INTERACTION OF WEED EMERGENCE, WEED DENSITY, AND HERBICIDE RATE IN SOYBEAN

by

AIFHELI MESHACK NDOU

B. Agric., University of Venda, South Africa, 1997
M. Inst. Agrar., University of Pretoria, South Africa, 2001

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2009

Abstract

Challenges in weed management include occurrence of multiple weed species in the field, variable emergence among weed species, different spatial distribution and weed densities, which leads to the persistence of weed patches. The overall objective of this research was to understand the interaction of weed emergence, weed density, herbicide choice, and herbicide rate in soybean. Specific objectives were 1) to characterize the seedbank and emergence patterns of shattercane (*Sorghum bicolor* L.), prickly sida (*Sida spinosa* L.), and ivyleaf morningglory (*Ipomoea hederacea* Jacq.) including initial, peak, end, and duration of emergence in response to crop and herbicide treatments in soybean, and 2) to evaluate large crabgrass (*Digitaria sanguinalis* L.), shattercane, Palmer amaranth (*Amaranthus palmeri* S.), and velvetleaf (*Abutilon theophrasti* Medik.) mortality and dry weight reduction in response to herbicide rates across varying weed densities as well as to determine the influence of velvetleaf growth stage and density on herbicide efficacy. In the emergence study of 2006 to 2008, four treatments were no-crop, no-residual herbicide, half-rate of residual herbicide and full-rate of residual herbicide. Reduction in weed emergence was observed over the years in the same species patch. Species emerged in mid-May in both years, coinciding with soybean planting. Extended emergence was observed for shattercane when moisture was low and temperature high, while for prickly sida and ivyleaf morningglory, extended emergence was observed when moisture was high and temperature low. Applying residual herbicide decreased weed emergence. Herbicide choice was the whole plot, herbicide rates were subplots and weed densities were sub-subplots in field experiments conducted in 2006 and 2007. Shattercane was more susceptible to both glyphosate and clethodim than large crabgrass. Increasing large crabgrass density reduced percent mortality with clethodim, while with glyphosate, density did not affect both species mortality. Shattercane dry weight was reduced to 0 g per plot with 0.1X labeled rate of clethodim or glyphosate while 0.5X of the labeled rate reduced dry weight of large crabgrass to 0 g per plot. For broadleaf weeds, higher percent mortality was observed with glyphosate than with lactofen at high densities. Palmer amaranth was more susceptible than velvetleaf. Velvetleaf response was density dependent, such that increasing density did not increase dry weight. Velvetleaf growth

stage was of importance, as stage affected herbicide efficacy, with higher mortality achieved at the two-leaf stage than the four- and six-leaf stages. For glyphosate, 0.125X of labeled rate on velvetleaf density of 5 seedlings per pot achieved more than 90% mortality when applied at the two-leaf stage, but dropped to 60 and 50% mortality when applied at the four- and six-leaf stage, respectively. The trend was the same for velvetleaf at a density of 30 seedlings per pot, which had 80, 60, and 55% mortality for the two-, four-, and six-leaf stages, respectively. Weed managers and farmers have the opportunity to better select herbicide choice and rate based on weed species, weed emergence patterns, and weed density.

INTERACTION OF WEED EMERGENCE, WEED DENSITY, AND HERBICIDE RATE IN SOYBEAN

by

AIFHELI MESHACK NDOU

B. Agric., University of Venda, South Africa, 1997
M. Inst. Agrar., University of Pretoria, South Africa, 2001

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2009

Approved by:

Major Professor
J. Anita Dille

Abstract

Challenges in weed management include occurrence of multiple weed species in the field, variable emergence among weed species, different spatial distribution and weed densities, which leads to the persistence of weed patches. The overall objective of this research was to understand the interaction of weed emergence, weed density, herbicide choice, and herbicide rate in soybean. Specific objectives were 1) to characterize the seedbank and emergence patterns of shattercane (*Sorghum bicolor* L.), prickly sida (*Sida spinosa* L.), and ivyleaf morningglory (*Ipomoea hederacea* Jacq.) including initial, peak, end, and duration of emergence in response to crop and herbicide treatments in soybean, and 2) to evaluate large crabgrass (*Digitaria sanguinalis* L.), shattercane, Palmer amaranth (*Amaranthus palmeri* S.), and velvetleaf (*Abutilon theophrasti* Medik.) mortality and dry weight reduction in response to herbicide rates across varying weed densities as well as to determine the influence of velvetleaf growth stage and density on herbicide efficacy. In the emergence study of 2006 to 2008, four treatments were no-crop, no-residual herbicide, half-rate of residual herbicide and full-rate of residual herbicide. Reduction in weed emergence was observed over the years in the same species patch. Species emerged in mid-May in both years, coinciding with soybean planting. Extended emergence was observed for shattercane when moisture was low and temperature high, while for prickly sida and ivyleaf morningglory, extended emergence was observed when moisture was high and temperature low. Applying residual herbicide decreased weed emergence. Herbicide choice was the whole plot, herbicide rates were subplots and weed densities were sub-subplots in field experiments conducted in 2006 and 2007. Shattercane was more susceptible to both glyphosate and clethodim than large crabgrass. Increasing large crabgrass density reduced percent mortality with clethodim, while with glyphosate, density did not affect both species mortality. Shattercane dry weight was reduced to 0 g per plot with 0.1X labeled rate of clethodim or glyphosate while 0.5X of the labeled rate reduced dry weight of large crabgrass to 0 g per plot. For broadleaf weeds, higher percent mortality was observed with glyphosate than with lactofen at high densities. Palmer amaranth was more susceptible than velvetleaf. Velvetleaf response was density dependent, such that increasing density did not increase dry weight. Velvetleaf growth

stage was of importance, as stage affected herbicide efficacy, with higher mortality achieved at the two-leaf stage than the four- and six-leaf stages. For glyphosate, 0.125X of labeled rate on velvetleaf density of 5 seedlings per pot achieved more than 90% mortality when applied at the two-leaf stage, but dropped to 60 and 50% mortality when applied at the four- and six-leaf stage, respectively. The trend was the same for velvetleaf at a density of 30 seedlings per pot, which had 80, 60, and 55% mortality for the two-, four-, and six-leaf stages, respectively. Weed managers and farmers have the opportunity to better select herbicide choice and rate based on weed species, weed emergence patterns, and weed density.

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGEMENT

I would like to thank my major advisor, Dr. J. Anita Dille for providing guidance, motivation, and positive criticism during the course of the study. I would like to acknowledge Dr. Lori Wiles, Dr. Kevin Dhuyvetter, Dr. David Hartnett, and Dr. Dallas Peterson for serving on my graduate committee. I want to thank Dr. Dale Bremer for serving as the Graduate School Chairperson on my committee. I would like to thank Dr. Mary Beth Kirkham for reviewing my chapters. I want to thank Dr. Higgins and Dr. Murray for statistical assistance.

I would like to thank the Department of Agronomy staff and my fellow graduate students for the help during my studies, and the Cooperative State Research, Education, and Extension Service (CREES), U.S. Department of Agriculture (award No. 2005-34103-15482) for funding this research.

Special thanks to Dr. Dwain Rule, Dr. Jamie Duesterhaus, Dr. Chris Schuster, Analiza Ramirez, Dayna New, Ben Cornelius, Anna Berry, Brandy Valek, Bobby White, Valerie Meyer, Srivani Lokeni, and Ashland Bottoms Farm staff (Neil Wickstrum and Stan Rundquist), and Cathy Minihan for help with the field experiments. Thanks to all “the weed bunch” members for positive criticism before congresses and Departmental seminar presentations.

To the Agricultural Research Council (ARC) of South Africa I say thank you for granting me the study leave to achieve my dream and for supporting me during my time at Kansas State University.

I would like to thank Masala Ramovha, Dr. Stanley Liphadzi, Livhuwani Ngwekhulu, Thiambi Netshiluvhi, Julia Domola, Godwin Khorommbi, Engelina Munarini, Chris Moila, Dr. Roger Pambu, Solange Uwituze, Dr. Daba Gedafa and William Baloyi for your support, thank you for the phone calls and e-mails, you kept me going.

