become a deterrent to the positive attributes of herbicides.

Paradigms like Sustainable Agriculture have been developed over the last decade to define the need for agricultural practices that conserve our natural environment and can provide for the needs of current and future generations (National Research Council 1991). Many researchers and agronomists believe that the way to accomplish Sustainable Agriculture is to base our management on the entire ecosystem, and develop new technologies and policies that are both resource efficient and environmentally sound while maintaining profitability (Francis and Youngberg 1990; Swanton and Weise 1991). In the past, a lack of understanding of the ecological principles upon which agricultural systems are based has in essence lead to the environmental concerns of today (NRC 1991). An alternative approach to traditional weed control practices that addresses environmental, economical and sociological issues has been developed called Integrated Weed Management (IWM) (Swanton and Weise 1991; Mortensen et al. 1998). Many alternative weed management strategies incorporate IWM including cultural, genetic, mechanical and chemical approaches (Shaw 1982; Walker and Buchanan 1982; Regnier and Janke 1990). These IWM strategies are ecologically based and incorporate all aspects of the agro-ecosystems.

Farmers, consultants and land managers have long recognised that agricultural fields are spatially heterogeneous, yet despite this lack of uniformity, resource management practices have been applied homogeneously across fields (Mortensen et al. 1998). The use of spatial information could be used to enhance weed management strategies by managing weeds on a sub-field scale. Spatially variable herbicide applications have the potential to result in significant reductions in herbicide inputs into the environment while maintaining efficiency and profitability for today's agricultural systems.

Site-Specific Weed Management

As stated above, agronomic management practices are applied across entire field areas regardless of spatial variation within the field and herbicide applications rarely differ from this practice. Weed populations within the field must be uniformly or randomly distributed for broadcast herbicide applications to be cost effective, yet weeds tend to be heterogeneously distributed (Wilson and Brain, 1991; Johnson, 1996a, 1996b; Cousens and Woolcock, 1997; Lutman and Rew, 1997; Cardina et al. 1997; Marshall, 1998). Site-specific weed management implies that the spatial variation within the field would be recognized and managed in zones that would be treated more distinctively. In principle, weed control is only needed for areas of fields that have weed infestations above an economic threshold at which yield loss incurs a greater monetary loss than the cost of herbicide treatment, while other areas of the field can be left untreated (Lutman and Rew 1997; Johnson et al. 1995).

Targeting herbicide applications to the areas or patches of weeds in the field should result in several benefits such as: a reduction of the amount of herbicide input into the environment (Lutman and Rew 1997), a reduction of costs for the farmer (Stafford and Miller 1996), and an increase in the efficiency of herbicide use. From desk studies, Stafford and Miller (1996) estimated that site specific herbicide applications, as part of an IWM system, could reduce herbicide inputs into the environment by 40 to 60%. These large herbicide reductions would give an indisputable physical reduction of herbicide inputs (Bennett, 1997).

Stafford and Miller (1996) suggested that increased concern about agricultural impacts on the environment combined with economic costs have lead to increased interest in site specific weed management. Lutman and Rew (1997) asserted the primary reason for this rapidly expanding interest in site specific management is due to the recent progress in precision management tools such as global positioning systems (GPS) and geographic information systems (GIS) coupled with mechanical advances in sprayer technology. Despite all this available technology, site-specific applications have not advanced in step with GPS and GIS (Lutman and Perry 1999). The main issue facing site-specific applications today is how to assess the levels and locations of weed infestations (Lutman and Perry 1999).

Weed Patch Detection

There are various methods proposed to assess weed patch location and density in fields, but none of them are adequate. For effective site-specific herbicide applications, the sprayer must be programmed or the applicator must know "what" and "where" to target for herbicide application in the field. The two possible approaches to determine target location are real time sensing of weeds and the use of predetermined maps. Obviously, an accurate method of weed patch detection that takes a minimal amount of time and effort would be ideal for cost and labour reasons.

A real time system requires sensors that can distinguish between the crop and the weed or better yet distinguish among different weed species. In addition, sprayer reaction time must be rapid enough so as to ensure timely herbicide application (Ruckelshausen et al. 1999). To target weeds in real time, sensors have to be mounted on the sprayer or tractor to detect the weeds. The first prototypes of real-time sensors could only distinguish between green matter and soil and therefore had to be used in fallow or burn-down situations. These limitations considerably restricted possible application timings (Lutman and Rew, 1997). More recently developed models can not only differentiate between vegetation and soil, but among the plants themselves. Unfortunately, accuracy of these newer models is still low, because spectral reflectance depends on the amount of sunlight and environmental stresses for each plant (Feyaerts et al. 1999). Feyaerts et al. (1999) were able to train a sensor to recognise crop rows or groups of similar shapes from weeds by using spectral analysis. Targets were reached correctly 89% of the time in controlled experiments.

Another approach to real-time sensing uses image sensors and photo diodes to detect single plants (Ruckelshausen et al. 1999). Obviously, most fields are not made up of one plant type and plants that are present tend to overlap creating increased difficulties for creating decision algorithms. Generating a plant database is crucial to this type of system. The database must be calibrated to growth stage, row width and environmental influences for every field. Ruckelshausen et al. (1999) were able to distinguish a weed plant from a corn plant in a controlled setting, but sensors must be very close to the corn plant and therefore could only be used for intrarow weeds. Both these real-time sensors show promise, but the equipment is far from being field ready.

Predetermined weed maps can be obtained by remote sensing or ground scouting. Remote sensing using spectral reflectance from aerial photos and satellite images is being investigated as a possible method to locate weeds in the field. Problems with remote sensing involve scale and timing. Smith et al. (2000) attempted to detect several common Mississippi State weeds using spectral reflectance. It was found that even at the end of the summer, when the test weeds were fully grown, only 57 to 81% of the species present could be identified. For effective weed control without yield loss, weeds must be targeted for herbicide application early in the season when they are small. Mortensen et al. (2000) calculated that for tactical decisions on weed control an extremely high level of detection was required. To accurately sense weed seedlings for early season weed control, considerably less than 1% ground cover must be detectable. Remote sensing of weeds is in its infancy and does not yet have the resolution required to produce accurate weed maps (Mortensen et al. 2000). As this technology develops, these methods will become more refined. In the interim, precision agriculture is rapidly becoming established and weed maps are an essential requirement if site specific weed applications are to be tested.

Real-time patch spraying would seem ideal as compared to targeting herbicide applications based on a predetermined map because of the low input requirement as compared to the extra time involved in developing a weed map prior to application. There are several reasons why site-specific applications using predetermined weed maps are preferred over real-time application systems. The main reason is flexibility. Prior knowledge of the weed infestation in a field allows the weed manager to optimise herbicide choices and placement (Christensen et al. 1999; Stafford and Miller 1996). A real-time sprayer does not give any information about the weed patches themselves, such as density, level of aggregation and temporal evolution. Currently, the only reasonable solution to acquiring accurate weed maps is weed surveying.

Typically, to estimate average weed density across a field, a small quadrat is randomly placed repeatedly throughout the field and an average is taken of the weeds found in each quadrat. This sampling method is used to minimise spatial dependence (Levin 1992) and is not useful to describe spatial density and location of weed patches (Cardina 1997). Accurate representation of weed density and location is required if the weed maps are to be useful for site-specific herbicide applications. So far grid surveying using a non-random regular sampling strategy is the most common method used to develop accurate maps (Christensen et al. 1999; Cardina et al. 1997). Sampling the data at intervals that capture the spatial dependence of the data are considered more appropriate for mapping weed patches (Cardina et al. 1997). Unfortunately, grid sampling requires a great deal of time and money to complete because of scouting costs and large field size. It is considered an unrealistic method for field scale site-specific applications, but must be used to acquire accurate weed maps until new technologies become available (Lutman and Perry 1999; Christensen 1999).

Formulation of Weed Maps

Traditional statistical procedures such as analysis of variance (ANOVA) are used to summarise and organise data so that meaningful information can be attained; however these procedures assume that the data are independent of each other (Rossi et al., 1992). Observed weed density values at a particular location are influenced by other weeds at close proximity because of biotic processes such as growth, reproduction, mortality and migration and therefore exhibit spatial dependence (Legendre 1993). Historically, spatial variability has been ignored or considered a nuisance.

Whenever spatial variability was considered it was described using measures of numerical aggregation like the negative binomial parameter *k*, (Johnson et al. 1996b). There is little evidence that low *k* values correspond to actual aggregation in the field (Williams et al. 1992).

Weed density data that is tagged with location co-ordinates can be analysed using geostatistics to draw accurate inferences about spatial dependence and arrangement of the weeds (Johnson et al. 1996a). Geostatistical tools allow for the detection, modelling and estimation of spatial patterns of weeds and have become more widely used in ecology (Rossi et al. 1992) and weed science (Zanin et al. 1998). The geostatistical approach begins with modeling and interpreting the semivariogram, which is a measure of the variance between sampled points (Isaaks and Srivastava 1989). The semivariogram is included in the kriging process that produces unbiased estimates of values at unsampled locations creating weed contour maps (Cardina et al. 1997). Distance between sampled points will greatly impact the accuracy and usefulness of the semivariogram; however, there is a compromise to be made between sampling intensity and time and/or labour available (Lutman and Perry, 1999).

As the distance between sampling points increases, the less accurate the semivariogram will be in interpreting spatial dependence and thus the less accurate the weed map (Lutman and Perry, 1999). As well, Wallinga (1995) indicated that as grid size increased so did the predicted percentage of the field infested with weeds. At a 10 x 10 m sampling grid the predicted area of the field that was infested with weeds was 50%, while at a 4.6 x 4.6 m sampling grid in the same field, only 25% of the field was infested. It seems that as grid size increases, the chance to reduce herbicide inputs decreases. Lutman and Perry (1999) asserted that sampling grids larger than 6 x 6m diminish the potential benefits from site-specific applications.

Development of Prescription Maps

Once the weed maps have been developed and entered into a GIS, they need to be divided into high resolution grid maps (Bennett, 1997). There are two important requirements for a functional prescription map: size of the grid blocks must be based on the application equipment and the prescription map must be referenced to a base point in the actual field (Bennett, 1997). The GIS system will indicate the weed density data within each block of the grid map (Brown and Steckler, 1995; Paice et al., 1995). A decision algorithm must be used to decide which areas of the field require treatment

(Williams et al. 1999). A prescription map can then be developed based on weed thresholds from evaluating weed densities in each grid block.

In a desk-study, Johnson et al. (1995) compared thresholds from 0 to 3 shoots m^{-2} and found that as weed threshold increased the area of the field that requires application decreased. Currently, weed thresholds are developed with the assumption that weed density is uniform or randomly distributed throughout the field and therefore over estimates of yield loss are common (Lindquist et al, 1998). Field-based research has not been completed to estimate thresholds when weeds are aggregated. Zanin et al. (1998) chose to base their prescription maps on estimated yield loss in each grid cell. They combined competitive indices and yield loss equations to decide where to target each cell for herbicide application. Unfortunately, site-specific applications were not tested in the field and results are therefore speculative.

Christensen et al. (1996) have developed a computer generated decision model for patch spraying broadleaf weeds. They included weed species competitiveness, weed density, crop, herbicide price and dose-response parameters to calculate total yield loss and economical optimal dose. There is, currently, no comparable system that is available in North America to produce prescription maps.

Patch Spraying

Traditional broadcast sprayers are only capable of applying a single herbicide dose (Bennett, 1997). Accurate broadcast application systems rely on three main requirements, constant travel speed, accurate mixing of herbicides and the random or uniform distribution of weed species (Bennett, 1997). Broadcast application systems have been increasingly criticised for their lack of flexibility for variable weed control and for ignoring the concept of weed patch heterogeneity (Cardina et al., 1996a; Stafford and Miller, 1996). Many researchers feel that the broadcast application system will be considered unacceptable as the push for sustainable agriculture increases (Johnson et al., 1995; Stafford and Miller, 1996).

The two main parameters that site specific applications depend on are: 1) accurate field positioning (the sprayer location must be known at all times in order for the application to accurately follow the prescription map) and 2) a good ON/OFF fluid response (Bennett, 1997; Miller and Paice 1997). A sprayer has been designed at the University of Guelph with a direct nozzle injection metering system for variable rate herbicide applications that meet these requirements (Bennett, 1997). Direct injection application systems (DIS) are capable of spatially variable herbicide applications, because the herbicide is introduced separately to the water through a metering system only when required. The metering system allows the herbicide to be introduced at variable rates, while the water is pumped through at a steady state.

Accurate field position can be accomplished using a dead reckoning system or GPS (Bennett, 1997; Miller et al. 1995). Dead reckoning begins at a base reference location in the field that corresponds to a point on the prescription map. Tracking is generally updated using a calibrated wheel (Bennett, 1997). GPS co-ordinates can be used to locate the sprayer and the weed patches in the field, but due to potential signal errors that can occur GPS navigation is not reliable enough to test precision applications.

The DIS would require no pre-mixing of chemicals and therefore no leftover spray solution for disposal; however, if spills where to occur it would be the concentrated form of the herbicide (Bennett 1997). Dual or multiple herbicides could be carried at one time when using a DIS system to allow for optimal herbicide choice and placement. The main disadvantage to DIS systems is the increased cost to purchase this technology.

Past research has mainly focused on developing workable patch spraying systems (Paice et al. 1995; Lutman and Perry 1999) and estimating herbicide saving if site-specific applications were utilised (Rew et al. 1996; Johnson et al. 1995; Mortensen et al. 1995: Brown and Steckler 1995; Zanin et al. 1998). Very little research has actually implemented site specific applications in the field. Investigations into site-specific herbicide applications in winter wheat, and corn have been conducted in Germany (Gerhards et al. 1997b; Williams et al. 1999). In both studies, sampling and spraying were conducted on a 12 x 12 m grid. Gerhards et al. (1997) were able to reduce herbicide use in winter wheat by 21% and Williams et al. (1998) separately targeted grasses and dicot weeds and reduced graminicide use by 51% and the broadleaf herbicide use by 11.5%. Williams et al. (1999) assessed weed control by comparing cumulative distribution of weed observations at each of the sampling points across time. They hypothesised that appropriate decisions about rate and area sprayed were made if the cumulative percent distributions of seedling densities were similar for areas that had received the full rates versus reduced rates, regardless of initial differences. The main weakness of these two studies is that the experiments were not replicated and that the weed control and yield were not compared to standard weed management practices.

Dieleman (1999) and Faechner and Hall (2000) both indicated that research investigating the efficacy of site-specific applications is required and spatially variable applications must be shown to be as effective as broadcast applications. Comparable weed control and crop yield are the key to the success of site-specific weed management.

Weed Patches: What Do We Know?

In recent years it has been well documented that weeds tend to be patchy or clumped in their distribution (Johnson, 1996 a,b; Marshall, 1998; Cousens and Woolcock, 1997; Lutman and Rew, 1997; Cardina et al., 1997). Little else is known about the nature of weed patch occurrence. To increase the effectiveness of weed management we need a better understanding of spatial distribution and behaviour of weed populations (Wiles, 1992; Mortensen and Dieleman, 1997; Dessaint, 1991; Cardina et al., 1996a; Cardina et al., 1997).

Generally a population is defined as a group of interbreeding organisms of the same species occupying a particular space at a particular time (Krebs 1994). Gerhards et al. (1997a) described a patch as an area of contiguous weed infestation of one species, and a population as the whole of one species in a field. On the other hand, Dieleman (1999) described a patch as a clearly defined area that contains a weed population. Whether a weed patch is a population on to itself depends on definition. For our research purposes a patch will be a clearly defined area that contains a weed of one species.

Ecological information on weed patches is very limited (Cardina et al. 1997; Gerhards et al. 1997a; Cousens and Woolcock 1997) and largely anecdotal. Mortensen and Dieleman (1998) observed that patches were persistent over a 5-year period and noted that patch centres were spatially stable amidst unstable edges. Within-patch density varied significantly among years (Mortensen et al. 1998) as well as across fields (Cardina et al. 1995; Johnson et al. 1996a). Little of this information has been quantified and has not been tested on a species by species basis. Thus far, reasons as to why weeds are located in patches are only speculative. Cousens and Woolcock (1997) suggested that likely reasons might be: patchy field attributes (abiotic factors) resulting in greater species abundance in preferable habitats, patchy weed mortality due to historical factors or localised predator outbreaks, implement traffic (specifically cultivation and combine movement), and finally, simply because the weeds have just not spread to the entire field.

Weed association with soil properties was investigated in Denmark by Andreasen et al. (1991) at the whole field level. Linear logistic regression indicated that crop type and clay content generally had the greatest influence, but year, pH, P, K, Mg, and Mn also had an effect on species occurrence. More recently, research by Dieleman (1999) supported Cousens and Woolcock's speculation and Andreasen's research that abiotic factors are linked to weed species abundance and location. Dieleman (1999) found that relative elevation, percent organic carbon, soil texture, nitrate-nitrogen and phosphate were associated with species abundance. Apart from abiotic factors specific to each weed, biotic factors such as competitiveness, seedbank longevity, dispersal, seedling emergence, dormancy etc, will also dictate weed patch location and these factors will be dependant on environmental conditions.

In many cases, weed seeds are introduced to a new field site via farming implements such as combines, tillage equipment, and manure spreaders. Weed seeds are dispersed as the equipment moves over the field and these implements may leave the weed seeds in strips. Anisotropic patch shape has been observed parallel to the direction of predominant implement traffic (Mortensen et al. 1998; Gerhards et al. 1997a). McCanny and Cavers (1988) found that proso millet (*Panicum miliaceum* L.) patches spread into the field following the direction of harvest implement traffic. Similarly, Rew and Cussans (1997) found lateral movement of weed seeds from cultivation, and indicated that quantification of this phenomenon will be important to the prediction of weed patch location.

As farm size increases, fields are being amalgamated into larger units. These larger units are being managed as one and past differences in management practices may lead to greater within-field variation (Christensen et al., 1999). Thomas et al. (2000) used a Partial Redundancy Analysis to determine if past management could explain some of the weed patchiness present in a study area. They found that historical factors could explain a significant amount of the variation present and could be of use to predict weed patch location. Understanding patch biology and behaviour will be a tremendous asset to the success of site-specific applications and more data on patch dynamics over time on a species by species basis is required.

Patch Stability

Are weed patches stable in space over time? Patch stability is perhaps the most fundamental issue for site-specific weed management in regards to weed patches (Cardina et al., 1997; Cousens and Woolcock, 1997). The stability issue greatly affects the economics of possible site specific weed applications (Cardina et al., 1997). If weed patches are relatively stable, weed maps of a field could theoretically be used for a number of years without having to recreate costly weed distribution maps year after year (Cardina et al., 1997). Another foreseeable benefit to weed patch stability would be the ability to predict weed distribution for pre-emerge applications or to predict weed problem areas where field scouting should be directed (Gerhards et al., 1997a).