To Unarine, Mbofho, and Mulisa, thank you guys for your love and understanding throughout my studies. Special thanks to my mother Evelinah, sisters Kuvhanganani, Tshifhiwa, and Lettie, brothers Maanda and Jacob for your continuous support and love during this study. Above all, I thank God Almighty for through Him I can achieve great things.

DEDICATION

I would like to dedicate this work to my late elder brother, Nndifheleni Shadrack Ndou, who passed on in January 27, 2007 when I was busy with this study. I recognize his support, both financially and otherwise during my BS and MS days. He put aside a lot of things to support my studies. He will be missed. May his soul rest in peace.

CHAPTER 1 - Introduction

BACKGROUND

A major concern for crop producers has always been how to reduce the amount of inputs required for crop production while maintaining or improving yields (Lamastus-Stanford and Shaw 2004). Weeds cause yield losses, reduce quality of harvested products and at times harbor insect pests and diseases that could harm the crop. Agricultural fields tend to exhibit spatial heterogeneity in soil characteristics, nutrients, topography, and pest infestations (Mortensen et al. 1998). This heterogeneity in soil characteristics can lead to weeds growing in patches in the field. Christensen et al. (1999) defined a weed patch as a group of weed plants delimited in space by gaps devoid of weed plants. Occurrence of weed patches in agricultural fields has been well documented (Cousens and Woolcock, 1997; Goudy et al. 2001; Mortensen et al. 1998; Wiles et al. 1992). Site-specific weed control represents a strategy to reduce herbicide use (Nordmeyer 2006). Oriade et al. (1996) reported that the higher the patchiness of the weed distribution, the higher is the potential for savings.

Site-specific management (SSM) is the concept of doing the right thing, at the right place, at the right time (Bongiovanni and Lowenberg-DeBoer 2004). Lowenberg-DeBoer and Swinton (1997) defined SSM as the electronic monitoring and control applied to data collection, information processing and decision support for the temporal and spatial allocation of inputs for crop production. Precision agriculture includes all those agricultural production practices that use information technology either to tailor input use to achieve desired outcomes, or to monitor those outcomes (e.g. variable rate application, yield monitors, remote sensing) (Bongiovanni and Lowenberg-DeBoer 2004).

Herbicides were applied to 98% of soybean hectares in Kansas in 2002 (USDA 2005). Herbicides usually are applied to the entire field even though spraying might not be necessary in some places (Dammer et al. 1999). High weed control input costs, development of herbicide resistant weeds and environmental contamination by herbicides have created great concerns in relying on uniform application of full doses of herbicides (Buhler 1999; Prostko and Meade 1993). Corn yields were similar for the conventional and site-specific treatments (Tredaway-Ducar et al. 2003). Reduced use of herbicide can reduce water and soil contamination without decreasing crop yield while increasing farmers' income. Postemergence herbicides are applied after weed species have emerged and growers are able to assess the severity of weed infestation before weed control.

There exists the potential to apply herbicides specifically to weed patches as opposed to applying the herbicides across the entire field (Cardina et al. 1997). A study by Rider et al. (2006) has shown that intensive sampling of weed populations can be used to apply site-specific rates of postemergence herbicide successfully to field crops in Kansas to control multiple weed species. Targeting weed patches for site specific herbicide application can potentially save cost and time for farmers, reduce environmental herbicide effects (groundwater contamination, wildlife, aquatic life) and increases efficiency of weed control (Goudy et al. 2001; Johnson et al. 1995; Williams et al. 1999).

The site-specific management concept is as old as agriculture but mechanization of agriculture in the 20th century put pressure to treat large fields with uniform agronomic practices (Bongiovanni and Lowenberg-Deboer 2004). Site specific herbicide application only targets areas in the field that have weed patches at densities that would affect crop yield or quality (Streibig et al. 1989).

Herbicides are the most frequently detected group of pesticides in ground and surface water (Carter 2000). Johnson et al. (1997) demonstrated the potential for site-specific weed management for better environmental result, due to reductions in total herbicide application. Recommended herbicide rates are often higher than required for efficient weed control as rates are adjusted to reduce the risk of non-control under field environments (Jensen and Streibig, 1994). A herbicide rate that provides a 90% reduction in weed dry matter is termed a biologically effective rate (Knezevic et al. 1998).

A study by Mortensen et al. (1994) indicated that post emergence herbicide applications could be reduced by 71 and 94%, respectively, for broadleaf and grass weeds if herbicides were applied only to existing populations. Timmermann et al. (2003) reported that an average of 54% of the herbicide could be saved with site-specific weed management, resulting in a monetary saving of 42 €/ha in maize, 32 €/ha in winter wheat, 27€/ha in winter barley and 20 €/ha in sugar beet. Herbicide savings of 66 to 75% in site-specific weed control in barley were reported by Heisel et al. (1996). A 47% reduction in herbicide application in cereal grains was observed in Denmark (Christensen et al. 1999).

The most important aspect of site-specific weed management (SSWM) is to locate weed patches in the field. Christensen et al. (1999) successfully used tractor-mounted Differential Global Positioning System (DGPS) units to enable application systems to spray weed patches automatically in the field. Herbicides doses could be adjusted by using a computer-assisted sprayer (Paice et al. 1996). Bajwa and Tian (2001) detected weed patches in soybean with 4.5-m pixels but could not identify patch composition. Lass et al. (2002) successfully detected spotted knapweed (*Centaurea maculosa* Lam.) infestation through the use of hyperspectral sensor. Medlin et al. (2000) were able to identify some weeds in soybean fields with 1-m pixels late in the spraying season if there were more than 10 plants m^{-2}. Herbicide reductions due to the use of site-specific applications were in the range of 40 to 60% (Stafford and Miller 1997); Medlin and Shaw (2000) reduced the amount of applied herbicide in corn by 77 to 84%. Site-specific ecologically based weed management (SSEWM) draws upon spatial and developmental information to manage local ecosystem for reduced weed interference with valued crops (Swinton, 2005). A variable herbicide rate application based on the treatment maps generated by Antuniassi et al. (2004) could save up to 59% of herbicides for controlling weeds in railways.

Weed management decisions are complicated by the occurrence of multiple weed species across a field, emergence patterns that vary among weed species, varying spatial distribution of weeds, and varying weed densities that lead to the persistence of weed patches. Herbicide decisions are further complicated by the number of herbicide treatments available for crops such as corn, cotton, peanut, and soybean (Bennett et al. 2003). During the past 20 years, many decision models have been developed to assist growers and other weed managers in weed control decision-making for several crops.

Knowing when weed species are likely to emerge can aid in developing effective integrated weed management programs (Hilgenfeld et al. 2004). Integrated weed management combines the use of multiple weed control methods such as herbicide application, cultural practices, biological practices etc. Empirical and mechanistic models are two common types of models used for weed emergence prediction. Empirical models are generally less complex than mechanistic models. The most basic empirical model involves a thermal time measure such as soil growing degree days (Forcella et al. 2000). They also reported that temperature-based emergence models have become popular because soil temperature can serve as a good predictor for weed seedling emergence. Mechanistic models are physiologically based, simulating several biological plant processes such as seed dormancy, germination, and emergence, along with radicle and seed elongation (Forcella et al. 2000). Benech Arnold et al. (1990) developed a mechanistic weed emergence model that integrated seed dormancy, seed germination, and soil temperature for johnsongrass (*Sorghum halepense* L.). Another mechanistic weed emergence model that combined seed dormancy, light and temperature fluctuations, seed germination, seedling growth, and soil temperature was developed by Vleeshouwers (1997). Forcella et al. (2000) reported that both of these models were fairly accurate for predicting weed emergence, but they were complex and could be difficult to use. Users prefer the easy to use GDD models.