Few studies conducted in North America and Europe have looked at weed patch stability. One of the first studies that has been quoted often in the literature, was conducted by Wilson and Brain (1991). Black grass (*Alopecurus myosuroides*) in England was surveyed on a 36 x 40m sampling grid in a number of fields that were planted in cereals for several years followed by a year of grass fallow. Black grass patches were found to be very stable over a 7-year period (Wilson and Brain 1991). These results have been referred to as evidence that patches are stable and as a result it has been used to support research into site-specific applications. Not only do results from this study not pertain to typical Ontario agricultural systems because of the cereal monoculture they were tested in, they have been criticised because of the exceptionally large grid sample size. A grid this large could have missed smaller patches or over estimated patch size by not sampling close enough together to capture the spatial complexity of the black grass (Cousens and Woolcock 1997).

More recently, research on patch stability has been conducted in Nebraska by Gerhards et al. (1997a). They followed four weed species, velvetleaf (*Abutilon theophrasti*), common sunflower (*Helianthus annuus*), foxtail (*Setaria* sp.) and hemp dogbane (*Apocynum cannabinum*) over four years to examine patch stability. Velvetleaf and common sunflower patch persistence was attributed, in part, to having a large seed size and localised preharvest dispersal. In the case of velvetleaf, they also found that seedbank longevity might also be important to patch stability. Perennial reproductive traits were believed to contribute to the high degree of patch stability exhibited by hemp dogbane. Foxtail species were not stable over the four years. As of yet there is not enough information to predict patch stability on a species by species basis, let alone how this may change under different management strategies. Their results have been supported by other researchers (Cardina et al. 1995; Johnson et al. 1996; Mortensen and

Dieleman 1997) who found patch centres were relatively stable while edges were unstable. Density values within a patch tended to vary. Dieleman et al. (1999) hypothesised that patch persistence is due to density-dependant mortality. They showed that patch centres have higher densities with greater survival as opposed to patch edges with lower densities and poor survival.

Cousens and Woolcock (1997) indicated that more long term, large-scale research in typical crop management systems is key to further understanding patch stability and patch dynamics. So far research on patch stability has been conducted on weed patches that receive uniform broadcast applications each year. It would be naive to assume patches would behave similarly when treated site-specifically as opposed to uniformly. Research on patch stability under spatially variable management would allow weed managers to decide if site-specific weed control is a worthwhile venture.

Objectives

Site-specific weed management may have tremendous potential, yet until it has been tested in a field setting, implications are only speculative. Therefore we initiated a replicated experiment aiming at comparing site-specific to conventional broadcast weed management systems. Our specific objectives were:

1) to monitor the efficacy of weed patch spraying relative to weed control and yield,

2) to monitor the dynamics of weed patches and weed-free areas over time,

3) to evaluate if the prescription map approach is a useful method for site-specific applications.

In order to attain our objectives the following hypothesis was formulated:

Hypothesis 1) Weed populations will be as effectively controlled by site specific weed management as conventional broadcast applications.

Hypothesis 2) Weed patches in the test area will remain stable in location from year to year.

Hypothesis 3) Site-specific applications, which utilise a prescription map approach, will be accurate and error free.

Methodology Rationale

In order to attain the objectives, the hypotheses were tested by conducting field experiments. The experiment was conducted on a commercial field site for several reasons: 1) a natural weed population was required, 2) a uniform agronomic plot history was required, and 3) a large enough site was required to ensure that weed patches would occur within each plot. At the initiation of the study, anecdotal evidence suggested that perennial weeds tended to be patchier than annual weeds and it is generally understood that no-till fields tend to have more perennial weeds because of the low soil disturbances favourable to these multi-season plants. Therefore, a no-till field was selected because patchier weed populations would have greater potential to reduce herbicide use.

Within the no-till field, a 4 ha area was grid sampled on a 6 x 6 m grid to ensure that the spatial dependency of the weeds was captured. Weed contour maps were developed using geostatistics to estimate unsampled data points. The experimental area was then divided up into the largest possible plot sizes (24 x 85 m). A simple randomised complete block design (RCBD) was chosen to effectively compare site-specific applications against broadcast applications. To apply each of the site-specific treatments, each plot weed density map was further divided into 3 x 5 m decision units based on the specifications of the direct injection application system developed at the University of Guelph. These decision units were individually assessed as to whether herbicide treatment was warranted based on a threshold of 1 shoot m^{-2}. This value is a general threshold for broadleaf weeds in corn and soybeans (C. Swanton personal communication. 1997). Prescription maps were created to input into the sprayer computer and herbicide was targeted site-specifically according to these prescription maps. Decisions whether to spray and the development of the prescription map were all completed by hand, because there are as yet no computer programs designed for this procedure.

To test the first hypothesis that weed populations will be as effectively controlled by site specific weed management as conventional broadcast applications, weed shoots were counted prior to the herbicide application at each of the 6 x 6 m sampling points and again at 3 to 4 weeks after the application. As well as this weed assessment in each plot, yields were taken during harvest in each plot. To test the second hypothesis, that weed patches in the test area will remain stable in location from year to year, weed counts were conducted at the same 6 m grid locations the following year to visually compare patch location and population density between years. The third hypothesis, that site-specific applications, which utilise a prescription map approach, will be accurate and error free, was tested by comparing the weed contour maps or prescription maps to the original data.

The results of the experiment that was undertaken to verify these hypotheses are presented in Chapters 1 and 2. These chapters have been written as scientific articles following the style required for submission to *Weed Science*.

Chapter 1. Evaluation of Site-specific Weed Management Using a Direct Injection Sprayer.

1.0 ABSTRACT

Targeting weed patches for site-specific herbicide applications potentially represents cost savings for operators, reduction in environmental herbicide impacts and increased efficiency of weed control. An experiment was initiated in a no-till corn field in Ontario, Canada, in 1998 and continued in rotation with no-till soybeans in 1999. Weeds were intensively scouted and distribution maps were generated for both years. A prescription map for each plot was made using the weed density maps. Treatment decisions were based on a threshold value of 1 shoot m^{-2}. Four herbicide treatments were compared: a conventional broadcast, a site-specific application over weed patches only, and two combinations of broadcast and site specific applications. Treatments were applied using a direct injection sprayer. Efficacy of weed control and yield were compared among treatments. In 1998 and 1999 there were no differences in the level of weed control or yield among treatments. The average percent area sprayed in the site-specific treatments was reduced by as much as 26% in the site-specific treatment in 1998 and up to 59% in the site-specific and broadcast combination treatments in 1999. For those species present in the field, levels of patchiness ranged from highly aggregated to completely random and patch stability ranged from very stable to very unstable over the two years.

1.1 INTRODUCTION

Modern agriculture requires effective and efficient weed control methods for successful crop production. Weed control is primarily achieved by a uniform herbicide application across an entire field. Traditional broadcast applications assume weed distribution is uniform or random throughout the field. Mortensen et al. (1998) indicated that instead of being homogeneous, agricultural fields tend to exhibit spatial heterogeneity in soil characteristics, nutrients, topography and pest infestations. Recently, the presence of weed patches has been well documented in agricultural fields (Cousens and Woolcock 1997; Johnson et al. 1996a; Mortensen and Dieleman 1997; Wilson and Brain, 1991).

Our chemically dependent agricultural systems are increasingly coming under scrutiny because of environmental concerns and increasing costs to farmers (Swanton and Weise 1991). The concept of site-specific herbicide applications offers the opportunity to reduce the environmental impacts of herbicide use in farming while maintaining efficacy and profitability (Mortensen et al. 1998). Mortensen et al. (1999) suggested that site-specific applications fit well the goals of integrated weed management (IWM). In theory, site-specific herbicide applications would only target the areas in the field that have weed patches at densities that would impact on crop yield and/or quality. Recently developed new technologies such as differential global positioning systems (DGPS) and geographic information systems (GIS) have enabled weed patches to be located and mapped in a field. As well, tractor mounted DGPS units enable application systems to target weed patches automatically in the field (Christensen et al. 1999). Site-specific herbicide applications would reduce environmental herbicide loading as well as economically optimise the use of herbicides and thus result in a cost reduction for the farmer (Johnson et al. 1995; Stafford and Miller 1996; Williams et al. 1999).

The effect of targeting weed patches for herbicide applications on patch stability is another important issue relating to site-specific applications that has not been adequately investigated. Documentation of patch stability has been attempted for a few weed species (Dieleman et al. 1999; Gerhards et al. 1997; Wilson and Brain 1991). Even fewer attempts have been made to document patch stability when under site-specific herbicide management. Williams et al. (1999) followed patch stability over two years in a maize-sugar beet rotational system and found patches of *Chenopodium album* and *Setaria viridis* remained relatively stable. It is assumed that developing accurate weed maps will be a costly aspect of site-specific herbicide applications; therefore, if patches remain relatively stable in a field from year to year, farmers could then use the same weed maps for several years without having to have their fields re-mapped yearly.

Estimates of herbicide reductions due to the utilization of site-specific herbicide applications generally are in the range of 40 to 60% (Stafford and Miller 1996). These projected reductions have primarily been developed from computer-based simulation models in cereals (Mortensen et al. 1998). From these models, results indicate that site-specific applications would be successful in real field situations, yet very little research has been attempted in field site-specific applications.

There have been a few examples of successful site-specific herbicide applications conducted in Europe. By targeting weed patches in cereals, Gerhards et al. (1997b) and

Heisel et al. (1997) were able to reduce herbicide use by 40 to 50% and 66 to 75%, respectively. Williams et al. (1998) were able to reduce herbicide inputs in corn as much as 12 to 51% using a variable rate site-specific application system.

To date, there have been no tests of site-specific herbicide applications in North America in a corn and soybean rotational system. Using a computer simulation model Brown and Steckler (1995) predicted a 40% reduction in herbicides required to treat a corn field using a site-specific approach. Out of the limited research that has been conducted on site-specific herbicide applications, there have been no side by side systematic comparisons between site-specific and traditional broadcast applications in the same field. The question of whether site-specific applications would perform as effectively (with regard to weed control and yield) as broadcast applications has yet to be answered. Christensen et al. (1999) suggested that the potential reductions in herbicide usage will be dictated not only by the density and distribution of the weeds, but also by the chosen spatial herbicide application strategy. For this reason actual herbicide reductions will be field specific.

To effectively test and implement site-specific applications on a large scale, a sprayer suited for precisely targeting weed patches in the field is necessary. On/off controls on a traditional sprayer are too coarse to efficiently target weed patches and optimize herbicide reductions. Bennett (1997) developed a direct injection sprayer (DIS) that utilizes site-specific weed patch information and is capable of applying herbicide in a precision application. The sprayer has been tested in a laboratory setting, as well as in a structured outdoor simulation and found to be very effective. Here we report on the field testing of the DIS in an actual agricultural setting.

The objectives of this research were to monitor the efficacy of site-specific herbicide applications compared to broadcast herbicide applications for weed control and yield, and to monitor the dynamics of weed patches and weed free areas over time in the field.

1.2 MATERIALS AND METHODS

1.2.1 Site Description

A no-till field site located on a private farm in Woodstock, Ontario, Canada (43° 0.8' N and 80° 46' W) was chosen for the study. The site had been in no-till seven years prior to the beginning of the study and followed a corn-soybean-winter wheat rotation. In 1997 the field had been in winter wheat and after harvest, the straw had been removed leaving only stubble. Glyphosate at a rate of 900 g ai ha^{-1} was applied in the fall of 1997, to control perennial weeds.

1.2.2 Weed Survey

In late April of 1998, a 100 x 400m portion of the field was flagged on a 6 x 6m grid giving 1105 sampling points. These points were further geo-referenced using a differential GPS backpack unit[1] with 10 cm accuracy. Flags were left at each point as semi-permanent markers throughout the summer of 1998. The points were relocated and reflagged in the spring of 1999. The field was planted into corn and soybeans in 1998 and 1999, respectively. Initial weed counts were conducted just prior to the fifth leaf stage of the corn and the second trifoliate stage of the soybeans. At each intersection point a 1 x 1m quadrat was laid down on the ground and weed shoots within the quadrat were identified and counted up to a maximum of 30 shoots m^{-2}. In 1998 the most prevalent weeds were spiny-annual sowthistle (*Sonchus asper*), dandelion (*Taraxacum officinale*) and field horsetail (*Equisetum arvense*). In 1999 the most prevalent species were *S. asper*, *E. arvense* and common lambsquarters (*Chenopodium album*).

1.2.3 Weed Mapping

To develop accurate weed contour maps, weed count data was interpolated using simple point kriging to estimate densities at unsampled locations. Kriging estimates an unsampled point by using a weighted moving average technique. Greater weight is placed on sampled values around the point to be estimated (Isaaks and Srivasta 1989). Kriging is the "best linear unbiased estimator" because it attempts to keep the mean residual error equal to zero and it aims to minimise the variance of errors. A model of the spatial autocorrelation of the data is incorporated into the kriging process using the semivariogram. The semivariogram is a measure of the relatedness of two points at lag distance *h*:

$$\gamma_i(h) = \left(\frac{1}{2}\right) N(h) \sum_{i=1}^{N(h)} \left[z(x_i) - z(x_i - h_i)\right]^2 \qquad [1]$$

where $\gamma_i(h)$ = the experimental semivariance for the lag distance *h*, N(h) is the number of pairs of points separated by *h*, and $z(x_i)$ is the value at the i^{th} location (Isaaks and Srivasta 1989). For each prevalent species a semivariogram model was fitted to the data. In every case the weed data was best-fit to either a spherical or an exponential model. There are several parameters that characterise the semivariogram model that are used in the kriging process. The nugget effect is a measure of pure random variance or sampling error inherent to the data. It is the semivariance value at extremely small lag distances.

A nugget value of 0 would indicate that there are no random effects and the data is highly spatially correlated. More random variation is present as the nugget value increases from 0. The range is the lag distance at which the variogram reaches a plateau (Isaaks and Srivastava 1989). Once the variogram reaches a plateau this indicates that the data at that separation distance are no longer spatially correlated or have become independent of one another. The sill is the semivariance at which the plateau is reached and is used to predict the range. The standard spherical semivariogram model is defined as:

$$\gamma(h) = Co + Cs\left[\left(\frac{3}{2}\right)\left(\frac{h}{Ao}\right) - \left(\frac{1}{2}\right)\left(\frac{h}{Ao^3}\right)\right] \qquad 0 < h < Ao \qquad [2a]$$

$$\gamma(h) = Co + Cs = sill \qquad h \geq Ao \qquad [2b]$$

where Co is the nugget variance, Cs is the structural variance, h is the lag distance and Ao is the range. The standard exponential semivariogram model is defined as:

$$\gamma(h) = Co + Cs\left[1 - \exp\left(-\frac{h}{a}\right)\right] \qquad [3]$$

where a is the range. Semivariogram models were fitted to the data using the geostatistical software Gstat[2] for each of the most prevalent weeds in the field in 1999. In 1998 the default semivariogram produced by the geographic information system (GIS) program Surfer[3] was used for each weed species. Anisotropy (directionality) was included in the kriging process if it was identified while fitting the variogram. A kriged weed contour map was developed for each weed using Surfer for both years.

1.2.4 Experimental Design.

The field was divided into 16 plot areas of 24 x 85m. The experiment was laid out according to a randomised complete block design with 4 replications and 4 treatments (Figure 1.1). Replications ran in an east/west direction lengthways in the field. A turn around area of 40m in length crossed through each replication. The same randomisation was used from year to year. The experimental design was overlain onto the weed contour map and each plot's weed contour map was divided into 136 management units of 3 x 5m. The size of the management unit was a function of the DIS. The boom of the DIS was 3m wide and the 5m length was chosen to minimise the percent area that was considered an error band around each decision unit (Bennett 1997). For each plot there were 136 decision units. Decisions on whether to spray or not were based on the presence of targeted weed species above the threshold density of 1 shoot m^{-2} in any portion of each management unit (Figure 1.2). Depending on the treatment, one or several weed contour maps were overlain. In the broadcast treatment plots the whole plot area was targeted for herbicide application. Once the decisions about what units would be sprayed had been made, prescription maps were created that could be read by a portable computer installed on the sprayer that controlled the sprayer injectors (Bennett and Brown 1999).

1.2.5 Application of Treatments

The direct injection sprayer system (Bennett and Brown 1999) was equipped with a water tank and a separate container for the herbicide that is to be injected according to the prescription map. The dilution rate of the carrier to herbicide was 20:1(v/v) (Bennett 1997). The sprayer constantly sprays the carrier and injects the herbicide only for those decision units that have been prescribed for application as described above. Therefore three types of applications were possible; 1) injection of herbicide for targeted areas only; 2) injection of herbicide for the targeted areas and simultaneous broadcast application over the entire plot area with another herbicide mixed into the carrier tank; or 3) a traditional broadcast application where herbicide was blanketed over the entire plot area.

In 1998 the herbicides sprayed were a formulated mixture of nicosulfuron/rimsulfuron (1:1, w/w), a formulated mixture of flumetsulam/clopyralid/2,4-D (1:2.7:5.4, w/w), and atrazine at 0.010 kg ai ha^{-1}, 0.28 kg ai ha^{-1} and 1.15 kg ai ha^{-1}, respectively. A non-ionic-surfactant[4] was added at 0.2% v/v. In 1999 the herbicides sprayed were chlorimuron-ethyl at 0.009 kg ai ha^{-1} and acifluorfen at 0.6 kg ai ha^{-1} with the addition of a non-ionic-surfactant[4] at 0.2% v/v. Applications were made at the six-leaf stage of the corn in 1998 and the second-trifoliate stage of the soybeans in 1999 (Tables 1.1 and 1.2). A broadcast application of glyphosate at 900 g ai ha^{-1} was applied preplant on May 5, 1999 over the entire experimental area to control *T. officinale*.

Three to four weeks after treatment, weed counts were conducted on the same 6 x 6m sampling grid used for the initial weed counts. Percent reduction in density was assessed by comparing the initial weed counts in each quadrat to the counts for that same quadrat 4 weeks after treatment according to the following formula:

$$\% \text{ Reduction in Density} = [1-(N_4/N_0)]\text{x}100 \qquad [4]$$

where N_4 represents density at 4 weeks after treatment and N_0 represents initial density. Crop yields were also measured in the autumn of both years using a small-plot combine in 1998 and a field-scale combine in 1999.

1.2.6 Statistical Analysis

Post treatment density data were first subjected to a covariate analysis using initial density values as covariates, treatments as fixed effects and replications as random effects using an ANOVA in PROC MIXED of SAS[5] (Littell et al., 1996). Once it was established that there were no differences among treatments using the covariate analysis, the data was analysed a second time to compare percent reduction in density where the treatments were the fixed effects and the replications and subsamples, nested in treatments, were considered random effects. The second analysis was conducted using an ANOVA in PROC MIXED (Littell et al., 1996). The LSmeans were compared using the Tukey test (Littell et al., 1996).

1.3 RESULTS AND DISCUSSION

1.3.1 Evaluation of Weed Control and Yield

Weed control was not reduced by site-specific herbicide applications as compared to broadcast applications in either year. This was confirmed by the analysis of variance of percentage reduction in density. In 1998, excellent control of *S. asper* and *E. arvense* was obtained with percent reduction in density values ranging between 76 to 92% and 86 to 99%, respectively. Control of *T. officinale* was lower (69 to 80%), but did not differ among treatments. This lower efficacy may be due to the relatively large size of the plants at time of spraying (data not shown). In 1999, control of *S. asper* did not differ among treatments and averaged 98%. Reduction of *C. album* and *E. arvense* density was lower ranging between 28 to 70% and 10 to 41%, respectively; nevertheless, there was no significant difference among treatments for either species. Efficacy of weed control was therefore identical whether herbicides were applied to the whole field or only targeted at management units. This shows that it is possible to target only weed patches with herbicides without significantly affecting weed control levels.