To assist weed managers in evaluating alternative strategies and tactics, computer programs have been developed. HADSS™ (Herbicide Application Decision Support System), Pocket HERB™, and WebHADSS™ which utilize field-specific information to estimate yield loss that may occur if no control methods are used, eliminate herbicide treatments that are inappropriate for the specified conditions, and to calculate expected yield loss after treatment and expected net return for each available herbicide treatment. Each program has a unique interactive interface that provides recommendations to three distinct kinds of usage: desktop usage (HADSS), internet usage (WebHADSS), and on-site usage (Pocket HERB) (Bennett et al. 2003). WeedSOFT® decision support system was developed and released in 1996 to help farmers and consultants in Nebraska with the selection of optimal weed management strategies (Neeser et al. 2004). Pl@ntInfo, a web-based decision support system developed by the Danish Institute of Agricultural Sciences (DIAS) and the Danish Agricultural Advisory Centre to provide a decision support system to farmers and their advisors, was launched in 1996 (Jensen et al. 2000). Wiles et al. (1996) developed the General Weed Management Model (GWM). It is a decision support system designed for evaluating soil-applied and post-emergence weed management options in row crops. A site-specific post emergence herbicide application decision algorithm was developed at K-State over the past four years (Rider 2004, Rider et al. 2006). In order to determine the profit maximizing herbicide rate to apply to each cell within a field, a series of equations was used to predict the yield for each cell given the weed species, density, and size observed. Looking at the number of decision making aids that have been developed in the past decade, it shows the importance of having decision-making tools to combat weeds. Developing computer decision aids is an expensive undertaking and a weed management decision aid that is not updated regularly to incorporate new information and to take advantage of computer hardware and software advances will rapidly become redundant (Bennett et al. 2003)

RESEARCH JUSTIFICATION

In agricultural fields, weeds germinate and emerge from seed in the soil. The seedbank is comprised of many weed species which have different emergence patterns (Cavers 1983; Forcella et al. 1992). Knowing when weed species are likely to emerge can aid in developing integrated weed management programs (Hilgenfeld et al. 2004). Herbicide decisions are complicated by the multispecies nature of weed complexes within field, and substantial differences in herbicide efficacies due to weed species, weed size, soil characteristics, and soil moisture conditions (Bennett et al. 2003).

Weed distribution is not uniform across a field. Weeds tend to be clumped in patches of high densities with areas of low density to no weeds (Wiles et al. 1992). Percent control, as a standard method of assessing herbicide efficacy, does not take into consideration the interaction between weed density and mortality. It can be predicted for foliar applied herbicides that increasing weed density could result in 'safe sites' for smaller individuals due to overlapping leaf canopies (Mortensen and Dieleman 1998). There is a need to understand weed species emergence and to match herbicide choice and rate to individual weed patches that vary in density.

OVERALL OBJECTIVE

The overall objective of this research project is to study the interaction of weed emergence, weed density, and herbicide choice and rate in soybean. Specific objectives are:

1. to characterize the seedbank and emergence patterns of shattercane (*Sorghum bicolor* L.), prickly sida (*Sida spinosa* L.), and ivyleaf morningglory (*Ipomoea hederacea* Jacq.) including initial time, peak, end, and duration of emergence in response to crop and residual herbicide treatments in Kansas soybean fields,
2. to evaluate the interaction of herbicide choice and rate based on weed species and density in field studies, and to evaluate the influence of velvetleaf growth stage and density on herbicide choice and rate in greenhouse studies.

REFERENCES

Antuniassi, U. R., E. D. Velini, and H. C. Nogueira. 2004. Soil and weed survey for spatially variable herbicide application on railways. Precision Agriculture 5:27-39.

Bajwa, S. G. and L. F. Tian. 2001. Aerial CIR remote sensing for weed density mapping is soybean field. Transaction of American Society of Agricultural Engineers 44:1965-1974.

Benech Arnold, R. L., C. M. Ghersa, R. A. Sanchez, and P. Insausti. 1990. A mathematical model to predict *Sorghum halepense* (L.) Pers. seedling emergence in relation to soil temperature. Weed Res. 30:91-99.

Bennett, A.C., A.J. Price, M.C. Sturgill, G.S. Buol and G.G. Wilkerson. 2003. HADSS™, Pocket HERB™, and WebHADSS™: Decision Aids for Field Crops. Weed Technol. 17:412-420.

Bongiovanni, R. and J. Lowenberg-Deboer. 2004. Precision agriculture and sustainability. Precision Agriculture 5:359-387.

Buhler, D. D. 1999. Expanding the context of weed management. New York: Haworth Press. 289p.

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

Carter, A.D. 2000. Herbicides movement in soils: Principles, pathways and processes. Weed Res. 40:113-122.

Cavers, P. B. 1983. Seed demography. Can. J. Bot. 61:3678-3590.

Christensen, S., A. M. Walter, and T. Heisel. 1999. The patch treatment of weeds in cereals. Pp 591-600. In: Proceedings of the Brighton Crop Protection Conference- Weeds. Farnham, UK: British Crop Protection Council.

Cousens, R. D. and J. L. Woolcock. 1997. Spatial dynamics of weeds: an overview. pp 613-618. In Proceedings of the Brighton Crop Protection Conference- Weeds. Farnham, UK: British Crop Protection Council.

Dammer, K. H., T. Schweigert, and C. H. Wittmann. 1999. Probability maps for risk assessment in a patchy weed control. Precision Agriculture 1:185-198.

Goudy, H. J., K. A. Bennett, R. B. Brown, and F. J. Tardif. 2001. Evaluation of site specific weed management using a direct injection sprayer. Weed Sci. 49:359-366.

Forcella, F., R. L. Benech Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crop Res. 67:123-139.

Forcella, F., R. G. Wilson, K. A. Renner, J. Dekker, R. G. Harvey, D. A. Alm, D. D. Buhler, and J. Cardina. 1992. Weed seedbanks of the U.S. Corn Belt: Magnitude, variation, emergence, and application. Weed Sci. 40:636-644.

Heisel, T., S. Christensen, and A. Walter. 1996. Weed managing model for patch spraying in cereal. pp. 999-1007. In: P.C. Robert, R.H. Rust and W.E. Larson, eds. Proceedings of the 3rd International Conference on Precision Agriculture, (ASA-CSSA. Madison, WI, USA).

Hilgenfeld, K. L., A. R. Martin, D. A. Mortensen, and S. C. Mason. 2004. Weed management in glyphosate resistant soybean: weed emergence patterns in relation to glyphosate treatment timing. Weed Technol. 18:277-283.

Jensen, A. L., P. S. Boll, I. Thysen, and B.K. Pathak. 2000. Pl@nteInfo- a wed-based system for personalized decision support in crop management. Comput. Electronics Agric. 25:271-293.

Jensen, J. E. and J. Streibig. 1994. Herbicide dose-response curves and sustainable agriculture. Pp 15-33. *In*: Quantitative methods for sustainable agriculture, EU-HARMA Concerted Action Workshop, Edinburg, UK. May 6-7.

Johnson, G. A., D. A. Mortensen, and A. R. Martin. 1995. A simulation of herbicide use based on weed spatial distribution. Weed Res. 35:197-205.

Johnson, G., J. Cardina, and D. Mortensen. 1997. pp. 131-147. Site-specific weed management: current and future directions. In: F. Pierce and E. Sadler, eds. The State of Site-Specific management for Agriculture. (ASA-CSSA-SSSA, Madison, WI, USA). Chapter 7.

Knezevic, Z. S., P. H. Sikemma, F. Tardif, A. S. Hamill, K. Chandler and C. J. Swanton. 1998. Biologically effective dose and selectivity of RPA 201772 for preemergence weed control in corn (*Zea mays*). Weed Technol. 12:670–676.

Lamastus-Stanford, F. E., and D. R. Shaw. 2004. Evaluation of site-specific weed management implementing the herbicide application decision support system (HADSS). Precision Agriculture 5:411-426.

Lass, L. W., D. C. Thill, B. Shafii, and T. S. Prather. 2002. Detection of spotted knapweed (*Centaurea maculosa*) with a hyperspectral remote sensing technology. Weed Technol. 16:426-432.

Lowenberg-DeBoer, J. and S. Swinton. 1997. Economics of site-specific management in agronomic crops. pp. 369-396. In: F. Pierce and E. Sadler, eds. The state of site-specific management for agriculture USA. (ASA-CSSA-SSSA, Madison, Wisconsin, USA).