There were no differences in yield among any of the treatments in either year. Corn yields in 1998 ranged from 9.0 to 9.5 tonnes ha^{-1} while soybean yields ranged from 2.93 to 3.54 tonnes ha^{-1} in 1999. There was, therefore, no yield advantage in applying herbicides to the whole field over site-specific applications. The fact that there was no difference between yields among the four treatments is in accordance with the identical weed control levels found among treatments.

1.3.2 Average Area Sprayed

Site-specific herbicide applications resulted in reductions in the amount of herbicide used. In 1998 the actual area sprayed in the site-specific treatment (T1) was 26% less than in the broadcast treatment T4 (Figure 1.3). There was no reduction in area sprayed when the site-specific component of the combination treatments T2 and T3 was considered. In 1999, there was no difference in the total area sprayed between the site-specific treatment (T1) and broadcast treatment (T4), but with combination treatments T2 and T3, reductions in area sprayed of 59 and 50%, respectively, were obtained.

1.3.3 Spatial Description of Prevalent Weed Species

The most prevalent weed species found over the two-year study were *E. arvense*, *S. asper*, *C. album* and *T. officinale* (Table 1.3). *E. arvense* populations were very high in 1998 when the field was in corn with an average of 5.18 shoots m^{-2} within a range of zero to >30 shoots m^{-2}; however, in 1999 when the field was in soybeans, the average was considerably lower at 1.89 shoots m^{-2}. *E. arvense* was the most abundant weed in 1998, but only occurred in 11.6% of the sampling points (Table 1.3). In 1999 *E. arvense* densities were reduced by approximately two thirds, but the percentage of sampling points infested remained almost unchanged.

E. arvense is a perennial weed that reproduces by horizontal rhizomes that are generally found about 1m below the ground surface (Marshall 1986). Because the field has been under no-till since 1990, it is expected that a weed that reproduces solely by rhizomes in Canadian climates would appear in very dense, concentrated patches (Swanton et al. 1993). Visually, the *E. arvense* patch was quite localised and very dense (Figures 1.4a & 1.4b.) and this observation was confirmed by the low nugget value seen in the geostatical analysis (Table 1.4). It is also expected that the location of shoots in the patch would closely be related to other shoots within the patch. The nugget value of zero, indicated by the semivariogram equations for both years reflected a high spatial correlation with no random effects (Table 1.4). The rhizomes of *E. arvense* can also spread out over large distances and this was reflected by the long range values of 31.48 and 61.54 m in 1998 and 1999, respectively. As well, most patches in the field are likely related because of the connectiveness of the rhizomes. *E. arvense* did not show anisotropy (directionality) in either year. Gerhards et al. (1997a) found that patches of hemp dogbane (*Apocynum cannabinum L.*) were very stable over 4 years and suggested that this stability could be a result of its perennial vegetative reproduction. The stability seen in the *E. arvense* patch is in accordance with Gerhards et al. (1997a) findings.

Semivariograms of *E. arvense* differed very little in shape from year to year and differences in sill and nugget values are likely due to changes in population density rather than differences in the patch dynamics of the weed from year to year (Figure 1.4a & 1.4b). In 1998 most of the *E. arvense* patch was above 30 shoots m^{-2} and only a small ring at the outer perimeter of the patch had low densities (Figure 1.4a). Inner patch configuration changed dramatically in 1999 with only a small area in the centre of the patch at >30 shoots m^{-2} and a large ring of low density areas around the outer perimeter (Figure 1.4b). These dramatic changes in density across the *E. arvense* patch, with virtually no change in size or shape of the outer border of the patch, indicate that *E. arvense* is a very stable weed that would fit well into a site-specific management strategy.

S. asper was the second most abundant weed present in the test area and occurred in 68.4% of the sampling points (Table 1.3). *S. asper* averages changed very little between years with 3.89 and 2.94 shoots m^{-2} in 1998 and 1999, respectively (Table 1.3). *S. asper* is an annual plant reproducing by windborn seeds and is known to flower from June to September (OMAF, 1992). The most noticeable characteristic of the *S. asper* patches was the strong north/south (N/S) anisotropy reflected in the semivariogram equations that corresponded with direction of the implement traffic and predominant winds.

S. asper appeared to be moderately patchy in the field and the semivariograms in both years indicated some spatial correlation as well as some randomness with nugget values of 14.50 and 2.94 in 1998 and 1999, respectively (Table 1.4). Presumably, with the variability of *S. asper*'s windborn seed dispersal mechanisms, some level of randomness will occur with location of seedling development sites; however, because the timing of *S. asper* flowering is often when the crop is already well established it can be expected that *S. asper* seed movement would be restricted by the crop canopy.

This restriction in seedling dispersal would cause localisation of seedlings in close proximity to the parent plant and therefore maintain some spatial dependency. Subsequently, it could be expected that the range of spatial dependency would be relatively short and patches located far away from one another would not be related. The relatively short range values derived from the variograms of 16.18 and 14.34 m in 1998 and 1999, respectively, support this isolation hypothesis (Table 1.4).

Despite excellent control of *S. asper* in 1998 population densities were only reduced by 30% which suggest a persistent seed bank in the soil. Gerhards et al. (1997a) proposed that weeds with a persistent seed bank tend to have a high level of patch stability. In 1999 the number of sampling points infested by *S. asper* were reduced by approximately 30%, which would seem to correspond to the 30% reduction in total weed abundance from 1998 to 1999; however, a visual comparison of 1998 and 1999 *S. asper* maps indicated that 1999 patches were located close to 1998 patches but not in identical locations (Figure 1.5a & 1.5b). These observations suggest that *S. asper* would be a good candidate for site-specific applications despite the fact that it is a small seeded annual species. It has been hypothesised that such annual weeds with small seeds would not have stable patches (Gerhards et al. 1997a). The variability in patch location observe here indicates that mapping should be done yearly to ensure accurate application maps unless movement of patches can be predicted.

C. album is an annual weed that has no apparent distribution mechanisms besides dispersal through agricultural practices and generally all seeds are dropped at the base of the parent plant (Bassett and Crompton 1978). *C. album* densities increased between years from an average of 0.09 shoots m^{-2} in 1998 to 1.38 shoots m^{-2} in 1999 (Table 1.3). Visually, *C. album* patches seemed very small and concentrated, which is expected if all the seeds are developing within close proximity to the parent plant (Figure 1.6a & 1.6b).

The variograms indicated that there was some spatial component to *C. album* patches but the population seemed to be closer to randomness with a nugget value of

14.32 in 1999 (population densities were too low to produce an accurate variogram of the 1998 *C. album* data, Table 1.4). Perhaps a sampling grid size smaller than the 6 x 6 m used would provide a better understanding of *C. album* patch dynamics. The range indicated by our variograms was very small and not much larger than our sampling grid size (Table 1.4). This short range also indicates that we may have not captured the spatial component of the weed using a 6 x 6m sampling grid.

Reasons for the dramatic increase in *C. album* densities between years are still unknown. *C. album* populations were controlled by the 1998 herbicide applications and no escapes were counted at 3 to 4 weeks after application. As well, initial density maps of *C. album* developed in 1999 were quite different than the initial maps developed in 1998. Buhler et al. (1996) investigated the effect of corn residues and tillage on the emergence of *C. album* and found that the response was highly variable among years. Roman et al. (1999) found similar results to Buhler et al. (1996) and attributed the high variation in *C. album* emergence to interactions of tillage, crop residue, seed return and environmental conditions.

From the two years of data collected it would appear that *C. album* may be suitable for site-specific applications if it can be mapped on a small enough scale after seedling emergence; however, patch stability may vary and predicting patches from year to year will be a problem. Walters (1996) found similar problems when trying to map dicotyledinous weeds in cereals in Europe. Contrary to our findings, Walters (1996) found that dicotyledinous weeds were stationary, but seedling emergence varied between years. Further research is necessary on *C. album* spatial dynamics in order to assist in predicting patch location.

T. officinale densities were relatively low with an average of 0.62 shoots m^{-2} and a maximum value of 5 shoots m^{-2} in 1998 (Table 1.3). After visual examination, *T. officinale* patches were difficult to identify in the field and the variogram indicated that there was no spatial correlation (Table 1.4). This indicates random distribution. *T. officinale* seemed to be present in the field at low densities with most sampling points showing only one or two shoots m^{-2}; however, it was present in 43% of the 1105 sampling points (Table 1.3). This relatively uniform distribution was also reflected by a small standard deviation (0.62 shoots m^{-2}).

The inherent random distribution of *T. officinale* could be related to the fact that it is a perennial that produces windborn seeds. Unlike *S. asper*, *T. officinale* produces seed very early in the season and dispersal would therefore occur before the crop canopy closes, thus allowing free movement of the seeds throughout the field. An attempt was made to target *T. officinale* for site-specific herbicide application in 1998 but not in 1999. A preplant application of glyphosate at 900 g ai ha^{-1} successfully controlled *T. officinale* in 1999. *T. officinale* is not a good candidate for site-specific applications.

The issue of patch stability is very important to the success of site-specific applications. If patches expand or shift location from year to year, the cost of creating expensive weed maps every year may outweigh the economic benefit of site-specific applications. From the two years of intensive data that were collected it seems that patch stability is very weed specific and not necessarily predictable. Prior to the initiation of this study one might have expected *T. officinale* to behave similarly to *S. asper* because of their comparable dispersal techniques. Closer investigation reveals that they differ both in patch stability and spatial distribution.

1.34 Implications

This is the first field study that has tested site-specific applications against broadcast applications. Site-specific herbicide applications provided encouraging results in both years. The reduction in herbicide inputs would be meaningful economically to a farmer as well as environmentally to society. Despite these promising results, site-specific applications need to be refined if they are to be used on a large scale.

The grid scouting based approach to the development of the application maps is very labour intensive and Lutman and Perry (1999) suggested that it is impractical for farm use. Christensen et al. (1999) agreed that manual grid scouting is too time consuming and more efficient methods for the development of weed maps need to be devised. Nevertheless, they suggested that there are benefits to grid scouting over real-time weed sensing. These benefits include a better understanding of the spatial dynamics of the weeds present, as well as the ability to choose a herbicide, a tank mix or several herbicides and tailor the application to the weeds present in the field. The level of reduction in herbicide inputs in the site-specific treatments could not have been achieved without prior knowledge of the weeds present and the nature of their patchiness. As technology progresses, better ways of accurately locating weed patches in the field, when the weeds are small and within the herbicide application window, will be developed.

Weed patch spraying systems are currently being developed all over the world and each research team has chosen to target different sized areas. Other site-specific research such as studies by Williams et al. (1999) and Gerhards et al. (1997b) used a 12 m boom width for site-specific applications. This experiment demonstrates that site-specific applications can be achieved at a relatively small scale in the field. As the decision grid increases in size, a greater area of the field will be sprayed simply because of proximity to the patches that require treatment. Large field scale applications made with commercial sprayers on a 3 x 5m grid may not be possible because of factors such as driving speed or spatial accuracy. Yet, a small application grid optimises herbicide reductions and therefore is crucial to the success of site-specific applications.

In this study, the decision whether to spray an area or not was based on a single criterion for all broadleaf weed species. Realistically, each weed species would have a different impact on the crop based on density, location in the patch (Mortensen et al. 1998) and time of emergence. A threshold of >1 and above shoots m^{-2} may have been too high for some weed species and too conservative for others. Leaving an area unsprayed because it did not have weeds above threshold densities may impacted the possibility of using the same weed maps over several years. Refinement and testing of decision support systems is needed for site-specific applications.

From the results of this experiment it seems that site-specific applications will be weed specific. Only when the dynamics of weed patches, as well as the impact of site-specific herbicide applications on these patches are better understood, the true implications of site-specific application will be known. Combining an increased knowledge of weed patches with other field characteristics such as soil properties, topography and nutrients could create new possibilities for diverse management strategies.

Site-specific applications were successfully implemented at the field level, using a direct injection application system, while maintaining weed control or yield as compared to broadcast herbicide applications. The average area sprayed was reduced by as much as 26% in site-specific treatments and by as much as 59% where site specific applications where combined with broadcast treatments. These reductions in bulk herbicide use represent very real possibilities for on farm herbicide reductions. From the two years of study weed patch stability appears to be weed specific, with some weeds better suited to site-specific management compared to others.

Source of Materials

[1] Ashtech GG-RTK GPS complete real-time system, Magellan Corporation 471 El Camino Real Santa Clara, CA 95050-4300

[2] Gstat, Free Software Foundation, Inc., 59 Temple Place - Suite 330, Boston, MA 02111, USA

[3] Surfer, Golden-Software Inc., 809 14th St, Golden, CO 80401, USA

[4] Nonionic surfactant, Agral 90, 90% nonylphenoxy-polyethoxy-ethanol, Norac Concepts Inc, Orleans, Ontario, Canada, K1C 7H8

Acknowledgements

We thank Bob Hart for allowing us to use his farm for our experiment, Peter von Bertoldi for geostatistical advice, Mike Cowbrough for assistance and input, and members of the Department of Plant Agriculture's weeds lab for their assistance and hard work surveying weeds. Support for this project was provided by the Ontario Corn Producers' Association, the Ontario Soybean Growers' Marketing Board and Ontario Ministry of Agriculture, Food and Rural Affairs through Food Systems 2002 program and OASIS program.

Table 1.1. Herbicides applied and weeds targeted in 1998

		Weeds targeted[a]		
Treatment	Herbicides	TAROF	SONAS	EQUIR
T1	Flumetsulam/clopyralid/2,4-D	I[b]	I	I
	Atrazine + nicosulfuron/ rimsulfuron	I	I	I
T2	Flumetsulam/clopyralid/2,4-D	BC	BC	BC
	Atrazine + nicosulfuron/ rimsulfuron	X	I	I
T3	Flumetsulam/clopyralid/2,4-D	BC	BC	BC
	Atrazine + nicosulfuron/ rimsulfuron	I	I	I
T4	Flumetsulam/clopyralid/2,4-D	BC	BC	BC
	Atrazine + nicosulfuron/ rimsulfuron	BC	BC	BC

[a] TAROF: *Taraxacum officinale*, SONAS: *Sonchus asper*, EQUIR: *Equisetum arvense*.

[b] I: herbicides injected for patches above threshold density, X: no injection even if density is above threshold; and BC: broadcast application of the herbicides to the whole plot area.

Table 1.2. Herbicides applied and weeds targeted in 1999

		Weeds targeted[a]		
Treatment	Herbicides	CHEAL	SONAS	EQUIR
T1	Chlorimuron +acifluorfen	I	I	I
T2	Chlorimuron	BC	BC	BC
	Acifluorfen	I	X	I
T3	Acifluorfen	BC	BC	BC
	Chlorimuron	X	I	X
T4	Chlorimuron +acifluorfen	BC	BC	BC

[a] CHEAL: *Chenopodium album*, SONAS: *Sonchus asper*, EQUIR: *Equisetum arvense*.

[b] Symbols as per table 1.

Table 1.3. Summary statistics of most prevalent weed populations in both years.

Year	Weed species	Total # of shoots at 1105 sampling points	Mean shoots m^{-2}	SD	Range	Frequency %
1998	SONAS[a]	4623	3.89	6.34	0 to >30	68.43
	TAROF	706	0.62	0.87	0 to >5	43.09
	EQUIR	6155	5.18	21.37	0 to >30	11.61
	CHEAL	111	0.09	0.35	0 to >5	8.08
1999	SONAS	3248	2.94	6.45	0 to >30	49.0
	EQUIR	2098	1.89	6.64	0 to >30	11.22
	CHEAL	1530	1.38	5.40	0 to >30	18.82

[a] SONAS: *Sonchus asper*, TAROF: *Taraxacum officinale*, CHEAL: *Chenopodium album*, EQUIR: *Equisetum arvense*.

SD: Standard deviation, Frequency %: percentage of all sampling points in which presence of the species was recorded.

Table 1.4. Estimated parameters for the semivariogram models for *S. asper*, and *E. arvense* for both 1998 and 1999, *T. officinale* for 1998 and *C. album* for 1999. Variograms estimated using all 1105 sampling points using Gstat.

Year	Code	Model	Nugget (C_0)	Sill (C_0+C_s)	Range (A)	Anisotropy
1998	SONAS[a]	Exponential	14.5	32.72	16.18	North/South
	EQUIR	Exponential	0	59.37	31.48	None
	TAROF	*N/A*[b]	0.77	*N/A*	*N/A*	*N/A*
1999	SONAS	Exponential	2.94	31.98	14.34	North/South
	EQUIR	Spherical	0	53.56	61.54	None
	CHEAL	Exponential	14.32	23.52	11.28	North/South

[a] SONAS: *Sonchus asper*, TAROF: *Taraxacum officinale*, CHEAL: *Chenopodium album*, EQUIR: *Equisetum arvense*

[b] *N/A: not applicable,*

Figure 1.1. Contour map of experimental area showing locations of experimental plots. Red lines represent plot edges and green patches represent weed density. Distance on x and y axis are in meters and density scale in shoots m^{-2}.

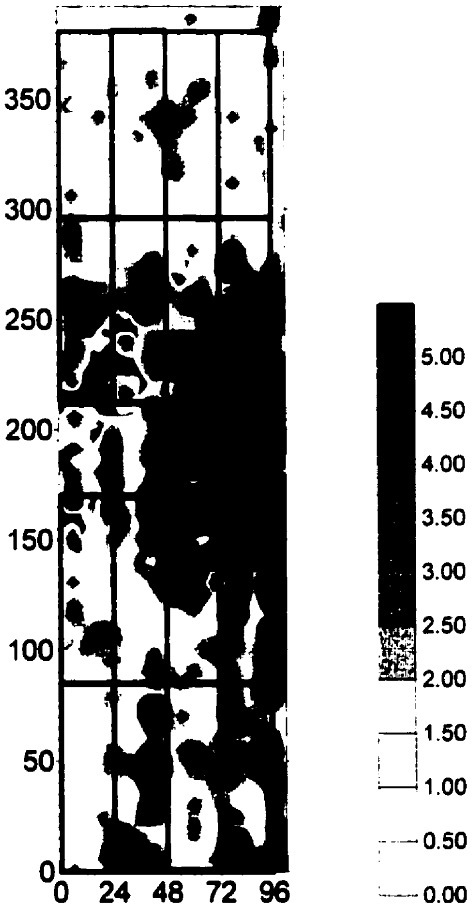

350
300
250
200
150
100
50
0
0
24
48
72
96
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00

Figure 1.2. Contour map of a site-specific plot showing division into 136 decisions units (a). Each decision unit is 3 x 5 m. Contour map showing areas that will be targetted for herbicide application (b). Cross-hatched areas will be targetted for herbicide application and areas without cross-hatching will be left untreated. Distance on x and y axis are in meters and weed density in shoots m^{-2}.

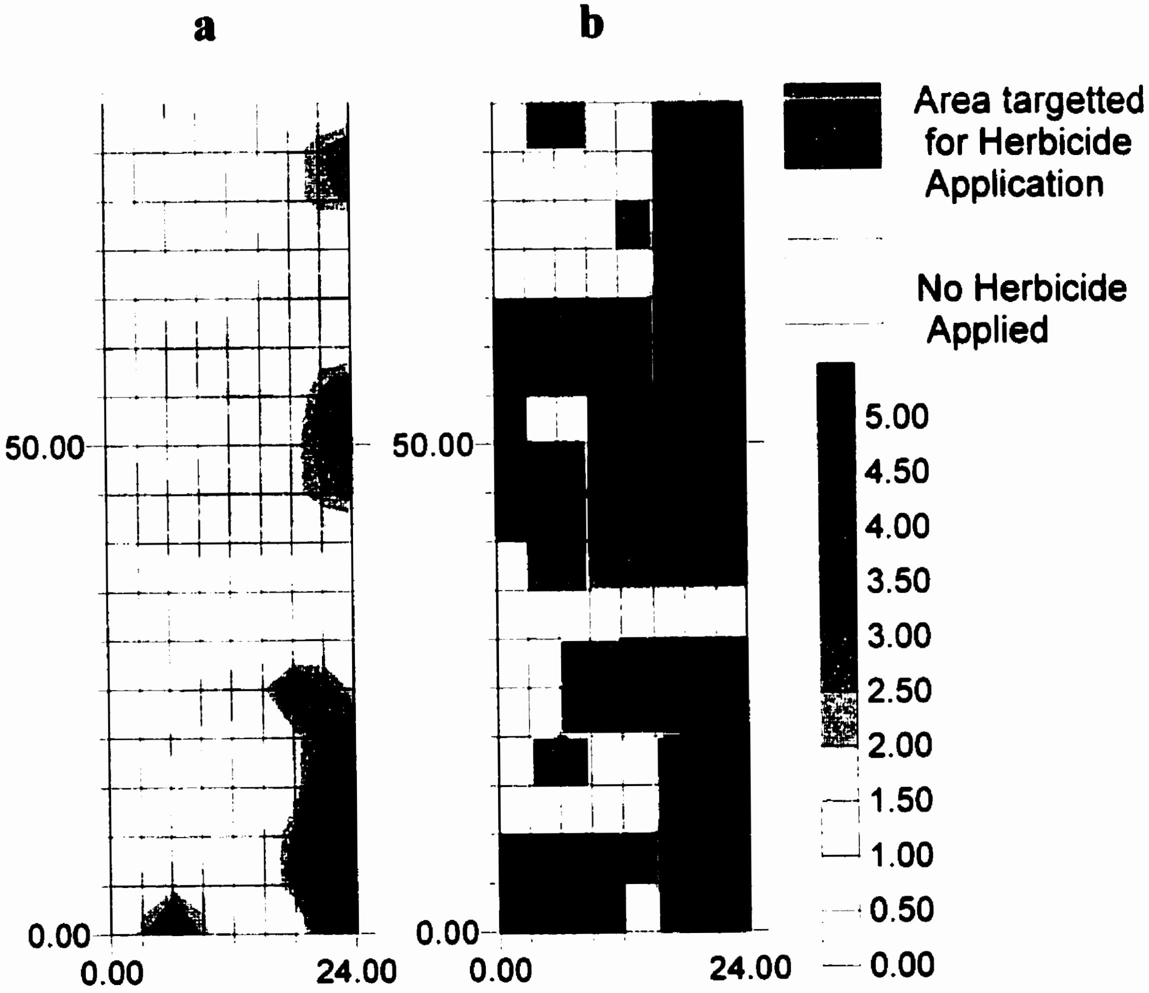

a
b
50.00
0.00
0.00
24.00
50.00
0.00
0.00
24.00
Area targetted for Herbicide Application
No Herbicide Applied
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00

Figure 1.3. Average area sprayed using site-specific herbicide applications (T1) or a combination of site-specific and broadcast (T2, and T3) as compared to broadcast herbcicide application (T4), in both 1998 and 1999. Each bar is the average of 4 replications shown with the standard error of the mean.

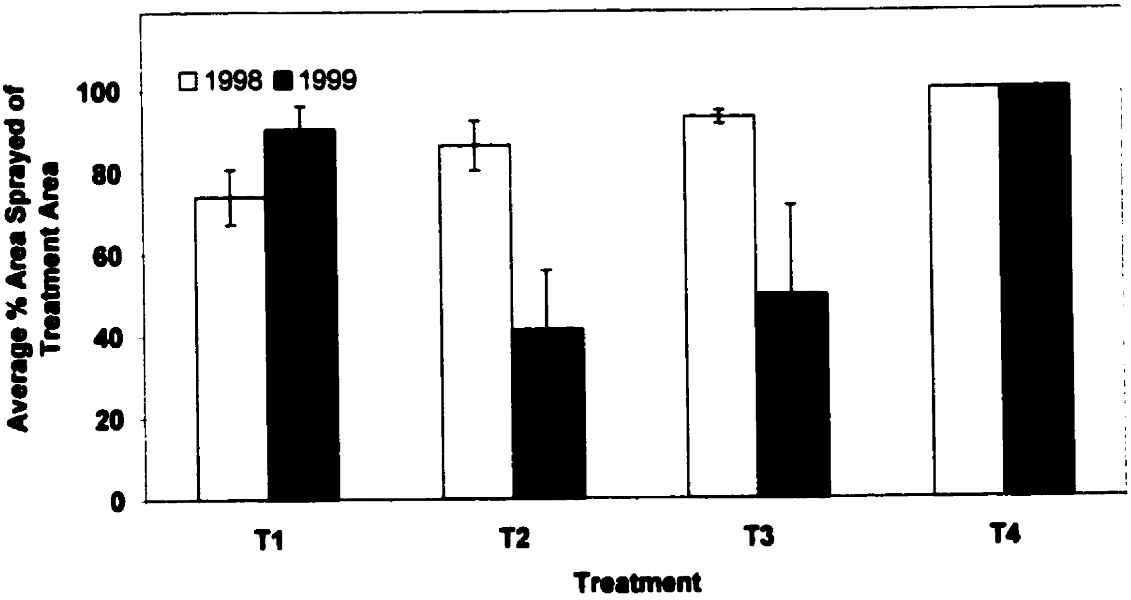

□ 1998 ■ 1999
Average % Area Sprayed of Treatment Area
0
20
40
60
80
100
T1
T2
T3
T4
Treatment

Figure 1.4. Comparison of 1998 (a) and 1999 (b) density contour map of *E. arvense* from the 1105 sampling points. Distances on x and y axis are in are in meters and density scale in number of shoots m^{-2}

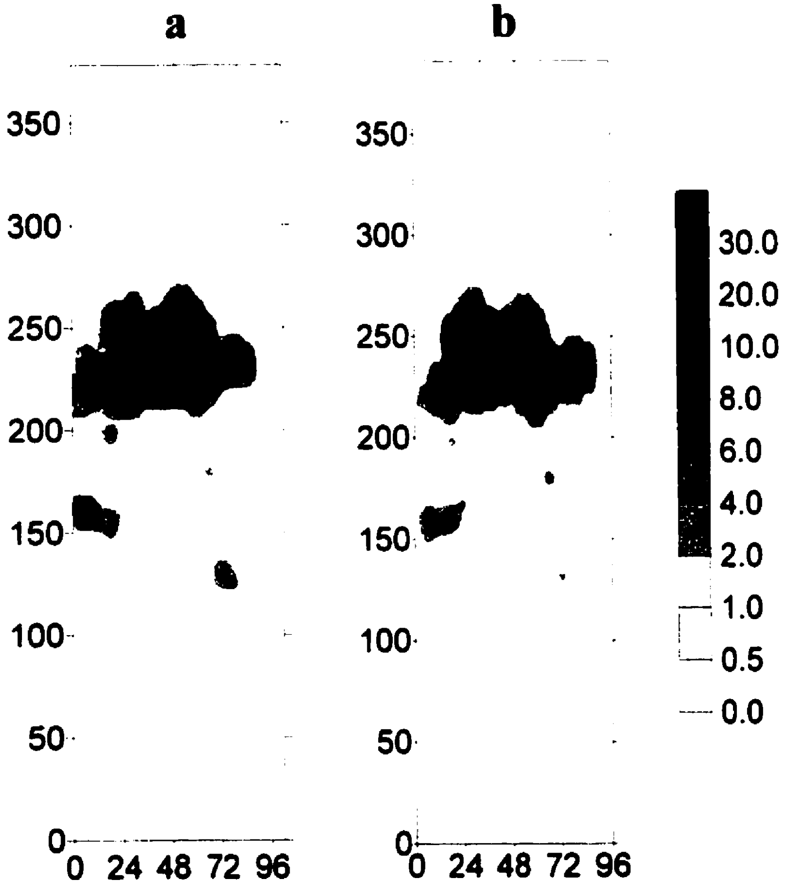

a
b
350
300
250
200
150
100
50
0
0 24 48 72 96
30.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

Figure 1.5. Comparison of 1998 (a) and 1999 (b) density contour map of *S. asper* from the 1105 sampling points. Distances on x and y axis are in are in meters and density scale in number of shoots m^{-2}

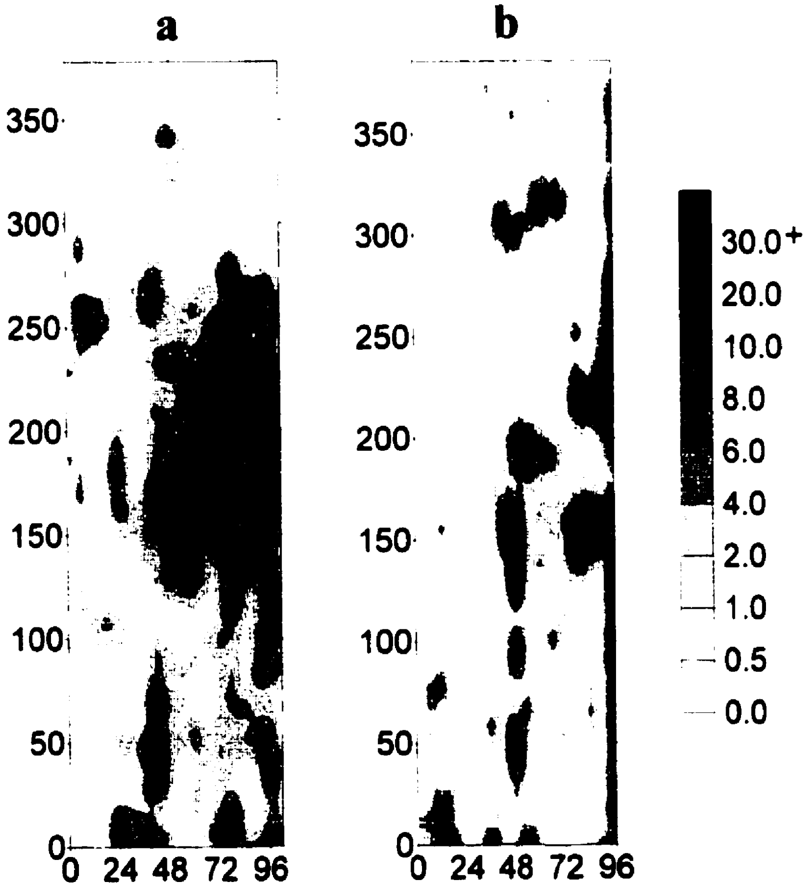
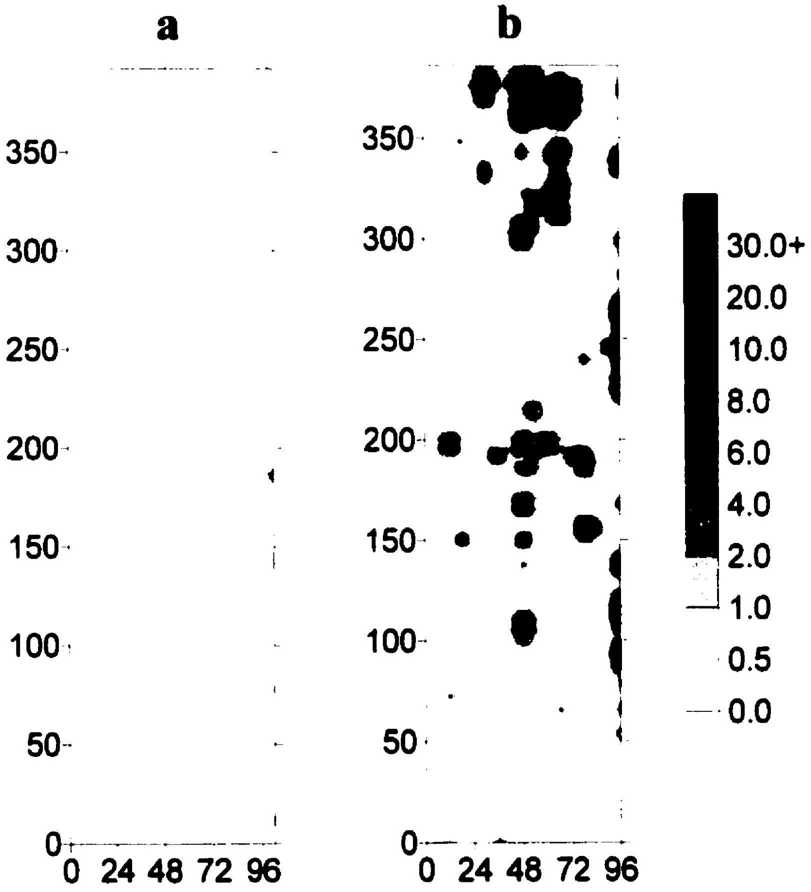

a
b
350
300
250
200
150
100
50
0
0
24
48
72
96
30.0+
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

Figure 1.6. Comparison of 1998 (a) and 1999 (b) density contour map of *C. album* from the 1105 sampling points. Distances on x and y axis are in are in meters and density scale in number of shoots m^{-2}


a
b
350
300
250
200
150
100
50
0
0 24 48 72 96
350
300
250
200
150
100
50
0
0 24 48 72 96
30.0+
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

Chapter 2: Evaluation of Site-Specific Procedures for Research Purposes

2.0 Abstract

Site-specific weed management aims to reduce herbicide inputs into agricultural fields. Research conducted on site-specific weed management has many approaches with various inaccuracies related to each approach. A site-specific weed management experiment conducted in Ontario, Canada was evaluated for errors associated with weed map accuracy, implications regarding sampling grid size and errors associated with prescription maps. Overall, weed maps were found to be very accurate with some species maps more accurate than others. As grid sampling distance increased weed map accuracy decreased for all species. Site-specific applications resulting from prescription maps using a 3 x 5m decision unit and a threshold of 1 shoot m^{-2} tended to target herbicide applications where they were not needed 18.7 % of the time, and tended to not target herbicide applications where they were needed 0.2% of the time, over the entire experimental area.

2.1 Introduction

Site-specific herbicide applications may provide a means to increase the effectiveness and efficiency of our modern agricultural weed management techniques. Mortensen et al. (1998) suggested that site-specific herbicide applications offer the opportunity to reduce the environmental impacts of herbicide use in farming while sustaining profitability. Site-specific herbicide applications would spatially manage weed populations by targeting weed-infested areas of the field only, leaving other areas of the field untreated.

Current techniques for site-specific weed management require predetermined weed maps that link weed density information with field location. Herbicide prescription maps are based on the targeting capabilities of the sprayer, and a decision algorithm that uses weed density thresholds as criteria. The prescription map is then loaded into the patch sprayer and the application is targeted accordingly.

Recently, research on site-specific weed management has moved from computer simulated desk studies to in-field applications. With this transition has come new obstacles related to methodology and approach. Research to evaluate the feasibility of site-specific weed management using a direct injection sprayer was conducted in Ontario, Canada in 1998 and 1999 (Goudy et al. 2000). Three site-specific treatments and a conventional broadcast treatment and compared in a replicated experiment which investigated if site-specific applications were as effective as broadcast applications. Site-specific herbicide applications resulted in the reduction of herbicide use by as much as 30% in 1998 and 59% in 1999 while maintaining weed control and yield (Goudy et al. 2000).

Intrinsic to the understanding of weed spatial biology and the effective implementation of site-specific applications, is the accurate characterisation of the spatial distribution of the weed species present in the field. Spatial statistics are now commonly used in weed research to map weed infestations (Donald 1994; Cardina 1995; Heisel et al. 1996; Johnson 1996; Gerhards et al. 1997; Zanin 1998; Goudy et al. 1999). Kriging has become the principal tool to model spatial structure of weed populations and is commonly used to estimate unsampled data points (Gotway et al. 1996 and Isaaks and Srivasta 1989). Spatially referenced weed density data is used in the kriging process to develop interpolated weed contour maps. Subsequently, it is important to assess the accuracy of these techniques, particularly when used for site-specific weed applications. Dieleman et al. (2000) compared weed map accuracy between various interpolation techniques, yet no other site-specific weed management research has addressed the accuracy of weed maps.

In most studies on weed spatial biology, a grid sampling strategy is used to acquire knowledge about weed species density at each geographical location (Cardina 1997). Grid scouting techniques may not be the most realistic method of acquiring weed maps for commercial site-specific applications; however, until new technologies can produce accurate information, research into site-specific applications must rely on intensive surveying techniques (Christensen et al. 1999; Lutman and Perry 1999).

Heisel et al. (1996) found that as sampling distance increased from a 10 x 10 m grid to 20 x 30 m grid that map accuracy severely decreased. Similarly, Wallinga (1995) found that as sampling distance increased, resulting weed maps tended to over-estimate weed infestations. Various grid sampling sizes have been used, from as small as 3 x 5 m (Cardina et al. 1995) to as large as 30 x 40 m (Wilson and Brain, 1991), yet no research has quantified the accuracy of the weed maps derived from the sampled data. Dieleman et al. (2000) indicated that the sampling distance clearly impacts the resulting weed map accuracy. The amount of error that can be tolerated may differ among site-specific systems and the implication of sampling grid size is important to weed map accuracy and needs to be quantified. This quantification of weed map accuracy would result in better guidelines for sampling protocols and the ability to compare results of site-specific applications.

Prescription maps used to target herbicide applications site-specifically in a field are also susceptible to errors. Prescription maps are created by dividing the weed contour maps into decision units based on the spray capabilities of the patch spraying system. Each decision unit within the prescription map is individually assessed as to whether herbicide applications are required based on a weed threshold criteria. An over-application would occur if a decision unit was targeted for application, but the actual weed density within that unit was below threshold. An under-application would occur if a decision unit was not targeted for application but the actual weed density within that unit was above threshold. Pannell and Bennett (1999) found that over-applications and under-applications can greatly impact the economics of site-specific applications, yet no current research has quantified application error due to prescription maps. Scale and precision are crucial to maximising the benefits of site-specific applications and the quantification and recognition of error occurring as a result of application techniques will benefit site-specific applications in the future.

Our aim was to investigate the accuracy of weed maps derived from extensive sampling conducted in a field in 1998 and 1999. We also wanted to determine what the effect of a simulated decrease in sampling effort would be on the resulting weed maps. Finally we aimed to assess the level of error occurring from over-application and under-application when prescription maps were derived from grid sampling of weeds.