Medlin, C. R., D. R. Shaw, P. D. Gerard, and F. E. LaMastus. 2000. Using remote sensing to detect weed infestation in *Glycine max*. Weed Sci. 48:383-398.

Medlin, C. R. and D. R. Shaw. 2000. Economic comparison of broadcast and site-specific herbicide applications in nontransgenic and glyphosate-tolerant *Glycine max*. Weed Sci. 48:653-661.

Mortensen, D. A. and J. A. Dieleman. 1998. Why weed patches persist: dynamics of edges and density. 154pp. In R.W. Medd and J.E. Patley, eds. Precision weed management in crops and pastures, Proceedings of a workshop, 5-6 May 1998, Wagga Wagga, (CRC for weed management system, Adelaide).

Mortensen, D. A., J. A. Dieleman, and G. A. Johnson. 1998. Weed spatial variation and weed management. pp 293-309. In J.L. Hatfield, D.D. Buhler, and B.A. Stewart, eds. Integrated Weed and Soil Management. Chelsea, MI: Ann Arbor Press.

Mortensen, D., G. Johnson, D. Wyse, and A. Martin. 1994. Managing spatially variable weed population. pp. 397-415. In: P.C. Robert, R.H. Rust and W.E. Larson, eds. Site-specific management for agricultural systems. Proceedings of the 2nd International Conference on Precision Agriculture. (ASA-CSSA-SSSA. Madison, WI, USA).

Neeser, C., J.A. Dille, G. Krishnan, D.A. Mortensen, J.T. Rawlinson, A.R. Martin, and L.B. Bills. 2004. WeedSOFT®: A weed management decision support system. Weed Sci. 52:115-122.

Nordmeyer, H. 2006. Patchy weed distribution and site-specific weed control in winter cereals. Precision Agriculture 7:219-231.

Oriade, C. A., R. P. King, F. Forcella, and J. L. Gunsolus. 1996. A bioeconomic analysis of site-specific management for weed control. Review Agricultural Economics 18: 523-535.

Paice, M. E. R., P. C. H. Miller, and W. Day. 1996. Control requirements for spatially-selective herbicide sprayers. Computers and Electronics in Agriculture 14:163-177.

Prostko, E. P. and J. A. Meade. 1993. Reduced rates of post emergence herbicides in conventional soybeans (*Glycine max*). Weed Technol. 7:365-369.

Rider, T. W, J. W. Vogel, J. A. Dille, K. C. Dhuyvetter, and T.L. Kastens. 2006. An economic evaluation of site-specific herbicide application. Precision Agriculture 7:379-392.

Rider, T.W. 2004. An Economic Evaluation of Site-Specific Herbicide Application. MSc. Thesis. Kansas State University, Manhattan, Kansas. 90 p.

Swinton, S. M. 2005. Economics of site-specific weed management. Weed Sci. 53:259-263.

Stafford, J. V. and P. C. H. Miller. 1997. Spatially variable treatment of weed patches. pp 465-473. In: P.C. Robert, R.H. Rust, and W.E. Larson, eds. Proceedings of the 3rd International Conference on Precision Agriculture, June 23-26, 1996, Minneapolis, MN. Madison, WI: American Society of Agronomy/Crop Science Society of America/Soil Science Society of America.

Streibig, J. C., Combellack, J. H., Prichard, G. H., and Richardson, R. G. 1989. Estimation of threshold for weed control in Australian cereal crops. Weed Res. 29:117-126.

Timmermann, C., R. Gerhards, and W. Kühbauch. 2003. The economic impact of site-specific weed control. Precision Agriculture 4:249-260.

Tredaway-Ducar, J., G. D. Morgan, J. B. Wilkerson, W. E. Hart, R. M. Hayes, and T. C. Mueller. 2003. Site-specific weed management in corn (*Zea mays*). Weed Technol. 17:711-717.

[USDA] U.S. Department of Agriculture. 2005. Agricultural Chemical Usage: 2002 Field Crops Summary. Washington, DC: National Agricultural Statistics Service, Agricultural Statistics Board, USDA, United States Government Printing Office.

Vleeshouwers, L. 1997. Modelling weed emergence patterns. Ph.D. dissertation. Wageningen Agricultural University, Wageningen, The Netherlands.

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*). Weed Sci. 40:554-557.

Wiles, L. J., R. P. King, E. E. Schweizer, D. W. Lybecker, and S. M. Swinton. 1996. GWM: general weed management model. Agric. Syst. 50:355–376.

Williams, M. M. II, R. Gerhards, and D. A. Mortensen. 1999. Spatiotemporal outcomes of site-specific weed management on maize. pp. 897-906. In: J.V. Stafford, ed. Precision Agriculture, Odense, Denmark, Sheffield, UK: Sheffield Academic Press.

CHAPTER 2 - Weed Emergence Patterns in Kansas Soybean

ABSTRACT

Weed management practices and the environment influence the emergence pattern of weeds. Emergence patterns of shattercane, prickly sida, and ivyleaf morningglory were evaluated over a two to three year period near Manhattan, KS, in patches initiated in 2006, 2007, and 2008. Four treatments imposed were no-crop, soybean with no-residual herbicide, one-half, or full-rate residual herbicide. Emergence counts were taken every three to four days. There were no differences among treatments for total shattercane emergence with 665, 293, and 17 seedlings 0.25 m^{-2} for patches initiated in 2006, 2007, and 2008, respectively. In subsequent years after patch initiation, treatment reduced the number of seedlings per patch based on management of the previous year. Low seedbank populations of ivyleaf morningglory resulted in low total cumulative emergence across treatments in both the initiation year and follow up year. For prickly sida, no differences among treatments were observed with average total emergence of 95 and 33 seedlings 0.25 m^{-2} for patches initiated in 2006 and 2007, respectively. All species began emergence in mid-May in all years, coinciding with soybean planting. Extended emergence is a term used to describe emergence that occurs over a period of time resulting in a number of emergence flushes. Shattercane had extended emergence in 2006; while in 2007 it had two primary flushes of emergence, and only one emergence flush in 2008. Prickly sida and ivyleaf morningglory had one flush of emergence in 2006; however, these species had two flushes of emergence in 2007. Extended emergence was observed for shattercane when moisture was low and temperature was high, while extended emergence was observed for prickly sida and ivyleaf morningglory when moisture was high and temperature was low. Applying residual herbicide decreased weed emergence, thus giving the crop a competitive advantage.

Nomenclature: s-metolachlor; metribuzin; sulfentrazone; ivyleaf morningglory, *Ipomoea hederacea* Jacq. IPOHE; prickly sida; *Sida spinosa* L. SIDSP; shattercane, *Sorghum bicolor* L. Moench ssp. *arundinaceum* SORVU; soybean, *Glycine max* L. Merr. 'DKB35-52'

Key words: weed management practices, weed patch, weed emergence pattern

INTRODUCTION

Management systems for specific weed species could be improved by knowing information about the species temporal emergence pattern, density, distribution, and variations among different cohorts. Cohorts are groups of seedlings that emerge at the same time. The challenge for farmers and managers is that weed species rarely emerge at the same time. Weed management practices influence the emergence pattern of weeds and a better understanding could improve the application of integrated weed management (IWM). Integrated weed management uses a variety of techniques such as grazing, herbicide application, land fallowing, and biological control to keep weeds under control.

In agricultural fields weeds germinate and emerge from seed in the soil, and the seedbank is comprised of many weed species which have different emergence patterns (Cavers 1983; Forcella et al. 1992). Fenner (1985) reported that seedbank size in agricultural land ranges from near zero to as many as one million seed m^{-2}. Average seedbank densities of annual weeds ranged from 600 to 162,000 viable seed m^{-2} among various locations in the Corn Belt (Forcella et al. 1992). Reduction or elimination of the seedbank is an important goal for IWM. Species composition and density of weed seeds in the soil vary greatly and are closely linked to the cropping history of the field (Buhler et al. 1997b). This is evident as more grass weeds are usually found in grass crops, for example, shattercane in grain sorghum fields.

Weed control measures are complicated by differing weed emergence patterns. Emergence characteristics of weed species include initial time of emergence (beginning of emergence), emergence pattern over time (length of emergence), mean time of emergence, and cumulative seasonal emergence (Buhler et al. 1997a, Hartzler et al. 1999, Mohler 2001). A peak of emergence is characterized by continuous high seedling emergence followed by low or no emergence. Extended emergence is a term used to describe emergence that occurs over a period of time resulting in a number of emergence flushes. The time of weed emergence influences what species will be most prevalent in a crop and this varies by location and weed species (Hilgenfeld et al. 2004). The period of weed emergence is a function of both the weed species and its interaction with micro-environmental factors such as soil temperature, soil moisture, soil type, and light quality (Forcella et al. 1997, 2000; Mohler 2001). In the Great Plains, including Kansas, there is high temporal and spatial variability in the environment and this influences weed emergence patterns.

Soybean production is frequently limited by competition from annual weeds that emerge with the crop (Burnside 1968; Knake and Slife 1969). Shattercane, ivyleaf morningglory, and prickly sida commonly occur in soybean because they emerge at the same time as soybean.

Hilgenfeld et al. (2004) reported that ivyleaf morningglory and shattercane emerged from late April to mid-August in Lincoln, NE, allowing these species to avoid postemergence glyphosate application timed to prevent early-season weed competition. Early emerging weeds are likely to be controlled with herbicide while late emerging weeds are likely to escape treatment (Jordan and Jannink 1997). Due to the fact that glyphosate is a non-residual herbicide, application timing is important and thus, understanding weed seedling emergence patterns is key in designing a weed management strategy. A non-residual herbicide is a herbicide that does not persist in the soil and does not injure or kill weeds that germinate and emerge after they are applied. A residual herbicide is a herbicide that persists in the soil and injures or kills germinating weed seedlings for a relatively short period of time after application (WSSA 2007). Understanding weed emergence patterns could aid scouts and managers in timing operations like planting and postemergence herbicide applications. Studies on the emergence patterns of weeds are important for the development of long-term weed management strategies. The objective of this study was to characterize the seedbank and seedling emergence patterns of shattercane, prickly sida, and ivyleaf morningglory including initial time, peak, end, and duration of emergence in response to crop and residual herbicide treatments in a soybean field.

MATERIALS AND METHODS

A study was conducted over a two- or three-year period (2006, 2007, and 2008) in a no-tillage field at the Department of Agronomy Ashland Bottoms Research Farm, near Manhattan, KS. This field had a known weed species history. Weed species were selected based on naturally occurring populations with known extended emergence patterns. A weed map developed in 2004 was used to identify areas in the field where the three weed species were located (Vogel 2005). A 12-m x 12-m area defined a weed patch for each species. Seedbank samples (five cores per patch per weed species) were taken randomly in each year before plots were established from the top 13 cm in each of the three patches using a soil auger that was 6 cm in diameter. Soil cores were kept separate and soil was washed out to identify and count weed seeds of the three species. Average number of seeds for each weed species and year was determined to document initial seedbank population and change over time. ANOVA in SAS[2] was used to test the differences in number of seed retrieved across years by weed species. Four treatments imposed were no-crop (soybean removed), soybean with no-residual herbicide, soybean with half rate residual herbicide, and soybean with full rate residual herbicide. These were replicated four times within each patch for a total of 16 experimental plots arranged in a completely randomized design. Each experimental plot was 1.5-m x 1.5-m; emergence counts were taken from a permanent quadrat (0.5-m x 0.5-m) established randomly in each plot. Soybeans were no-till planted at 300 000 seeds ha^{-1} in 0.76-m rows throughout the field on May 12, 2006, May 14, 2007, and May 5, 2008. The labeled rate residual herbicide treatments were S-metolachlor (2.13 kg ha^{-1}) for shattercane, metribuzin at 0.84 kg ha^{-1} for prickly sida, and sulfentrazone (0.046 kg ha^{-1}) for ivyleaf morningglory. Herbicides were applied preemergence on May 13, 2006, May 16, 2007, and May 8, 2008. Shattercane plots were initiated in 2006, 2007, and 2008 with all patches repeated in 2007 and in 2008. Plots for prickly sida and ivyleaf morningglory were initiated in 2006 and 2007, while the 2006 patches were repeated for a second year (2007). Prickly sida and ivyleaf morningglory were not evaluated in 2008 because the seedbank was very low and variable. As soybeans emerged they were removed from the no-crop treatment plots. First date of observation equals cumulative emergence over several days. Weed seedlings were counted and removed from the emergence quadrat every three to four days; glyphosate was applied across the entire field for removal of remaining weed seedlings as needed and for overall weed management.

Cumulative total emergence was determined and compared among weed species, treatments, and years. ANOVA in SAS[2] was used to test for treatment effects. The relationship of total cumulative emergence of weed species to cumulative GDD was analyzed by fitting the logistic model to each data set separated by weed species, treatment, and year.

The logistic model fitted was:

$$\text{CumEm} = Em_0 + [Em_h / (1 + (\text{GDD} / GDD_m)^b)] \qquad [1]$$

where CumEm is the cumulative emergence of a weed species (cumulative number of seedlings that emerged), Em_0 is the initial emergence (number of seedlings), Em_h is the upper asymptote (maximum number of emerged seedlings), GDD is cumulative growing degree days (°C), GDD_m

is the GDD value at inflection of the curve (°C), and *b* is the slope. Lawson et al. (2006) successfully used equation 1 to model emergence timing of volunteer canola in spring wheat fields in Manitoba.

Parameter estimates were determined for equation 1 for each weed species, treatment, and year using nonlinear regression techniques in Sigma Plot 10.0[1]. A test for lack of fit of equation 1 was performed by partitioning the nonlinear sums of squares into the error for lack of fit and pure experimental error. If the value of lack of fit was significant at the 5% level as outlined by Seefeldt et al. (1995), equation 1 was deemed appropriate for that weed species, treatment, and year. Differences among treatments were tested using Proc GLM in SAS[2] and means were separated using LSD at a significant level of 0.05. If no differences existed among treatments for a given weed species and year, data were combined and equation 1 was re-fit to the data such that one model explained the emergence pattern for that given weed species.

Weather data were obtained from the Kansas State Weather Data Library (Mary Knapp, Climatologist, Department of Agronomy, Kansas State University, personal communications, 2006-2008). Maximum and minimum air temperatures were used to calculate daily GDD in °C and cumulative GDD (°C) were calculated from the date of soybean planting in each year:

$$GDD_{daily} = [(T_{max} + T_{min})/2] - T_{base} \qquad [2]$$

$$\text{Cumulative GDD} = \sum^{n}_{i=1} GDD_{daily} \qquad [3]$$

where T_{max} is the maximum daily air temperature, T_{min} is the minimum daily air temperature, T_{base} is the base temperature (0°C), and n is the number of days elapsed after the planting date (Bullied et at. 2003, Donald 2000, Hacault and Van Acker 2006). Differences in cumulative total emergence among the four treatments were evaluated for each weed species across years using Proc GLM in SAS[2]. Individual observations of weekly weed emergence counts were selected to highlight treatment effects. Total counts for shattercane emergence in week 4 and 5 as well as ivyleaf morningglory emergence in week 4 were tested for treatment effects using Proc GLM in SAS[2] and means were separated using LSD at a significant level of 0.05.

RESULTS AND DISCUSSION

Mean number of shattercane seeds per soil core (#/0.0078 m^2) were 47, 16, and 19 in 2006, 2007, and 2008, respectively (Table 2.1). Mean numbers of prickly sida seeds retrieved per soil core were 12 and 3, while for ivyleaf morningglory, they were 1 and 0, for 2006 and 2007, respectively (Table 2.1). Shattercane was the predominant species in the field, followed by prickly sida, and then ivyleaf morningglory. There was a significant reduction in weed seed retrieved from soil cores in 2007 compared to 2006 due to germination losses and degradation of seed over winter for shattercane by 66% and prickly sida by 75% (Table 2.1). No new seed were added to the seedbank as all weeds were controlled in 2006. This is important as weed seed bank is the primary source of future weed infestations in crop fields (Buhler, 1999). Nothing was retrieved from ivyleaf morningglory soil cores in 2007. The results support the findings of Gallandt et al. (2004) and Leon and Owen (2004) that natural seed banks decline significantly due to seed germination and degradation losses. These results suggest that not allowing weeds to produce seed greatly reduced the seed bank.