2.2 Materials and Methods

2.2.1 Assessment of the Interpolated Map Accuracy

The collection of weed count data and the interpolation process using kriging to develop weed contour maps has been performed as described in Goudy et al. 2000. By taking into account spatial dependence and placing greater weight on sampled values around the point to be estimated, kriging can approximate unsampled grid points. The semivariogram is a model of spatial autocorrelation and is incorporated into the kriging process (Isaaks and Srivastava 1989). The residual differences of the predicted value at each 6 x 6 m sampling point on the interpolated map and the original value at that same sampling point was used to assess the accuracy of the kriged maps. The mean absolute difference (MAD) between the observed and estimated values can be used to assess the precision of the spatial interpolation (Gallichand et al., 1992):

$$MAD = \frac{\sum_{i=1}^{N} \left| \hat{Z}(x_i) - Z(x_i) \right|}{N} \qquad \text{Equation 1.}$$

where $\hat{Z}(x_i)$ is the estimated value of the variable Z at point x_i and N is the total number of observed values used in the interpolation. Both Isaaks and Srivastava (1989), and Gallichand et al. (1992) suggested that MAD is a criterion that incorporates both the bias and spread of the error. The global difference between the observed and estimated surfaces can be estimated with the root mean square (RMS).

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} \left(\hat{Z}(x_i) - Z(x_i) \right)^2}{N}} \qquad \text{Equation 2.}$$

Dieleman et al. (2000) used RMS to compare the accuracy of various interpolation methods for weed data. A lower MAD value indicates a more precise interpolation, and a lower RMS value indicates a better fit between the estimated values and the observed values. The MAD and RMS values were calculated for initial weed maps in both 1998, when the default semivariograms supplied by Surfer[1] were used for interpolation, and in 1999 when the semivariograms modelled using Gstat[2] were used for interpolation. Each of the weeds present in 1998, *Equisetum arvense*, *Sonchus asper*, and *Taraxacum officinale* and in 1999, *E. arvense*, *S. asper*, and *Chenopodium album* were individually assessed in this manner.

2.2.2 Assessment of Sampling Grid Size

In order to determine the effect of sampling grid size on weed map accuracy, a simulation of a less intensive sampling effort (increased distance between points) was performed starting with the actual 6 m grid. By systematically removing alternate sampling points in both the x and y directions starting at the lower left-hand corner of the experimental area, a 12 m sampling grid was created and further removal resulted in a 24 m sampling grid. Data sets had 1105, 297, and 90 sampling points for the 6 m, 12 m and 24 m grids, respectively. Semivariograms were modelled using Gstat[2] for each of the three most prevalent weed species present in 1999 in the 12 m grid data set and the 24 m grid data set. Semivariograms (Table 2.3) were input into Surfer[1] and kriging was used to interpolate the weed contour maps. MAD and RMS values were calculated, as previously described, comparing the predicted values at 6 m for each of the new maps developed from the larger sampling grids. Each of the weeds present in 1999, *E. arvense*, *S. asper*, and *C. album* were individually assessed in this manner.

2.2.3 Assessment of Prescription Maps

Prescription maps were based on the weed contour maps developed from the kriging process (Goudy et al. 2000). The generated weed maps were divided into 16 experimental plots, each 24 x 85 m in size. Each plot was further divided into 136 decision units each 3 x 5 m in size, based on the sprayer capabilities. Any area within each decision unit exceeding the 1 shoot m^{-2} threshold, was targeted for application. Each plot was assessed in a similar manner regardless of original treatment imposed by Goudy et al. (2000). The resulting on/off prescription maps where then compared to the actual 6 m data. Because of the different grid scales (management units are 3 x 5 m and sampling grid is 6 x 6 m) only 56 of the decision units out of the 136 in each plot could be assessed.

The analysis then consisted of computing the number of times false decision would be derived from our algorithm. There are four possible outcomes, two of which were considered correct decisions and two of which were considered false decisions. Applications were considered correct if we sprayed the decision unit and there were weeds over threshold or we did not spray the unit and there were weeds below threshold. Applications were considered false if we did spray while weeds were actually below threshold or if we did not spray and weeds were above threshold. Each of the weeds present in 1999, *E. arvense*, *S. asper*, and *C. album* were individually assessed in this manner.

2.3 Results and Discussion

2.31 Accuracy of Original Weed Contour Maps

Accurate estimations of weed population density can be generated by kriging grid sampled data. The interpolated weed maps generated in both years by Goudy et al. (2000) were good estimates of the actual weed populations present in the field. This is indicated by the relatively low MAD and RMS values compared to values reported by Dieleman et al. (2000). *E. arvense* had higher MAD and RMS values in 1998 when the default semivariogram provided by Surfer was used as opposed to 1999 values when the semivariogram modelled in Gstat was used for interpolation (Table 2.1). Weed contour maps used in 1999 showed a better fit between the observed and the predicted data points. Surprisingly, the weed map developed for *S. asper* using the default semivariogram supplied by Surfer was more accurate than the map developed using the semivariogram modeled in Gstat. There was little difference between years for *S. asper* and MAD and RMS values were higher than what was found with *E. arvense* in both years (Table 2.1). Both *C. album* and *T. officinale* had lower MAD and RMS value than *S. asper*, yet all three species had good agreement between the predicted and observed values (Table 2.1).

Low MAD and RMS values for *T. officinale* are unexpected as the default semivariogram, which assigns a nugget value of zero was used for the development of the weed contour maps in 1998; however, the semivariogram modelled in Gstat indicates that the population is closer to randomness than aggregated (Goudy et al. 2000). It would be expected that the weed contour map produced by Surfer would not accurately represent where *T. officinale* was located in the field due to the considerable inaccuracy of the semivariogram it used.

MAD and RMS values for *E. arvense, C. album* and *T. officinale* did not differ greatly from values Dieleman et al. (2000) found for common sunflower (*Helianthus annuus*) and hemp dogbane (*Apocynum cannabinum)* sampled on a 7 m grid, while *S. asper* was slightly greater. The MAD and RMS values we found in our study (Table 2.1) were considerably lower than the MAD values of 7.85 and 5.99 and the RMS values of 10.28 and 10.54 that were found by Dieleman et al. (2000) for velvetleaf (*Abutilon theophrasti*) and annual grasses, respectively. Dieleman et al. (2000) compared various interpolation methods and found that kriging did not appear to have superior accuracy compared to other methods such as inverse-distance weighting, minimum surface curvature and multiquadric radial basis function. Gotway et al. (1996) and Heisel et al. (1996) indicated that kriging is a reliable and a relatively safe method in terms of accuracy of interpolation, provided that the semivariogram has accurately modelled the spatial autocorrelation. From these results we can confirm that the weed contour maps developed by Goudy et al. (2000) were adequate and reliable representations of actual field populations.

2.3.2 Implications of Sampling Distance

Simulations using a less intensive sampling effort with the 1999 data set greatly affected the accuracy of the predicted weed maps. As the number of sampling points dropped from 1105 (6 m grid) to 90 (24 m grid), the predicted average shoot density almost doubled for *S. asper* and *C. album* (Table 2.2). For *E. arvense* average density only varied over 0.5 shoots m^{-2}. Similarly, the frequency of occurrence of *S. asper* and

C. album increased as sampling distance increased while that of *E. arvense* remained identical. As sampling distance increased, the accuracy of the estimated average weed population density decreased.

Not only was the accuracy of estimated population statistics reduced when sampling distance increased, but the accuracy of the modelled semivariogram was also reduced. Percent variation due to nugget effect or randomness, which is measured as the ratio of the nugget value to the sill value, increased from 0% to 4.4% for *E. arvense* as sampling distance increased from 6 to 12 m (Table 2.3). A further increase in sampling distance to 24 m resulted in a model with no spatial dependency and a nugget of 25. All variation in the 24 m grid was due to nugget effect. This latter model and resulting map (Figure 2.1) contradicted visual observations which indicating a high level of patchiness for this species in the field (Goudy et al. 2000). Despite the fact that maps of *E. arvense* at the 12 m sampling grid appeared to accurately describe where the weed patches were located, actual density values within the patch were inaccurately estimated as shown by the dramatic increase in the MAD and RMS values as sampling distance increased (Table 2.4 and Figure 2.1).

Contour maps of *S. asper* at the 6 m sampling grid and 12 m sampling grid appeared very similar (Figure2.2 a, b), yet there was an increase in the predicted area that would be targeted for herbicide application as sampling distance increased (Figure 2.2a, b). Increasing sampling distance also resulted in less robust semivariograms. Doubling grid size from 6 m to 12 m increased the percent variation due to nugget effect from 9.2% to 20.0%. Further increasing to 24 m resulted in a model that had no spatial dependency. As observed with *E. arvense*, the MAD and RMS values found with *S. asper* were much larger with the 12 m sampling grid as compared to the 6 m sampling grid and continued to enlarge as the grid was increased to 24 m.

Even at the 6 m grid size the semivariogram indicated a high level of random variability in the *C. album* population with 60.9% percent variation due to nugget effect (Table 2.3). Obviously, increasing sampling distance to 12 m and 24 m resulted in even more inaccurate models. Contour maps of *C. album* at the 12 m and 24 m sampling distances differed greatly from the weed map generated from the 6 m sampling grid (Figure 2.3). The MAD and RMS values greatly increased as sampling distance increased from 6 m to 12 m (Table 2.4). There was little further increase in values as the sampling grid size was increased to 24 m (Table 2.4). The results confirm the fact that as the distance between sampling points increases, the less accurate the semivariograms will be in interpreting spatial dependence and thus the less accurate the weed maps (Lutman and Perry 1999).

Visually the contour maps for *E. arvense* and *S. asper* at the 12 m grid may have been considered acceptable, yet our research shows them to be relatively poor predictions of the actual weed densities present in the field. If weed maps are to be used simply to indicate weed patch location, then maps sampled on a 12 m grid may be useful; however to obtain accurate predictions of density as well as location. a smaller grid size must be used. Similar results were found by Wallinga et al. (1995), who found that as sampling distance decreased so did the predicted percent area of the field infested with weeds. Heisel et al. (1996) found that weed contour maps developed from kriging at a 10 m sampling grid gave reasonable agreement with the actual field counts as opposed to kriging at a 20 x 30 m sampling grid, which gave erroneous density estimates. In either study, the amount of error was not quantified. The potential benefits from site-specific applications decrease as grid size increases (Lutman and Perry 1999).

Ideally, grid sampling would be done on the smallest possible grid sample size but compromise must be met between map accuracy and the time and money required for scouting (Lutman and Perry, 1999). There is always some level of error present in weed maps developed using kriging techniques (Gotway et al. 1996) and knowledge of how this uncertainty changes as sampling grid size increases is crucial. If the level of map accuracy that is required is known then it would be possible to choose an appropriate sampling grid size based on the degree of acceptable error. Therefore it is important to assess the feasibility of weed mapping and limitations for site-specific applications.

2.3.3 Implications for Prescription Map Accuracy

Overall, incidence of application errors would have been relatively low, indicating that our approach to mapping and generating prescription maps was adequate. Generating whole field prescription maps, using the 1999 data, tested the accuracy of our decision algorithm. This prescription map was then compared with actual density data from each of the 1105 quadrats. Applying our algorithm (Goudy et al. 2000) showed that some management units would have been targeted for herbicide application even though weed density was actually lower then threshold. These occurrences are referred to as over-applications. Under-applications would have occurred when management units were not targeted to receive treatment while weeds are present at or over the threshold.

For the three species examined in 1999, over-application was more frequent than under-application (Table 2.5). *E. arvense* was the most effectively targeted of the three species. There was 6.6% incidence of over-application while under-application was only

0.2% (Table 2.5). For *S. asper* and *C. album*, the incidence of over-application was about 3 times higher at 18.2% and 16.1%, respectively. The incidence of decision units where under-application would have occurred was about 5% for these two species. *E. arvense* was more effectively targeted because of its high level of patchiness compared to the two other species. The fact that over-applications were the most frequent type of errors compared to under-application is auspicious. While over-application in some decision units results in herbicide being applied where it is not needed, the potential impact on crop yield is much less than if under-application occurs. In this case, weeds are likely to highly compete with the crop, thereby reducing yields and/or quality.

Measures of error for weed maps and prescription maps have rarely been attempted before. Pannell and Bennett (1999) indicate that determination of application error is important to the assessment of the economics of precision weed management. Their model showed that an incidence of application error set at 5% had significant negative impact on the economic benefits of site-specific weed management in an in-crop situation. This level of error was much lower than what we observed in 1999 (Table 2.5); however, Pannell and Bennett (1999) modelled site-specific application using a Weed Activated Spray Process (WASP) which relies on boom fitted sensors to detect weeds. This is intrinsically different than our map based approach, which could make conclusions from similar economic study very different. Recognising where error is occurring will help to improve accuracy of economic models as well as improve techniques used to develop site-specific weed control methods in the future.

Previously, researchers had little more than intuition to guide them as to proper and accurate techniques to implement site-specific weed management. Clear and critically assessed information about how well a methodology performs with related measures of error can be used to compare and advance various site-specific applications systems. Dieleman (1998) indicates that approaches and technological advances need to be assessed for reducing risk and increasing success. Baseline standards for map accuracy have yet to be set so that true comparisons can be made between methodologies. Improved techniques for creating prescription maps that reduce the amount of over-application and under-application could greatly improve the feasibility of site-specific applications. Results presented here effectively show that methodologies used for field testing of our sampling approach (Goudy et al. 2000) were accurate and useful, yet there is still room for improvement.

Evaluation of a site-specific weed management experiment gave insight into areas of site-specific research that need improvement. Weed maps developed from kriging on a 6 m grid gave more accurate maps as compared to maps developed on a 12 m or 24 m grid. Prescription maps can create situations of over-application and under-application that could impact on the cost effectiveness of site-specific weed applications. Information acquired from this investigation needs to be used in future research to improve the accuracy of experimental site-specific weed applications.

Source of Materials

[1] Surfer, Golden-Software Inc., 809 14th St, Golden, CO 80401, USA

[2] Gstat, Free Software Foundation, Inc., 59 Temple Place - Suite 330, Boston, MA 02111, USA

Acknowledgements

We thank members of the Weed Ecology Lab at the University of Lincoln Nebraska, in particular Dr. David Mortensen and Marty Williams II, for their insight into the project, and Dr. Anita Dieleman of Kansas State University for her guidance. Support for this project was provided by the Ontario Corn Producers' Association, the Ontario Soybean Growers' Marketing Board and the Ontario Ministry of Agriculture Food and Rural Affairs, through the Food Systems 2002 program and.

Table 2.1. Mean absolute difference (MAD) and root mean square (RMS) of residuals between interpolated weed contour map and original sampled data (Goudy et al. 2000) reported in shoots m^{-2} for 1998 and 1999.

Weed Species	Year	MAD	RMS
EQUIR[a]	1998	0.31	1.13
	1999	0.11	0.42
SONAS	1998	0.88	1.79
	1999	0.99	1.92
CHEAL	1998	N/A	N/A
	1999	0.30	0.83
TAROF	1998	0.21	0.35
	1999	N/A	N/A

[a] EQUIR: *Equisetum arvense*, SONAS: *Sonchus asper*, CHEAL: *Chenopodium album*, TAROF: *Taraxacum officinale*.

Table 2.2. Summary statistics for the original data (Goudy et al. 2000) and sub-sampled data sets for 1999.

Weed species	Sampling distance	Number of sampling points	Mean shoots/m^2	SD	Range	Frequency %
EQUIR[a]	6 x 6m	1105	1.89	6.64	0 to >30	11.22
	12 x 12m	297	1.73	6.41	0 to >30	10.77
	24 x 24m	90	1.45	5.57	0 to >30	11.10
SONAS	6 x 6m	1105	2.94	6.45	0 to >30	49.0
	12 x 12m	297	3.91	8.02	0 to >30	48.8
	24 x 24m	90	5.45	9.66	0 to >30	51.0
CHEAL	6 x 6m	1105	1.38	5.40	0 to >30	18.82
	12 x 12m	297	1.68	6.06	0 to >30	20.20
	24 x 24m	90	2.54	7.5	0 to >30	23.30

[a] EQUIR: *Equisetum arvense*, SONAS: *Sonchus asper*, CHEAL: *Chenopodium album*. SD: Standard deviation, Frequency %: percentage of all sampling points that the weed was present in.

Table 2.3. Estimated parameters for the semivariogram models for *E. arvense, S. asper*, and *C. album* for the original data (Goudy et al. 2000) and the sub-sampled data sets for 1999.

Weed species	Sampling distance	Model	Nugget (C_o)	Sill (C_o+C_s)	Range (A)	Anisotropy
EQUIR	6 x 6m	Spherical	0	53.56	61.54	None
	12 x 12m	Spherical	2.2	50.19	63.37	None
	24 x 24m	N/A[b]	25	N/A	N/A	N/A
SONAS	6 x 6m	Exponential	2.94	31.98	14.34	North/South
	12 x 12m	Exponential	12.77	63.11	18.19	North/South
	24 x 24m	N/A	95.78	N/A	N/A	N/A
CHEAL	6 x 6m	Exponential	14.32	23.52	11.28	North/South
	12 x 12m	Exponential	29.23	36.94	37.74	None
	24 x 24m	N/A	50	N/A	N/A	N/A

[a] EQUIR: *Equisetum arvense*, SONAS: *Sonchus asper*, CHEAL: *Chenopodium album*.

[b] N/A = not applicable

Table 2.4. Mean absolute difference (MAD) and root mean square (RMS) of residuals between the interpolated weed contour maps for the original data (Goudy et al. 2000) and the sub-sampled data for 1999.

Weed species	Sampling distance	MAD	RMS
EQUIR	6 x 6m	0.11	0.42
	12 x 12m	1.37	4.16
	24 x 24m	2.90	6.46
SONAS	6 x 6m	0.99	1.92
	12 x 12m	2.52	4.35
	24 x 24m	4.80	6.64
CHEAL	6 x 6m	0.30	0.83
	12 x 12m	2.12	4.87
	24 x 24m	2.28	5.14

Table 2.5. Incidence of over application and under application due to inaccuracy of prescription map. Comparison of on/off prescription maps to actual data points for the entire field for 1999.

Weed species	Over-application [a]	Under-application [b]
	--------------%	--------------
EQUIR	6.6	0.2
SONAS	18.2	4.7
CHEAL	16.1	5.8

[a] Over-application = incidence of management units receiving a herbicide treatment while initial weed count data indicated below threshold density.

[b] Under-application = incidence of management units not targeted for herbicide application despite initial weed count data indicating over-threshold density.

Figure 2.1. Contour maps of *E. arvense* for a) the original data set of 1105 sampling points at 6 x 6m grid (Goudy et al. 2000), b) the sub-sampled data set of 297 sampling points at the 12 x 12m grid and c) the sub-sampled data set of 90 sampling points at the 24 x 24m grid from 1999. Distances on x and y axis are in are in meters and density scale in number of shoots m^{-2}

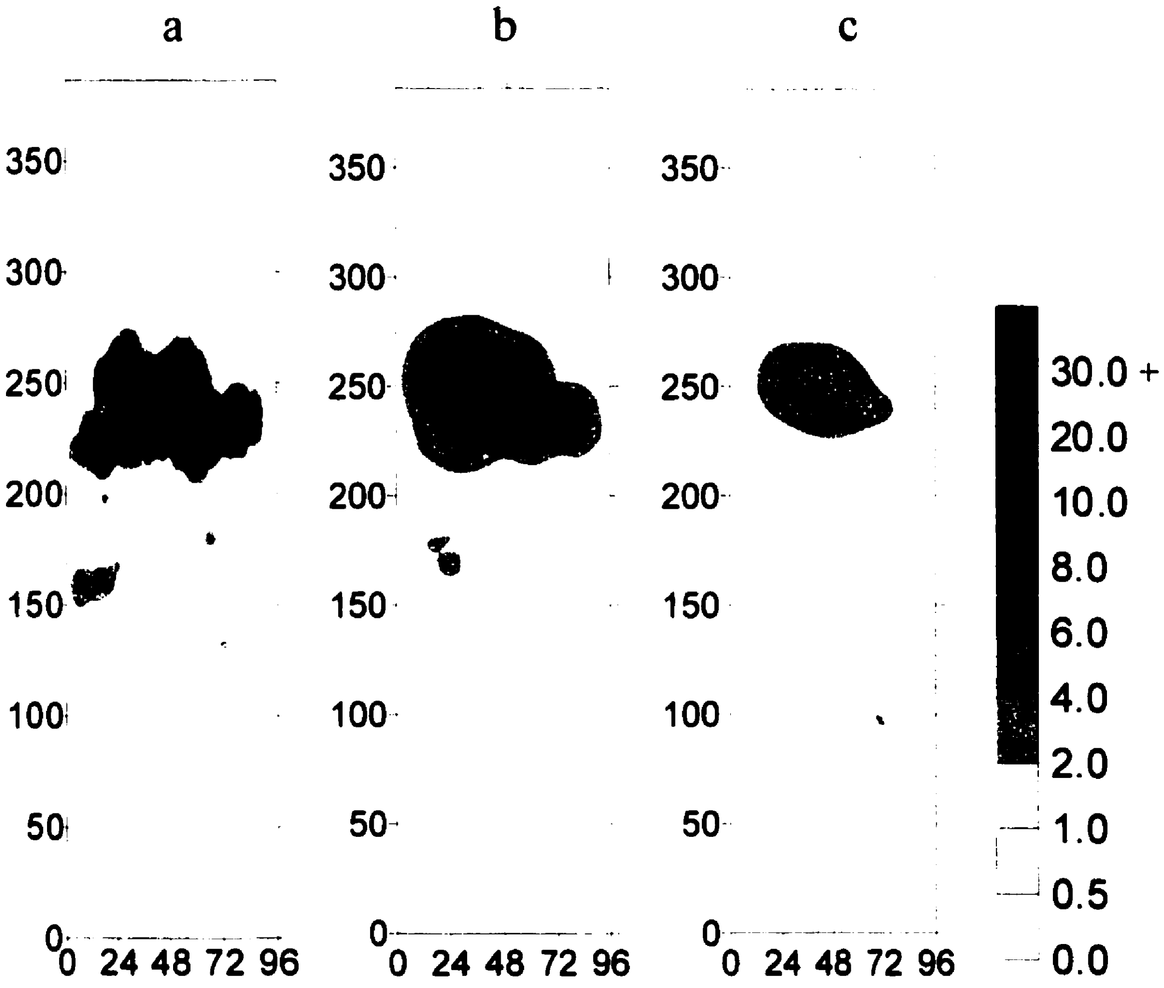

a
b
c
350
300
250
200
150
100
50
0
0 24 48 72 96
30.0 +
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

Figure 2.2. Contour maps of *S. asper* for a) the original data set of 1105 sampling points at 6 x 6m grid (Goudy et al. 2000), b) the sub-sampled data set of 297 sampling points at the 12 x 12m grid and c) the sub-sampled data set of 90 sampling points at the 24 x 24m grid from 1999. Distances on x and y axis are in are in meters and density scale in number of shoots m^{-2}

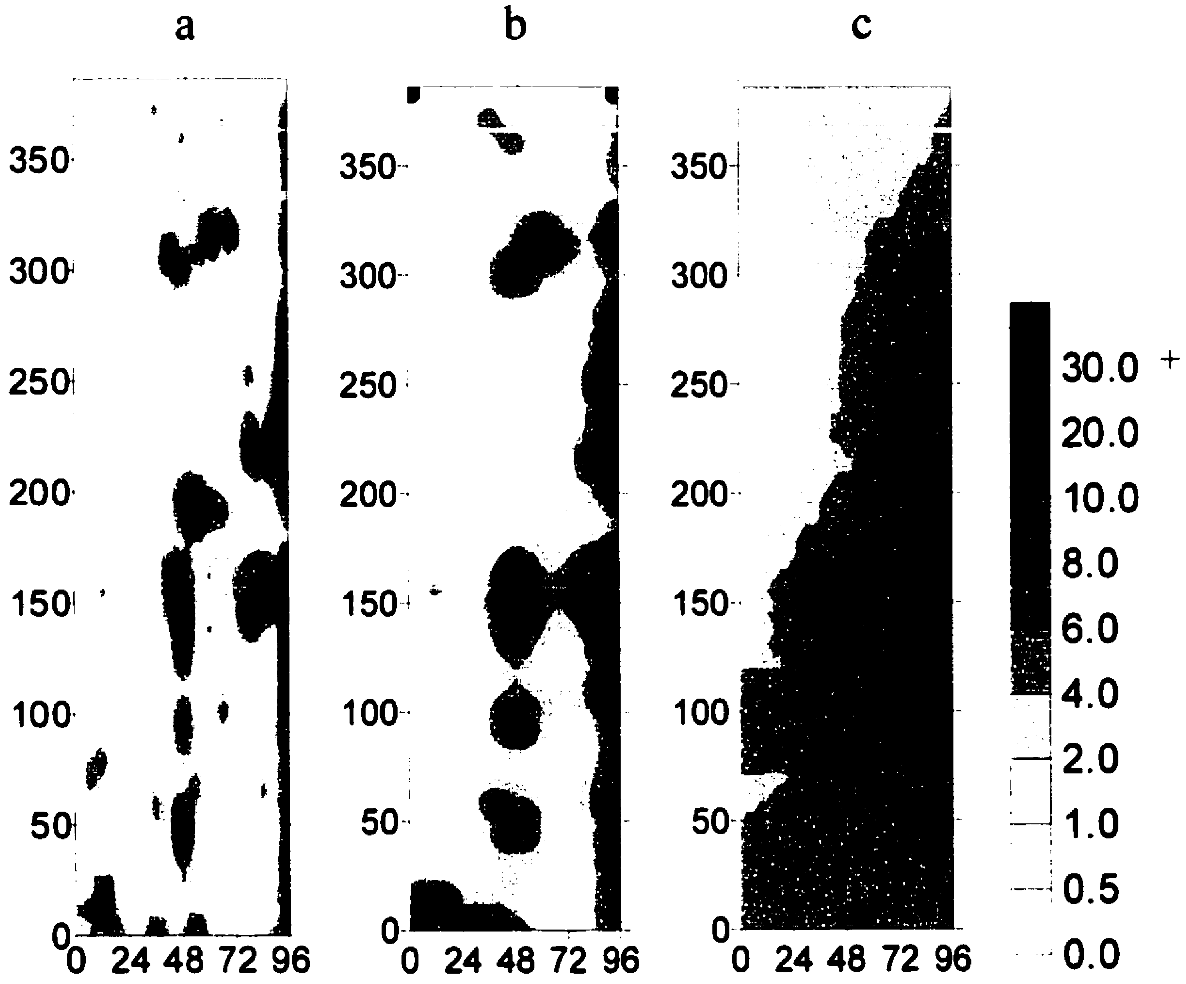
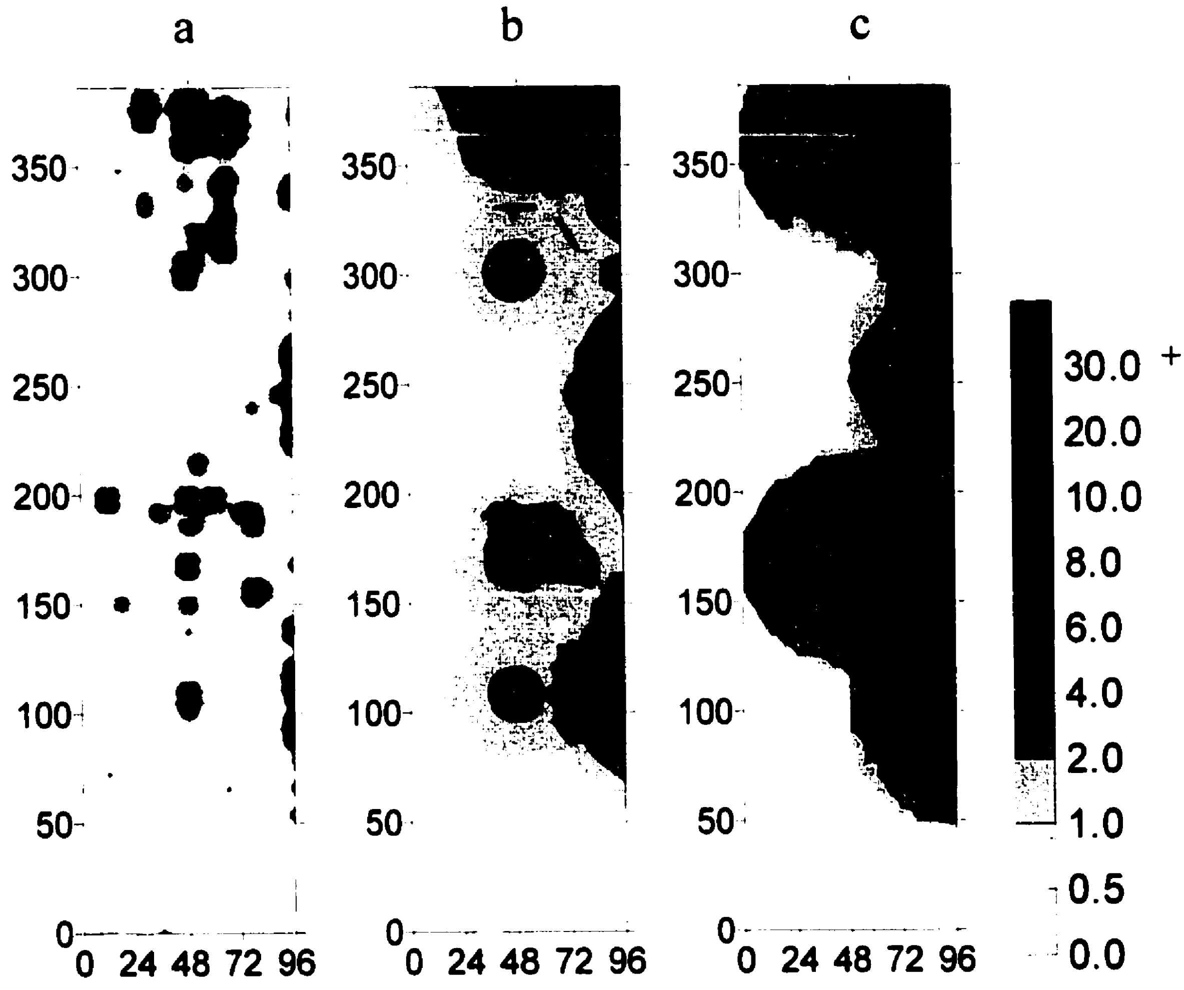

a
b
c
350
300
250
200
150
100
50
0
0
24
48
72
96
30.0 +
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

Figure 2.3. Contour maps of *C. album* for a) the original data set of 1105 sampling points at 6 x 6m grid (Goudy et al. 2000), b) the sub-sampled data set of 297 sampling points at the 12 x 12m grid and c) the sub-sampled data set of 90 sampling points at the 24 x 24m grid from 1999. Distances on x and y axis are in are in meters and density scale in number of shoots m^{-2}


a
b
c
350
300
250
200
150
100
50
0
0 24 48 72 96
30.0 +
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

General Discussion

Contributions of this Study

Site-specific weed management utilises weed spatial biology to target herbicide applications solely to the weedy areas of the field, leaving other areas untreated. Predicted benefits of these herbicide reductions are an economic benefit to farmers, a reduction in environmental impact and increased efficiency of herbicide use. Three hypotheses were proposed within the rationale for this study. The following section will revisit those observations and conclusions that have arisen from testing the hypothesis.

Hypothesis 1: Site-specific vs. Broadcast

To date, research on site-specific weed management has been conducted primarily in computer desk studies. Few site-specific studies were actually carried out in the field and of those that were, none where tested against a standard or control. Without in-field comparisons and quantifiable results, trying to anticipate what will be the impacts of site-specific weed management remains only speculative. This research project is the first site-specific weed management experiment that actually addresses the question: Are site-specific applications as effective as broadcast applications? This research project has been the closest attempt to approach a typical field application that would be conducted by a grower. The closer the site-specific application is to a real field application, the more useful the information is for developing a field ready system.

The following conclusions were reached based on the hypothesis that weed populations will be as effectively controlled by site specific weed management as conventional broadcast applications:

1. Site-specific applications are as effective as broadcast applications in terms of weed control.
2. Crop yield is not decreased when using site-specific herbicide applications as compared to broadcast applications.
3. The average area sprayed can be reduced as much as 30% in site-specific application and as much as 59% in a combination site-specific and broadcast application.

Hypothesis 2: Patch Stability

This research project intensively monitored weed patch dynamics on a tight 6 x 6 m sampling grid over the two years of the study. The effects of site-specific weed management on patch dynamics will be crucial to the usefulness of weed maps in future seasons. No other study has addressed the issue of patch stability under site-specific herbicide applications. Although more years of research are warranted for strong conclusions to be made, this research is a solid step in the right direction. The following conclusions were reached based on the hypothesis that weed patches in the test area will remain stable in location from year to year:

1. Weed patch stability overtime is weed specific: *E. arvense* is very stable, *S. asper* is somewhat stable and *C. album* is not stable.

Hypothesis 3: Accuracy and Error

It is important to recognise that site-specific applications are in their infancy and techniques for obtaining weed maps and developing prescription maps will change in the future. Methods that were used in this research project could be considered time consuming, labour intensive and perhaps a little crude; yet, with the resources available to us at the time, these methods provided the most reliable results. Accuracy and occurrence of errors are rarely reported on in research on site-specific applications. Techniques used in this project were not only critiqued for accuracy, as in the case of weed maps, but errors of over-application and under-application resulting from the prescription maps used were quantified. This type of collected information can greatly enhance and improve research on site-specific weed management in the future. As well, it can increase the accuracy of modelling the cost effectiveness of site-specific applications. The following conclusions were reached based on the hypothesis that site-specific applications, which utilise a prescription map approach, will be accurate and error free:

1. Weed contour maps developed using kriging based on a 6m sampling grid pattern are accurate.
2. Sampling on a 12 m or 24 m grid would not have provided accurate weed contour maps.
3. Low levels of over-application and under-application do occur using the prescription map approach based on decision units as outlined in Chapter 1.

Overall, my research project has answered some of the fundamental questions about site-specific weed management that had previously not been answered. Of course, as with any research project, many new questions have become evident and investigation of these questions will further bring site-specific applications closer to commercial use.

Limitations

Having only one field site limits the projected implications of this site-specific weed management experiment to a seven year no-till corn – soybean rotational field which contains *E. arvense, S. asper, C. album and T. officinale*. Multiple field sites would have allowed the results to be applied to different cropping systems, different weed species or other geographical areas.

As for actual research methodology, plot size was more than adequate for the objectives of the study and accurate characterisation of spatial dependency of all the weed species, with perhaps the exception of *C. album*, was accomplished. Although, the analysis of *C. album* weed contour maps indicated that interpolated weed maps were very accurate, closer investigation of the semivariogram parameters showed that 61% of the variance was due to random effects. Perhaps a smaller grid sample size could have been used to better characterise the *C. album* semivariogram.

The site-specific applications carried out in this project were under tremendous time constraints. Weed counts had to be completed within a few days prior to application so that accurate weed maps could be created for the development of prescription maps for the application. The application itself took over eight hours and therefore had to be completed over night. Spray conditions at 5:00 pm would often differ from spray conditions at 4:00 am. While spraying was discontinued when winds were causing drift, effects of temperature and relative humidity could not be controlled. Applications over a shorter time span could have allowed for more uniform application conditions.

Yield data collected was limited to comparisons within the experimental area within each year. Harvest equipment was accurate relative to each plot but the combine was not calibrated, so yields can not be compared to other fields. Strips were harvested through the middle of each plot lengthways for the full 85 m (except 2 m buffer zone at each end). Because site-specific applications varied within each plot it would have been ideal to harvest the entire plot. Unfortunately because of plot size (24 x 85 m), harvesting the entire plot was not possible.

Future Research and Recommendations

As with any research project, knowledge that you acquire throughout the study would have been very useful at the beginning of the project. Geostatistics is a very new tool available to weed science and prior knowledge of this very interesting and powerful statistical technique would have been very useful. Although the first year of the field study was successfully completed and weed contour maps proved to be more than adequately accurate for our purposes, these results could have just as easily turned the other way. I would recommend that in future research endeavours involving geostatistical weed mapping, an expert in the area of geostatistics should be included in the team for guidance.

The greatest reduction in the average area sprayed for the site-specific treatment over the two years was 26% in 1998. If a grower has to pay technology costs as well as assume the risk of not applying herbicide over the whole field, a 30% reduction may not seem worth the hassle. Hopefully, reductions as high as 59% seen in the treatment that combined site-specific and broadcast would be well worthwhile. Economic analysis for site-specific systems that could be used in Ontario are needed. The combination site-specific/broadcast treatments showed the greatest reduction in injected herbicide. This option of a combination application offers weed managers a lower risk alternative to leaving some areas of their fields totally untreated. Another type of combination application that was not part of this experiment that might be successful would be a broadcast pre-emergence application combined with a site-specific post-emergence application. The site-specific post-emergence application could target escapes or hard to control weed patches. These types of combination applications may be more realistic options for reducing herbicide inputs on conventional tilled farms. Conventional tilled fields tend to have more annual weeds, and it has been suggested that annuals tend to be less patchy in nature. A site-specific application could target those weeds that are patchy or have escaped after initial weed control. Site-specific applications are going to be field specific. Some fields lend themselves better to spatially variable herbicide applications than others. In a practical sense, the decision whether to use site-specific herbicide applications will be dependent on the fields weed distribution. Approaching weed management with site-specific herbicide applications as a tool rather than the only approach may be the best use of precision technology. In the future, I would recommend that weed management uses all the information available on field attributes and characteristics in order to develop a weed management plan that optimises herbicide use. Using site-specific weed management as one of the many tools available to the weed manager may be the best use of precision technology.

So far, information on the spatial distribution of weeds has been very limited and the contributions of this research is only a small part of a much bigger picture. We need to know what influences weed patch dynamics. It would be naive to assume that understanding weed patch dynamics is not important because eventually grid sampling for weed maps will be obsolete or patch spraying will be fully automated. History has shown us that manipulating something that is not fully understood may lead to unfavourable outcomes. Understanding weed patch dynamics could help predict where new weed patches will be created and what factors cause them to change over time. Abiotic, biotic and anthropogenic factors all influence patch dynamics, yet our ecological understanding of these influences are minimal.