Total cumulative emergence of shattercane was not different among treatments for any patch within each initiation year (Table 2.2). Initiation year is the year the plots were established. Large differences among herbicide treatments would not be expected because S-metolachlor is not consistent for shattercane control. In 2006, average total cumulative emergence across treatments was 665 seedlings 0.25 m^{-2}, while in the patch initiated in 2007, there were 293 seedlings 0.25 m^{-2} and for the new patch initiated in 2008, average total emergence was 17 seedlings 0.25 m^{-2}. In subsequent years, treatment effects were different based on previous year's management resulting in fewer emerged seedlings per patch. In the plot initiated in 2006, the no-crop treatment had higher total cumulative emergence in 2007 than the other treatments, which were similar to one another, while in 2008, the no-crop treatment had higher emergence than the full rate residual herbicide treatment (Table 2.2). For the plot initiated in 2007, however, no-crop and no-herbicide treatments were similar and differed from the two residual herbicide treatments, which were similar.

For ivyleaf morningglory, significant differences were observed in total cumulative emergence across treatments in the initiation year such that the no-crop treatment differed from the full rate residual herbicide treatment in 2006 (Table 2.2). In the same patch, no treatment effects were observed in 2007, likely because of low initial seedbank populations, and the average total emergence was 8 seedlings 0.25 m^{-2}.

For prickly sida, no differences were observed among treatments neither for any initiation patch nor in subsequent years (Table 2.2). In 2006 average total cumulative emergence across treatments was 95 seedlings 0.25 m^{-2} and, for the new patch in 2007, 33 seedlings 0.25 m^{-2}, while the follow-up on patch from 2006 had 36 seedlings 0.25 m^{-2} in 2007. It should be noted that each species had a different patch history and the number of seeds retrieved shows the potential density of each species in the soil seedbank. It is for that reason that shattercane was followed up for a third year. Through three years in the same patch, there was a reduction in shattercane emergence (Table 2.2), which likely indicates reduction in seedbank size due to seed germination over time, natural seed degradation, and no addition of new seed to the seedbank because of control by multiple glyphosate applications.

Emergence patterns can be described based on the start of weed emergence (10% cumulative emergence) and the end of new emergence (90% emergence), with the difference in days equal to the duration of emergence. Emergence patterns for each species were described based on the no-herbicide treatment. All species began emergence in mid-May in all years, which coincided with soybean planting (Figures 2.1 and 2.2). Emergence for all species began after 42 GDD in 2006 (Table 2.3). Shattercane emergence began after 153 GDD in 2007 and after 484 GDD in 2008. Ivyleaf morningglory began emergence after 570 GDD in 2007 while prickly sida began emergence after 200 GDD in 2007. Ninety percent of shattercane emergence occurred by 950 GDD in 2006, 1410 GDD in 2007, and 1010 GDD in 2008, which corresponded to late June in each year. Ivyleaf morningglory had 90% emergence after 867 GDD in 2006 and 2280 GDD in 2007. Prickly sida had 90% emergence after 525 GDD in 2006 and 1400 GDD in 2007. The duration of shattercane emergence (between 10 and 90% emergence) was 38, 35, and 24 days in 2006, 2007, and 2008, respectively. Duration of ivyleaf morningglory emergence was 35 days in 2006 and 45 days in 2007. The duration of prickly sida emergence was 21 and 33 days in 2006 and 2007, respectively. Prickly sida had the shortest while ivyleaf morningglory had the longest duration of emergence across years (Table 2.3).

A peak or flush is a period of high emergence for a species for a number of days. Another descriptor of emergence pattern is the number of peaks or flushes of emergence, that is, periods of high emergence for a weed species over a few days. Extended emergence would be defined as continuous high seedling emergence over several days rather than a single peak. Shattercane had an extended emergence flush (continuous high seedling emergence with no single peak) from May 15 to June 30 in 2006 (Figure 2.1A). In 2007, shattercane had two flushes of emergence with one in mid-May and another in mid-June (Figure 2.1B). One emergence peak was observed for shattercane in 2008 (Figure 2.1C). Most shattercane emerged in June in all years. Prickly sida and ivyleaf morningglory each had two peaks of emergence in 2006 (Figures 2.2A and D) and in 2007 (Figures 2.2B and E). The emergence pattern for the two broadleaf weed species was similar across years although ivyleaf morningglory emergence was a week later than prickly sida (Figures 2.2B and E).

The emergence pattern (start, end, and duration of emergence) of these weed species was greatly influenced by weather conditions, i.e., timing and amount of rainfall. Forcella et al. (1997) reported that the period of weed emergence is a function of weed species and its interaction with the environment. In 2006, timing of rainfall promoted emergence and also activated the pre-emergence herbicide. Boyd and Van Acker (2003) reported how soil moisture and temperature affect germination, emergence, and the number of weed species in annually cropped fields. Monthly mean temperatures were near the 30-yr normal values for 2006, 2007, and 2008 during the growing season but 2006 was slightly warmer overall as compared to 2007 and 2008. Total cumulative growing days from May 1 to August 31 was 2212 GDD in 2006, 2108 GDD in 2007, and 1974 GDD in 2008. Total precipitation received from May 1 to August 31 was 487 mm, 610 mm, and 670 mm for 2006, 2007 and 2008, respectively. Even though 2006 was a drier year compared to 2007 and 2008, it was wetter than the 30-yr normal precipitation of 392 mm. The 670 mm of rainfall received in 2008 was distributed over the first 1000 GDD, while the 610 mm of rainfall in 2007 was well distributed across the whole growing season from May 1 to August 31. The first May rainfall came at 265, 66, and 170 GDD for 2006, 2007, and 2008, respectively (Figure 2.3). This study was initiated in a warmer and drier year in 2006, while 2007 and 2008 were cooler and wetter.

Four weeks after soybean planting in 2006 and 2007, significant differences among treatments for shattercane emergence were observed; the no-crop treatment had higher emergence than the no-herbicide treatment, and the no-crop and no-herbicide treatments had higher seedling emergence than the half rate and full rate residual treatments, which were similar (Figure 2.4). The influence of residual herbicide on shattercane emergence was evident at week

4. The no-crop treatment had two to three times more emergence in 2007 as compared to other treatments (Figure 2.4). These are not cumulative emergences but are the observed number of seedlings emerging during that given week. A different trend was observed for shattercane in week 5, where the no-crop treatment had higher emergence than any of the soybean crop treatments (Figure 2.4). This same trend was observed for weeks 3, 6, and 7 in 2007 (data not shown). The observed response could be attributed to the effect of soybean canopy presence on shattercane emergence.

In week 4 of 2006, differences were observed among treatments for ivyleaf morningglory emergence counts (Figure 2.5). The no-crop treatment had more seedlings than the no-herbicide treatment and these two treatments were higher than the two residual treatments, which were similar. Prickly sida had no differences among treatments that were observed in both years. Ellis and Griffin (2002) highlighted the benefits of soil-applied herbicides to reduce weed emergence in glyphosate-resistant soybean. Our study indicated that half-label rates were as effective as full rates in controlling weeds. Applying residual herbicide decreases weed emergence, thus giving the crop a competitive advantage. Huarte and Arnold (2003) reported that, with canopy development of alfalfa, the soil micro-climate beneath the vegetation was altered as compared to a no-crop environment; it seemed that alteration of the micro-environment suppressed weed emergence. Forcella et al. (2000) reported that canopy development, which affects soil thermal amplitude and light quality near the soil surface, has a direct effect on seedling emergence. Johnsongrass (*Sorghum halepense* L.) emergence was strongly inhibited beneath leaf canopies because temperature fluctuations were not sufficient for germination (Benech-Arnold et al. 1988).The same response was observed for shattercane; where fewer seedlings were observed in soybean than no-crop once the soybean canopy developed.

Cumulative emergence was described by equation 1 and fit to each weed species by treatment and by year (Table 2.4 and 2.5). Parameter Em_h, which represents the upper asymptote (maximum emergence), had higher values in the initiation year and decreased in subsequent years. Values for Em_h were generally higher for the no-crop treatment compared to other treatments. For pooled data, Em_h values for shattercane were 665, 393, and 14 seedlings for 2006, 2007, and 2008, respectively (Table 2.5). These values are close to the actual values on Table 2.2. Parameter b, which represents the slope, was -2.5, -0.6, and -6.9 for shattercane across treatments in 2006, 2007, and 2008, respectively (Table 2.5). For ivyleaf morningglory in 2006, the value of *b* was -1.9, while prickly sida had values of -13, 1.3, and -0.99 in 2006, 2007 (patch initiated in 2006), and 2007 (new patch initiated in 2007) (Table 2.4). For pooled data, parameter Em_o, which represents the lower limit of the response curve, was 52, -0.6, and 1 in 2006, 2007, and 2008 for shattercane. Prickly sida had 20, 35, and -1.02 in 2006, 2007 (patch initiated in 2006), and 2007 (patch initiated in 2007). Lawson et al. (2006) reported negative values for *b* and Em_o on volunteer canola (*Brassica napus* L.) emergence. It should be noted that some seedlings had already emerged before counting started. The negative values for be indicates negative slope of the curve and some negative values would be positive when taking into account the standard errors. Most of them are not really different from zero. Parameter GDD_m, which represents the GDD value at inflection of the curve, was 655, 292, and -600 degree days in 2006, 2007, and 2008 for shattercane. Prickly sida had -397, -288, and 459 degree days in 2006, 2007 (initiated in 2006), and 2007 (initiated in 2007).The coefficient of regression between GDD and total cumulative prickly sida emergence was high (R^2 = 0.79) and higher R^2 values were obtained for all other fits.

Ninety percent of shattercane emergence occurred by 1000 GDD across both years irrespective of treatment (Figure 2.6). Shattercane patches initiated in 2006 and in 2007 had the same emergence trend (Figures 2.6). Ivyleaf morningglory had 90% emergence after 1000 GDD in 2006 and after 2000 GDD in 2007 (Figure 2.7A, B, C). Ivyleaf morningglory cumulative emergence for no-crop and no-herbicide treatments were six times higher compared to residual treatments in 2006 (Figure 2.7A). Few ivyleaf morningglory seedlings emerged in 2007. Ninety percent of prickly sida emergence occurred at 500 GDD in 2006 and at 1400 GDD in 2007 (Figure 2.8). In a patch initiated in 2007, treatment effects were not observed, because that part of the field was flooded and preemergence herbicide could have been washed away.

Weed and farm management practices influence weed emergence. A single application of non-residual herbicide is unlikely to control these weeds adequately as they have extended emergence patterns. Variability in precipitation plays a significant role in the emergence patterns of these weeds species. Start of emergence seems to be influenced by GDD and precipitation. These weed species emerge in mid-May, which coincides with soybean planting. Extended emergence was observed for shattercane when moisture was low and temperature was high while for prickly sida and ivyleaf morningglory, extended emergence was observed when moisture was high and temperature was low. Scouts and managers can optimize herbicide application timing to control the greatest percentage of emerged seedlings. These findings would aid in designing proper integrated weed management programs as they provide information on the emergence pattern of naturally occurring weed populations in the field. Managers and farmers should continue to scout for weeds in their fields in order to determine the need to apply post emergence treatments.

SOURCES OF MATERIALS

[1]Sigma Plot 10.0. Aspire Software International, 20448 Charter Oak Drive, Ashburn, VA 20147.

[2]Statistical Analysis Systems, Version 9.1. 2003. Statistical Analysis Systems Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414.

REFERENCES

Benech-Arnold, R. L., C. M. Ghersa, R. A. Sanchez, and A. E. Garcia Fernandez. 1988. The role of fluctuating temperatures in the germination and establishment of *Sorghum halepense* (L.) Pers. Regulation of germination under leaf canopies. Funct. Ecol. 2:311-318.

Boyd, N. S. and R. C. Van Acker. 2003. The effects of depth and fluctuating soil moisture on the emergence of eight annual and six perennial plant species. Weed Sci. 51:725-730.

Buhler, D. D. 1999. Expanding the context of weed management. J. Crop Prod. 2:1-7.

Buhler, D. D., R. G. Hartzler, F. Forcella, and J. Gunsolus. 1997a. Relative emergence sequence for weeds of corn and soybeans. Ames, IA: Iowa State University publication on pest management, file 9 (SA-11).

Buhler, D. D., R. G. Hartzler and F. Forcella. 1997b. Implication of weed seedbank dynamics to weed management. Weed Sci. 45:329-336.

Bullied, W. J., A. M. Marginet, and R. C. Van Acker. 2003. Conventional and conservation-tillage systems influence emergence periodicity of an annual weed species in canola. Weed Sci. 51:886-897.

Burnside, O. C. 1968. Control of wild cane in soybeans. Weed Sci. 16:18-22.

Cavers, P. B. 1983. Seed demography. Can. J. Bot. 61:3678-3590.

Donald, W. W. 2000. A degree-day model of *Cirsium arvense* shoot emergence from adventitious root buds in spring. Weed Sci. 48:333-341.

Ellis, J. M. and J. L. Griffin. 2002. Benefits of soil-applied herbicides in glyphosate-resistant soybean (*Glycine max*). Weed Technol. 16:541-547.

Fenner, M. 1985. Chapter 4. In Seed Ecology. New York, NY: Chapman Hall, pp. 87-104.

Forcella, F., R. G. Wilson, K. A. Renner, J. Dekker, R. G. Harvey, D. A. Alm, D. D. Buhler, and J. Cardina. 1992. Weed seedbanks of the U.S. Corn Belt: Magnitude, variation, emergence, and application. Weed Sci. 40:636-644.

Forcella, F., R. G. Wilson, J. Dekker , R. J. Kremer, J. Cardina, R. L. Anderson, D. Alm, K. A. Renner, R. G. Harvey, S. Clay, and D. D. Buhler. 1997. Weed seedbank emergence across Corn Belt. Weed Sci. 45:67-76.

Forcella, F., R. L. Benech-Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crops Res. 67:123-139.

Gallandt, E. R., E. P. Fuerst, and A. C. Kennedy. 2004. Effect of tillage, fungicide seed treatment, and soil fumigation on seed bank dynamics of wild oat (*Avena fatua*). Weed Sci. 52:597-604.

Hacault, K. M. and R. C. Van Acker. 2006. Emergence timing and control of dandelion (*Taraxacum officinale)* in spring wheat. Weed Sci. 54:172-181.

Hartzler, R. G., D. D. Buhler, and D. E. Stoltenberg. 1999. Emergence characteristics of four annual weed species. Weed Sci. 47:578-584.

Hilgenfeld, K. L., A. R. Martin, D. A. Mortensen, and S. C. Mason. 2004. Weed management in glyphosate resistant soybean: weed emergence patterns in relation to glyphosate treatment timing. Weed Technol. 18:277-283.

Huarte, H. R. and R. L. Benech Arnold. 2003. Understanding mechanisms of reduced annual weed emergence in alfalfa. Weed Sci. 51:876-885.

Jordan, N. R. and J. L. Jannink. 1997. Assessing the practical importance of weed evolution: a research agenda. Weed Res. 37:237-246.

Knake, E. L. and F.W. Slife. 1969. Effect of time of foxtail removal from corn and soybeans. Weed Sci. 17:281-283.

Lawson, A. N., R. C. Van Acker, and L. F. Friesen. 2006. Emergence timing of volunteer canola in spring wheat in Manitoba. Weed Sci. 54:873-882

Leon, R. G. and M.D.K. Owen. 2004. Artificial and natural seed banks differ in seedling emergence patterns. Weed Sci. 52:531-537.

Mohler, C. L. 2001. Weed life history: Identifying vulnerabilities. *In* M. Liebman, C.L. Mohler, and C.P. Starver, eds. Ecological Management of Agricultural Weeds. Cambridge, UK: Cambridge University Press. Pp. 40-98.

Seefeldt, S. S., J. E. Jensen, and E. P. Fuerst. 1995. Log-logistic analysis of herbicide dose-response relationships. Weed Technol. 9:218-227.