An ecological approach is needed when looking at weeds in a field setting. The field could be thought of as a metapopulation of local populations or patches that interact, with individuals moving among the local populations. Some patches would be considered sources where individuals would originate from and these source patches would be relatively stable and supply a constant flow of new individuals. Hypothetically a source patch would have optimal growing conditions and the natality rate would be larger than the mortality rate, thus allowing for a high emigration rate. Other patches would be considered sinks, where surrounding environmental conditions are not ideal and survivorship of individuals would not be as great as in the source patches. In a sink patch, mortality would exceed natality and patch persistence would rely on immigration from other source patches. Closer examination of natality, mortality, immigration and emigration rates for individual patches could help distinguish between source and sink patches. Plant processes such as seed dormancy, restricted dispersal and spatial structure are important aspects to include when considering a metapopulation perspective. Questions of density dependent mortality are also important to consider with respect to the mortality of weeds. It has been hypothesised that density dependent mortality, if it occurs, could alter the way in which weed patches are targeted, such that areas of higher density would be targeted more vigorously than areas with lower densities. Field studies aimed at acquiring layers of data for a field area could help develop our understanding of these influences. Once data from all aspects of a field are entered into a GIS program then associations and influences can be teased out. If this intensive data collection occurred over several years the influence of weather may also be isolated and identified. The sporadic emergence of *C. album* between years might be better explained if an intensive experiment like this was initiated.

Another issue relating to research of weed spatial dynamics is methods of quantification. Too many studies are relying on visual assessments to define weed patchiness and weed patch stability. Numerical quantification of patchiness and stability must be introduced if information is to be compared between researchers. Percent area infested compared between years may or may not accurately indicate patch stability. As well, weed maps are often presented to support research, but the accuracy of these weed maps are may influence how the data is interpreted. For example weed maps developed on very large sampling grids may provide false information, yet unless the accuracy of the maps is indicated, results may be taken more seriously than they should. All future research pertaining to weed maps should have a standard measure of error similar to an r –value or perhaps a CV when using an ANOVA.

The entire premise of site-specific weed management is based on the fact that weeds are patchy and that herbicide applications can be targeted to utilise weed spatial distribution. Historically, weed research has ignored weed spatial heterogeneity and subsequently estimates for weed parameters used in models are all based on a uniform distribution. Yet, some areas of the field are at a low enough density that the weed population that is present will not significantly impact yield. Yield loss tends to be over-estimated when based on a uniform or homogeneous weed distribution and economic threshold values are based on these yield loss estimates. Spatial variability needs to be included in the development of economic thresholds if they are to be used in the decision criterion for patch spraying. As well, multi-species associations with respect to yield loss also need to be addressed. Rarely, do you find a field that has one single species present.

Literature Cited

Andreasen, C., J. C. Streibig, and H. Haas. 1991. Soil properties affecting the distribution of 37 weed species in Danish fields. Weed Research. 31:181-187.

Bennett, K. A. 1997. Development of a Herbicide Direct Injection System for Precision Farming. M.Sc. Thesis, University of Guelph, Guelph, Ontario. 37, 42pp.

Bennett, K. A. and R. B. Brown. 1999. Field Evaluation of a site specific direct injection herbicide sprayer. Presented at 1999 ASAE Annual International Meeting, Paper No. 99-1102. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659 USA.

Brown, L. R. 1981. World population growth, soil erosion, and food security. Science. 214:995-1001

Brown, R. B. and J. P. G. A. Steckler. 1995. Prescription maps for spatially variable herbicide application in no-till corn. American Society of Agricultural Engineers. 38(6):1659-1666.

Buhler, D. D., T. C. Mester, and K. A. Kohler. 1996. The effect of maize residues on emergence of *Setaria faberii, Abutilon theophrasti, Amaranthus retroflexus* and *Chenopodium album*. Weed Research. 36:153-165.

Cardina, J., D.H. Sparrow, and E. L. McCoy. 1995. Analysis of spatial distribution of common lambsquarters (*Chenopodium album*) in no-till soybeans (*Glycine max*). Weed Science. 43:258-268.

Cardina, J., D. H. Sparrow, and E. L. Mc Coy. 1996. Spatial relationships between seedbank and seedling populations of common lambs-quarters (*Chenopodium album*) and annual grasses. Weed Science. 44:298-308.

Cardina, J., D.H. Sparrow, and G.A. Johnson. 1997. The nature and consequence of weed spatial distribution. Weed Science. 45:364-373.

Christensen, S., T. Heisel, and A. M. Walter. 1996. Patch spraying in cereals. Pages 963-968 *in* Proc. Second International Weed Control Congress, Copenhagen, Denmark.

Christensen, S., A. M. Walter, and T. Heisel. 1999. The patch treatment of weeds in cereals. Pages 591-600 *in* Proc.,Brighton Crop Protection Conference – Weeds, Surrey, UK.

Cousens, R. D. and J. L. Woolcock. 1997. Spatial dynamics of weeds: an overview. Pages 613-618 *in* Proc.,Brighton Crop Protection Conference – Weeds, Surrey, UK.

Dessaint, F., R. Chadoeuf, and G. Barralis. 1991. Spatial pattern analysis of weed seeds in the cultivated soil seed bank. Journal of Applied Ecology. 28:721-730.

Dieleman, J. A. 1998. Spatial Biology of Weed Populations: Influence of Abiotic, Biotic and Anthropogenic Processes. Ph D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA.

Dieleman, J. A., M. M. Milner, J. Groeteke, D. A. Mortensen, and M. M. Williams II. (2000) How good is your weed map? A comparison of spatial interpolators. Weed Science (submitted)

Dieleman, J. A., D. A. Mortensen, A. R. Martin, and D. Y. Wyse-Pester. 1999. Influence of velvetleaf (*Abutilon theophrasti*) and common sunflower (*Helianthus annuus*) density variation on weed management outcomes. Weed Science. 47:81-89.

Donald, W.W. 1994. Geostatistics for mapping weeds, with a Canada thistle (*Cirsium arvense*) patch as a case study. Weed Science. 42:648-657.

Faechner, T. L. M. Hall, and R. MacMillan. 2000. Landscape influence on wild oat (*Avena fatua*) distribution. WSSA Abstracts: 2000 Meeting of the Weed Science Society of America. 40:101.

Feyaerts, F., P. Pollet, L. Van Gool, and P. Wambacq. 1999. Vision system for weed detection using hyper-spectral imaging, structural field information and unsupervised training sample collection. Pages 607 – 614 *in* Proc., Brighton Crop Protection Conference – Weeds, Surrey UK.

Francis, C. A., and G. Younberg. 1990. Sustainable agriculture - an overview. Pages 1-23 *in* Sustainable Agriculture in Temperature Zones. John Wiley and Sons, NY.

Gallichand, J., G. D. Buckland, D. Marcotte, and M. J. Hendry. 1992. Spatial interpolation of soil salinity and sodicity for a saline soil in Southern Alberta. Canadian Journal of Soil Science. 72:503-516.

Gerhards, R., D. Y. Wyse-Pester, D. A. Mortensen, and G. A. Johnson. 1997a. Characterising spatial stability of weed populations using interpolated maps. Weed Science. 45:108-119.

Gerhards, R., M. Sökefeld, K. Schulze-Lohne, D. A. Mortensen, and W. Kühbauch. 1997b. Site specific weed control in winter wheat. Journal of Agronomy and Crop Science. 178:219-225.

Gotway, C. A., R. B. Ferguson, G. W. Hergert, and T. A. Peterson. 1996. Comparison of kriging and inverse-distance methods for mapping soil parameters. Soil Science Society of America Journal. 60:1237-1247.

Goudy, H. J., R. B. Brown, K. A. Bennett, and F. J. Tardif. 1999. Evaluating site-specific weed control in a maize-soybean rotation system. Pages 621-626 *in* Proc. Brighton Crop Protection Conference – Weeds, Surrey, UK.

Heisel, T., C. Andreasen and A. K. Ersbøll. 1996. Annual weed distributions can be mapped with krigging. Weed Research 36:325-337.

Heisel, T., S. Christensen, and M. Walter. 1997. Weed managing model for patch spraying in cereals. Proceedings of the 3rd International Conference on Precision Agriculture (eds. Robert P.C., Rust R.H. and W.E. Larson). Minneapolis, MN. USA., 999-1007.

Isaaks, E. H., and R. M. Srivastava. 1989. An Introduction to Applied Geostatistics. Oxford University Press, New York, NY.

Johnson, G. A., D. A. Mortensen, and A. R. Martin. 1995. A simulation of herbicide use based on weed spatial distribution. Weed Research. 44:704-710.

Johnson, G. A., D. A. Mortensen, and C. A. Gotway. 1996a. Spatial and temporal ananlysis of weed seedling populations using geostatisics. Weed Science. 44:704-710.

Johnson, G. A., D. A. Mortensen, L. J. Young, and A. R. Martin. 1996b. Parametric sequential sampling based on multistage estimation of the negative binomial parameter *k*. Weed Science. 44:555-559.

Krebs, C. J. 1994. Ecology: The Experimental Analysis of Distribution and Abundance. Harper Collins College Publishers, New York, NY. 151 p.

Legendre, P. 1993. Spatial autocorrelation: trouble of new paradigm. Ecology.74:1659-1673.

Levin, S.A. 1992. the problem of pattern and scale in ecology. Ecology 73: 1943-1967.

Lindquist, J. L., A. J. Dieleman, D. A. Mortensen. G. A. Johnson and D. Y. Wyse-Pester. 1998. Economic importance of managing spatially heterogeneous weed populations. Weed Technology. 12:7-13.

Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. SAS system for mixed models. SAS Institute Inc., Cary NC, USA. 171-228 pp.

Lutman, P. J. W. and L. J. Rew. 1997. Spatially selective weed control in arable crops – where are we now? Pages 637 – 640 *in* Proc., Brighton Crop Protection Conference – Weeds, Surrey UK.

Lutman, P. J. W. and N. H. Perry. 1999. Methods of weed patch detection in cereal crops. Pages 627 – 634 *in* Proc., Brighton Crop Protection Conference – Weeds, Surrey UK.

Marshall, G. 1986. Growth and development of field horsetail (*Equisetum arvense* L.). Weed Science. 34:271-275.

Marshall E. J. P. 1988. Field-scale estimates of grass weed populations in arable land. Weed Research. 28:191-198.

McCanny, S. J. and P. B. Cavers. 1988. Spread of proso millet (*Panicum miliaceum* L.) in Ontario, Canada. II. Dispersal by combines. Weed Research. 28:67-72.

Miller, P. C. H., J. V. Stafford and M. E. R. Paice. 1995. The patch spraying of herbicides in arable crops. Pages 1077-1086 *in* Proc., Brighton Crop Protection Conference – Weeds, Surrey UK.

Miller, P. C. H. and M. E .R. Paice. 1997. Methods of controlling sprayer output for spatially variable herbicide applications. Pages 641-644 *in* Proc., Brighton Crop Protection Conference – Weeds, Surrey UK.

Mortensen D. A. and J. A. Dieleman. 1995. Managing spatially variable weed populations. Pages 397-415 *in* Site-Specific Management for Agricultural Systems, ASA-CSSA-SSSA Publication, Minnesota, US.

Mortensen, D. A. and J. A. Dieleman. 1997. Why weed patches persist: dynamics of edges and density. Pages 14 – 19 *in* R. W. Medd and Pratley J.E., eds. Proc., Precision Weed Management in Crops and Pasture. Wagga Wagga, Australia.

Mortensen, D. A., J. A. Dieleman and G. A. Johnson. 1998. Weed spatial variation and weed management. Pages 293-306 *in* J. L. Hatfield, D. D. Buhler and B. A. Stewart, eds. Integrated Weed and Soil Management. Michigan: Ann Arbor Press.

Mortensen, D. A., J. A. Dieleman, and M. M. Williams II. 2000. Weed population assessment using remote sensing: what do we need to see? Soil Science Society of America Journal (*in press*).

National Research Council, 1991. Defining the Need, in Towards Sustainability. National Academy Press, Washington D.C.

[OMAFRA] Ontario Ministry of Agriculture Food and Rural Affairs. 1992. Ontario Weeds: Publication 505. Toronto, Ontario: Ontario Ministry of Agriculture Consumer information Centre. 248p.

Paice, M. E. R., P. C. H. Miller, P. C. H. Bodle. 1995. An experimental sprayer for the spatially selective application of herbicides. Journal of Agricultural Engineering Research. 60:107-116.

Pannell, D. J. and A. L. Bennett. 1999. Economic feasibility of precieion weed management: is it worth the investment? *in* R. W. Medd and Pratley J.E., eds.Proc., Precision Weed Management in Crops and Pasture. Wagga Wagga, Australia. (*in press*)

Regnier, E. E., and R. R. Janke. 1990. Evolving strategies for managing weeds. Pages 174-202 *in* C.A. Edwards. R. Lal. P. Madded. R.H. Miller, and G. House, eds. Sustainable Agricultural Systems. Soil and Water Conservation Society, Ankeny, IA.

Rew, J. L., G. W. Cussans, M. A. Mugglestone and P. C. H. Miller. 1996. A technique for mapping the spatial distribution of *Elymus repens*, with estimates of the potential reduction in herbicide usage from patch spraying. Weed Research. 36:283-292.

Rew, J. L., G. W. Cussans. 1997. Horizontal movement of seeds following tine and plough cultivation: implications for spatial dynamics of weed infestations. Weed Research. 37:247-256.

Roman, E. S., S. D. Murphy, and C. J. Swanton. 1999. Effect of tillage on *Zea mays* on *Chenopodium album* seedling emergence and density. Weed Science. 47:551-556.

Rossi, R. E., D.J. Mulla, A. G. Journel, E. H. Franz. 1992. Geostatistical tools for modeling and interpreting ecological spatial dependence. Ecological Monographs. 62:277-342.

Ruckelshausen, A., T. Dzinaj, F. Gelze, S. Kleine-Horsetkamp, A. Linz, J. Marquering. 1999. Microcontroller-based multi-sensor system for online crop/weed detection. Pages 601 – 606 *in* Proc., Brighton Crop Protection Conference – Weeds, Surrey UK.

Shaw, W. C. 1982. Integrated weed management systems technology for pest management. Weed Science. 30(suppl. 1):2-12.

Smith, M. C., D. R. Shaw, F. L. Lamastus, and B. Henry. 2000. How species and population densities influence spectral reflectance and detection capabilities. WSSA Abstracts: 2000 Meeting of the Weed Science Society of America. 40:103

Stafford J.V., and P. C. H. Miller. 1996. Spatially variable treatment of weed patches. Pages 465-473 *in* P. C. Roberts, R. H. Rust, and W. E. Larson, eds. Precision Agriculture. ASA, CSSA, SSSA, Madison, Wisconsin.

Swanson, J. A. and D. C. Dahl. 1989. The U.S. pesticide industry: usage and trends and market development. Staff Paper. Department of Agricultural Economics, University of Minnesota, St. Paul. pp. 89-5

Swanton C. J. and S. F. Weise. 1991. Integrated weed management: the rationale and approach. Weed Technology. 5:657-663.

Swanton, C. J., D. R. Clements, and D. A. Derksen. 1993. Weed succession under conservation tillage: hierarchical framework for research and management. Weed Technology. 7:286-297.

Thomas, A. G., J. Y. Leeson, B. L. Frick, S. A. Brandt, D. A. Derksen, A. P. Moulin, and F. Selles. 2000. Are weed distributions prior to initiation of experimental treatments important? WSSA Abstracts: 2000 Meeting of the Weed Science Society of America. 40:103

Walker, R.H., and G.A. Buchanan. 1982. Crop manipulation in integrated weed management systems. Weed Science. 30(suppl. 1):17-24.

Wallinga, J. 1995. A closer look at the spatial distribution of weeds – perspectives for patch spraying. Pages 647-653 *in* Challenges for Weed Science in a Changing Europe: Proc. 9th European Weed Research Society Symposium. Budapest, Hungary.

Walter, A. M. 1996. Temporal and spatial stability of weeds. Proceeding of the Second International Weed Control Congress, 125-130.

Wiles, L. J., G. W. Oliver, A. C. York, H. J. Gold, and G. G. Wilkerson. 1992. Spatial distribution of broadleaf weeds in North Carolina soybean (*Glycine max.*) fields. Weed Science. 40:554-557.

Williams, L., D. J. Schotzko, and J. P. McCaffery. 1992. Geostatistical description of the spatial distribution of *Limonius californicus* wireworms in the northwestern united states, with comments on sampling. Environmental Entomology. 21:983-995.

Williams, M. M. II, R. Gerhards, S. Reichart and D. A. Mortensen. 1998. Weed seedling population responses to a method of site-specific weed management. *in* Proc. of the Fourth International Conference on Precision Agriculture, Madison, Wisconsin, USA, ASA-CSA-SSA.

Williams, M. M. II, R. Gerhards, and D. A. Mortensen. 1999. Spatiotemporal outcomes of site-specific weed management on maize. Pages 897 – 906 *in* J. V. Stafford, ed. 2nd European Conference on Precision Agriculture, Odense, Denmark. SCI Publishers, UK.

Wilson, B. J. and P. Brain. 1991. Long-term stability of distribution of *Alopecurus myosuroides* Huds. within cereal fields. Weed Research. 31: 367-373.

Zanin, G., A. Berti and L. Riello. 1998. Incorporation of weed spatial variability in the weed control decision-making process. Weed Research. 38:107-118.

Zimdahl, R.L., 1993. Fundamentals of Weed Science. Academic Press, Inc., San Diego, California.

Appendix A.

The following series of maps are from the field site studied in Woodstock Ontario. In each map distance on the x and y axis are in meters.

Figure A-1. Spatial arrangement of the sampling points (6 x 6 m) at which weed identification and counts were conducted within a 1 m^2 quadrat.

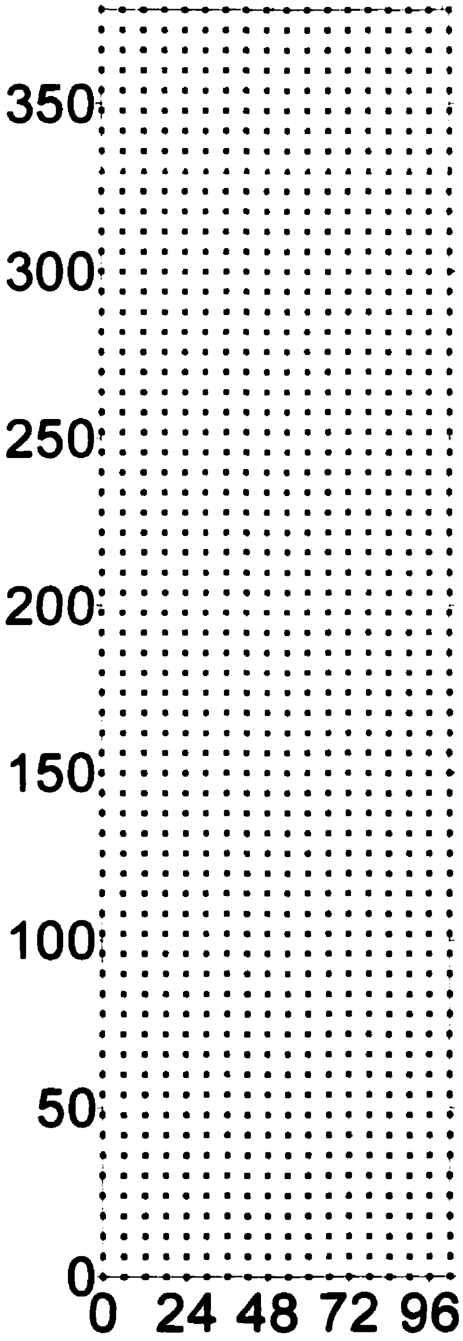

350
300
250
200
150
100
50
0
0
24
48
72
96

Figure A-2. Management units: overlay of weed contour maps for a) *T. officinale*, b) *S. asper*, and c) *E. arvense* from the 1105 sampling points in 1998 with the 3 x 5 m decision unit grid. Density scale in number of shoots m^{-2}.

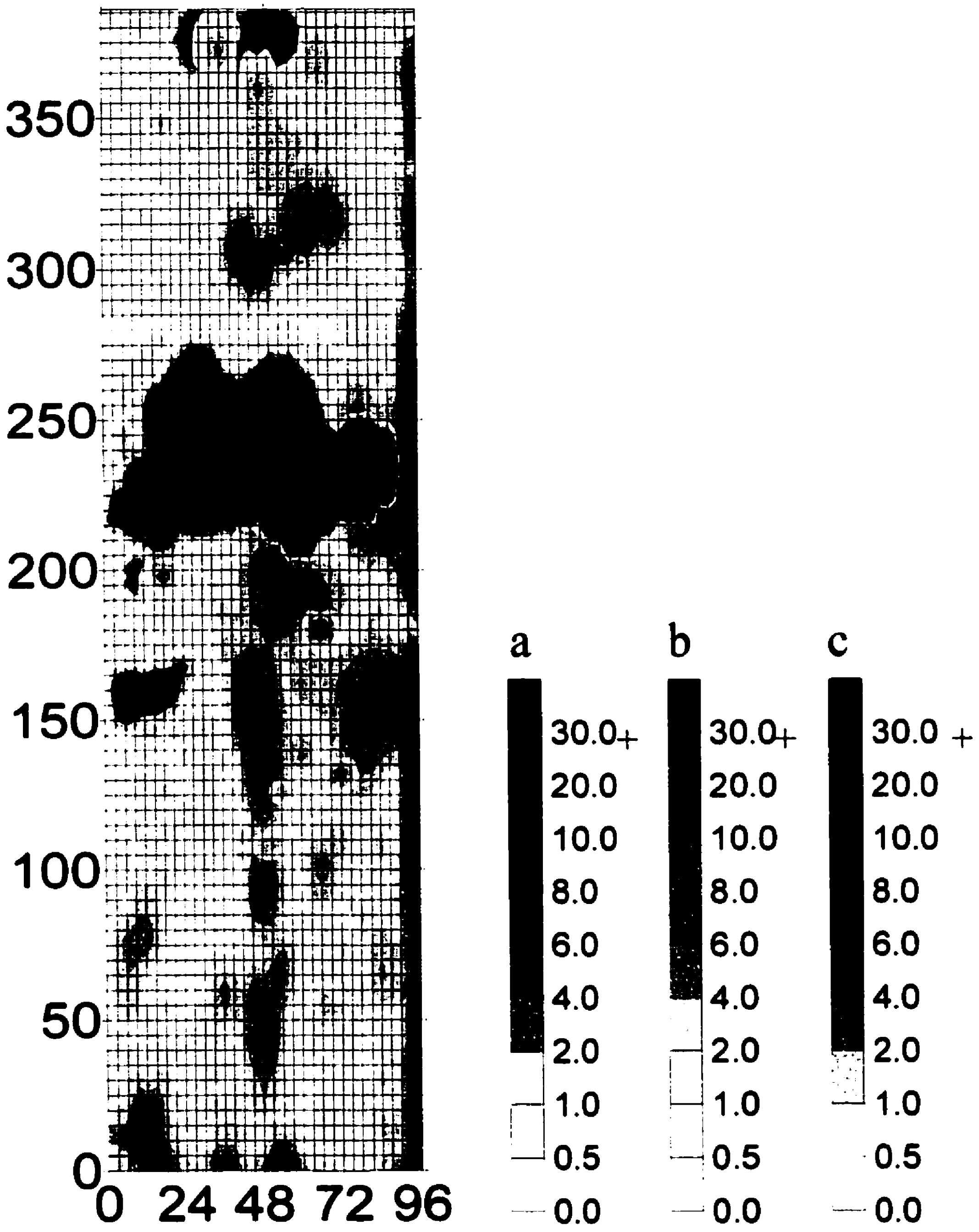
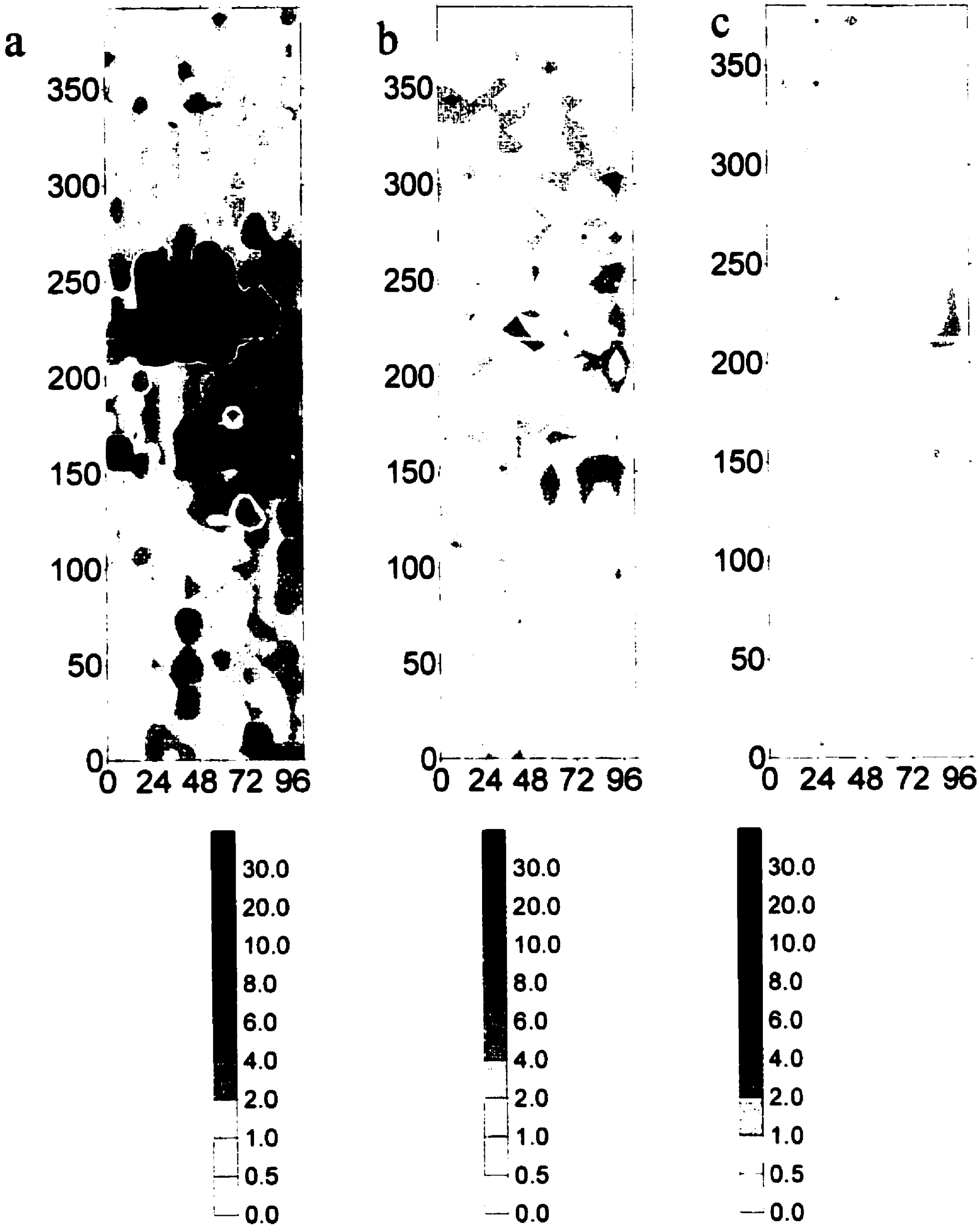

350
300
250
200
150
100
50
0
0
24
48
72
96
a
b
c
30.0+
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0
30.0+
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0
30.0 +
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0

Figure A-3. Maps showing change in weed maps over time after treatments. Overlay of weed contour maps for *E. arvense*, *S. asper*, and *T. officinale* from the 1105 sampling points in 1998 at a) initial count, 3-4 days prior to treatment application, b) 2 weeks after treatment application, c) 4 weeks after treatment application. Density scale in number of shoots m^{-2}.



E. arvense *S. asper* *T. officinale*

Figure A-4. Maps showing change in weed maps over time after treatments. Overlay of weed contour maps for *E. arvense*, *S. asper*, and *C. album* from the 1105 sampling points in 1999 at a) initial count, 3 - 4 days prior to treatment application, b) 3 - 4 weeks after treatment application. Density scale in number of shoots m^{-2}.

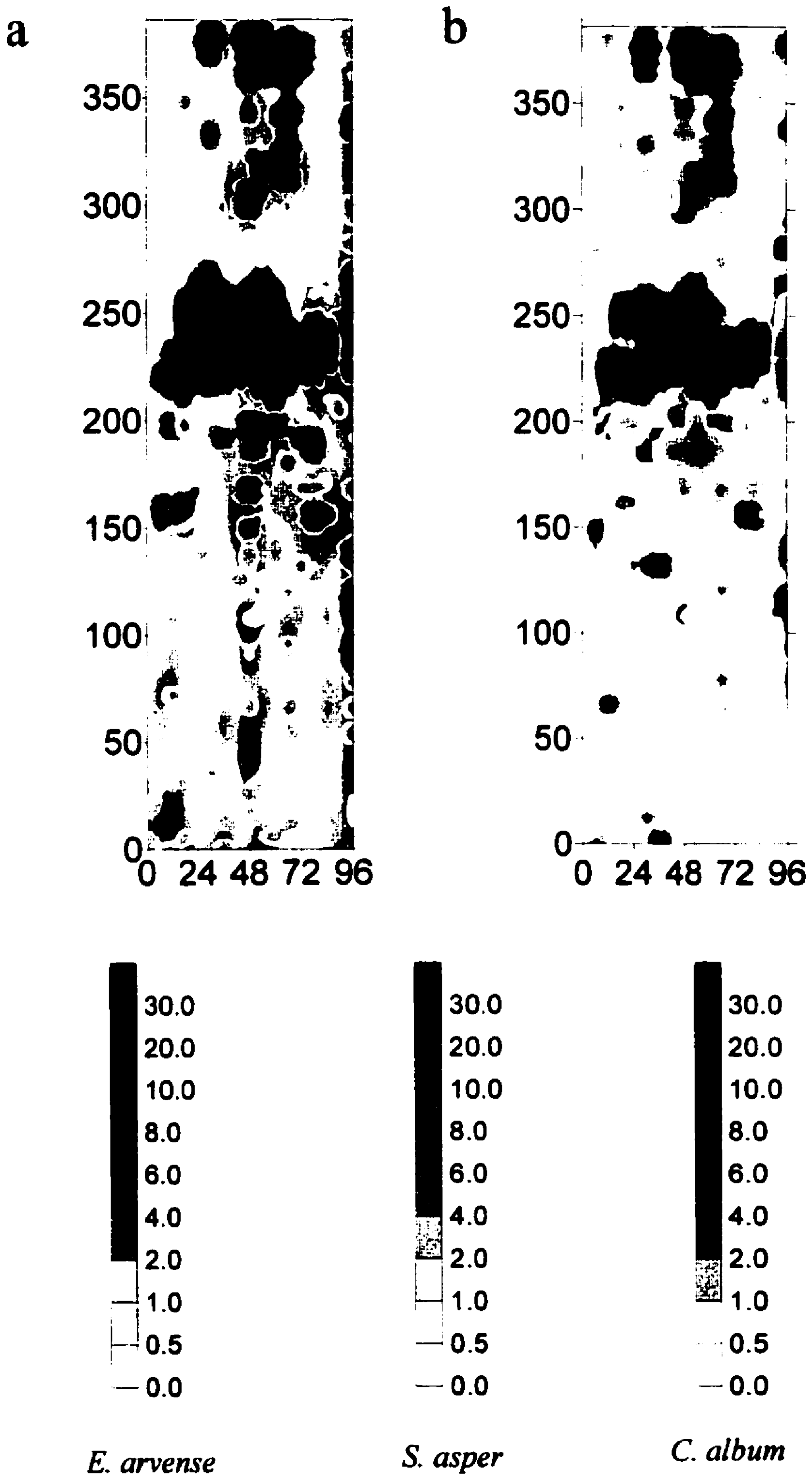
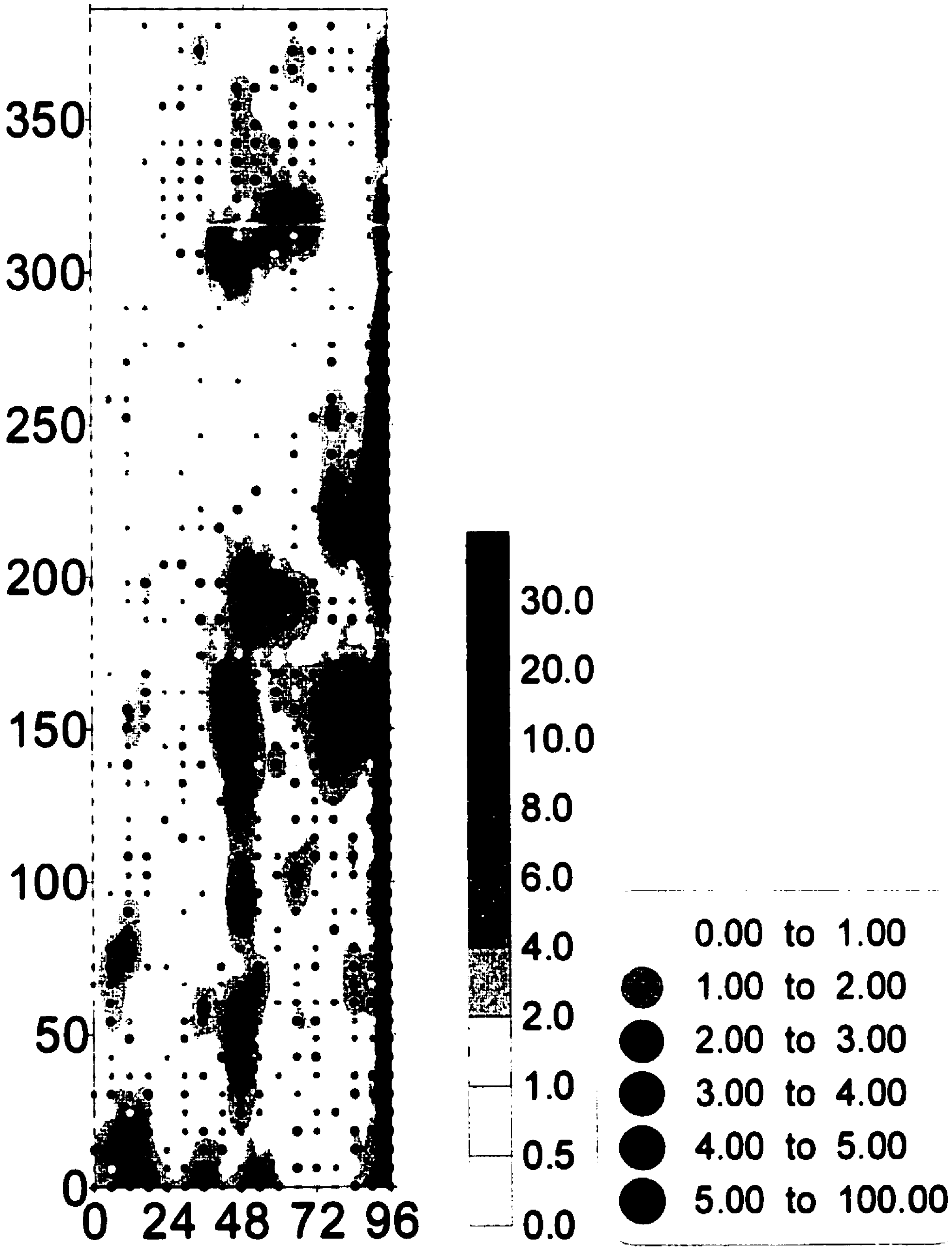

a
b
0
50
100
150
200
250
300
350
0 24 48 72 96
30.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0
E. arvense
S. asper
C. album

Figure A-5. Overlay map of *S. asper* weed contour maps from the 1105 sampling points in 1999 with the actual weed counts at the 6 x 6 m sampling grid from weed counts conducted 3-4 days prior to treatment. Density scale in number of shoots m^{-2}.



350
300
250
200
150
100
50
0
0
24
48
72
96
30.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.5
0.0
0.00 to 1.00
1.00 to 2.00
2.00 to 3.00
3.00 to 4.00
4.00 to 5.00
5.00 to 100.00

Appendix B

Adjustment of Threshold Parameter

The entire experimental area was assessed assuming that a site-specific treatment was to be applied. As the threshold parameter was adjusted in the decision algorithm, the resulting prescription map simulated the changes in area that would have been treated across the entire experimental area. Threshold values were set at 0.5, 1.0, 1.5, and 2.0 shoots m^{-2}. The area sprayed was calculated as a percent of the total experimental area.

Implications of Threshold Levels

Site-specific applications are based on weed density thresholds to assess what areas of the field that require application. Accurate information about weed location and density are crucial to optimising herbicide reductions. Apart from accurate weed maps, criteria for making decisions where to spray are also important to maximising potential benefits of site-specific herbicide applications. In a Chapter 1, we chose a threshold of 1 shoot m^{-2} to decide what decision units required treatment. If a threshold of 0.5 shoots m^{-2} had been used over the entire experimental area, 82.7% of the field would have required treatment. Using the 3 x 5 m decision units to develop prescription maps would have resulted in 89.7% of the field receiving herbicide treatment. As the threshold value increased to 1.0, 1.5, and 2.0 shoots m^{-2}, the area of the field above threshold decreased to 70.3%, 60.0% and 52.4%, respectively, while area targeted for application would have decreased to 75.5%, 65.8% and 58.1%, respectively. Johnson et al. (1995) found similar results as threshold was increased from 0 shoots m^{-2} to 3 shoots m^{-2}. It is important to recognized that there is no threshold data available for species such as *E. arvense, S. asper* and *T. officinale*. Obviously, accurate information about thresholds for more weed species as well as multi-species situations in aggregated populations are needed to make better decisions about where to spray.