Vogel, J. W. 2005. Implementing site specific weed management in Kansas row crops. MS Thesis, Kansas State University, Manhattan, Kansas. Pp 195.

WSSA. 2007. Herbicide handbook. 9th edition. P458.

Figure 2.1 Observed emergence (number of seedlings/0.25 m^2) on each date for shattercane in soybean with no residual herbicide at Manhattan, KS for patches initiated in 2006 (A, B, C), in 2007 (D, E) and in 2008 (F).

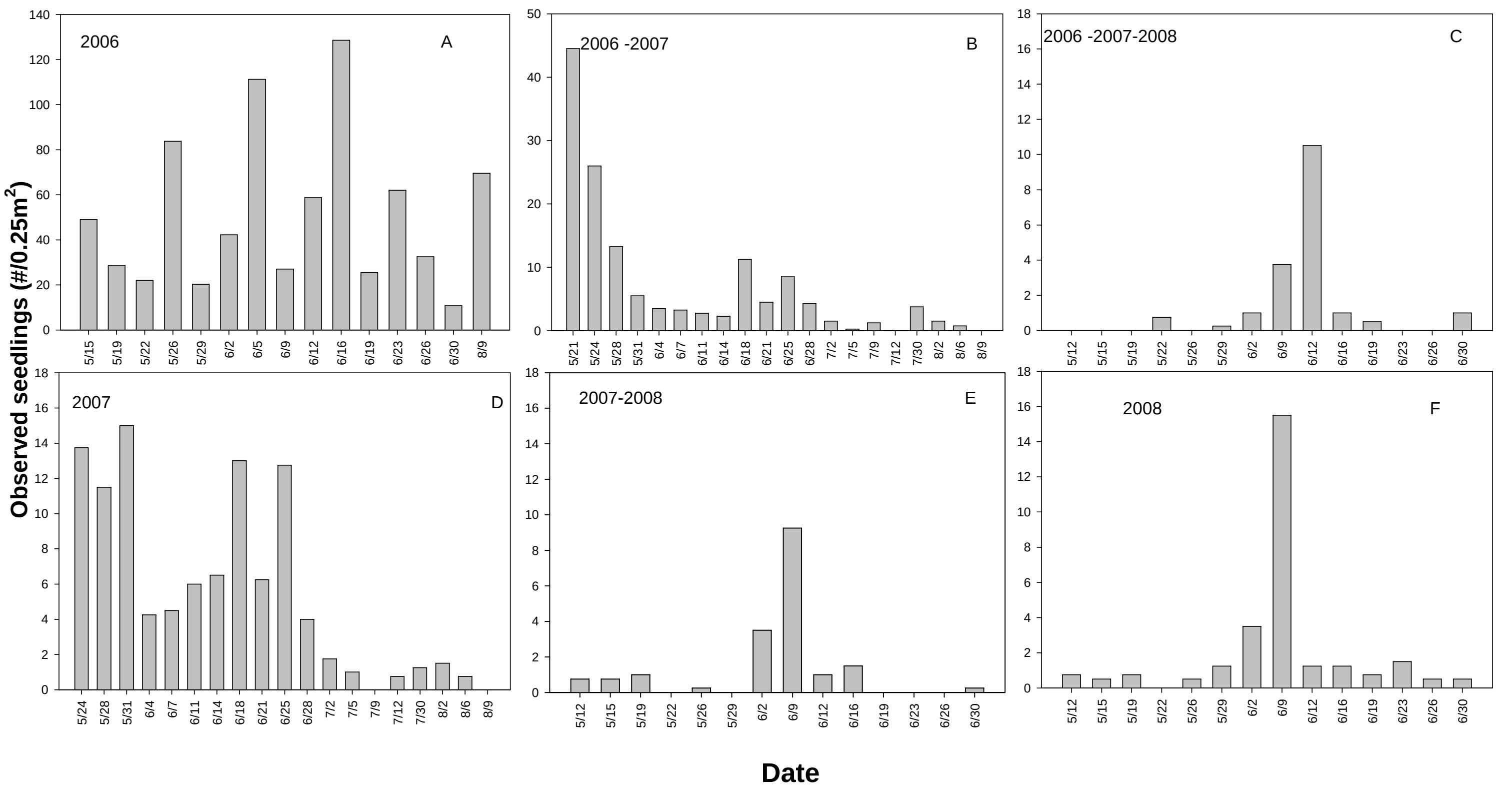

Figure 2.2 Observed emergence (number of seedlings/0.25 m^2) on each date for prickly sida and ivyleaf morningglory in soybean with no residual herbicide at Manhattan, KS for patches initiated in 2006 (A, B, D, E) and in 2007 (C, F).

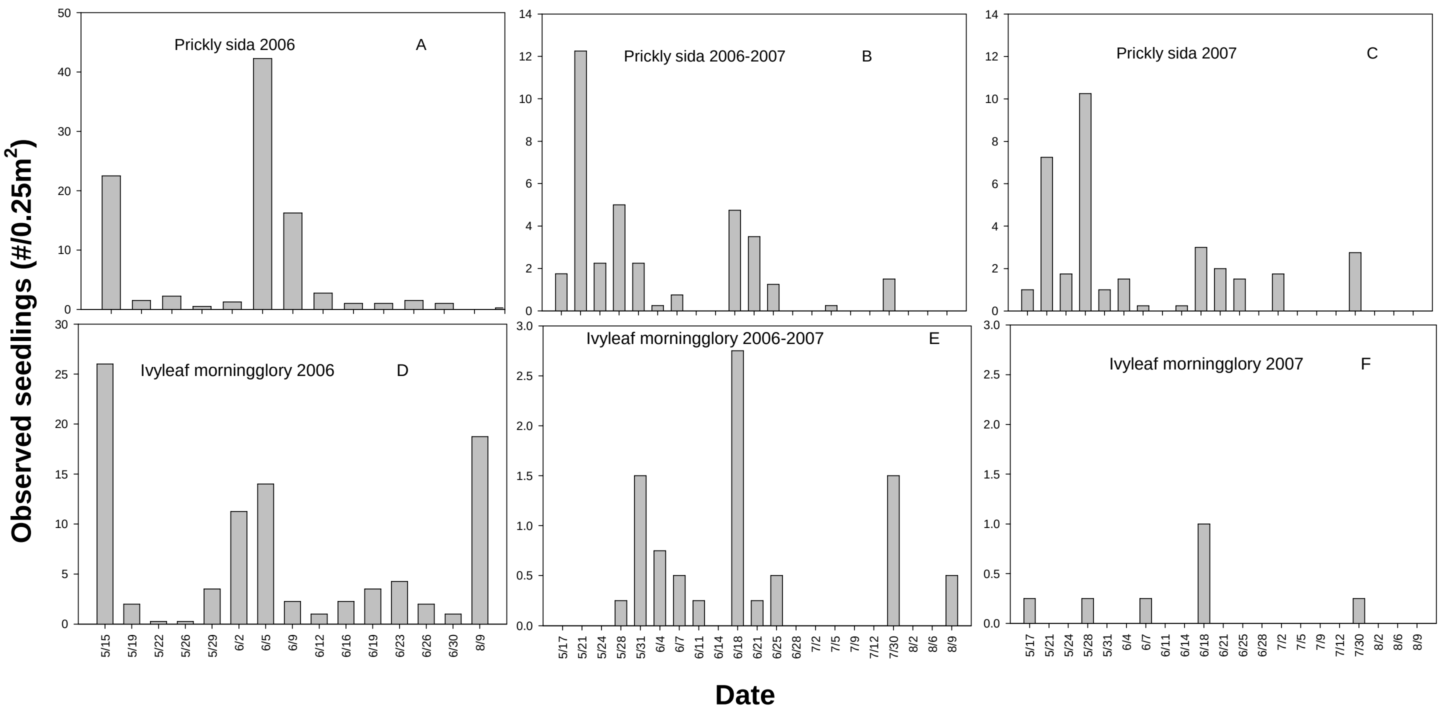

Figure 2.3 Precipitation in relation to GDD for 2006, 2007, and 2008 in Manhattan, KS.

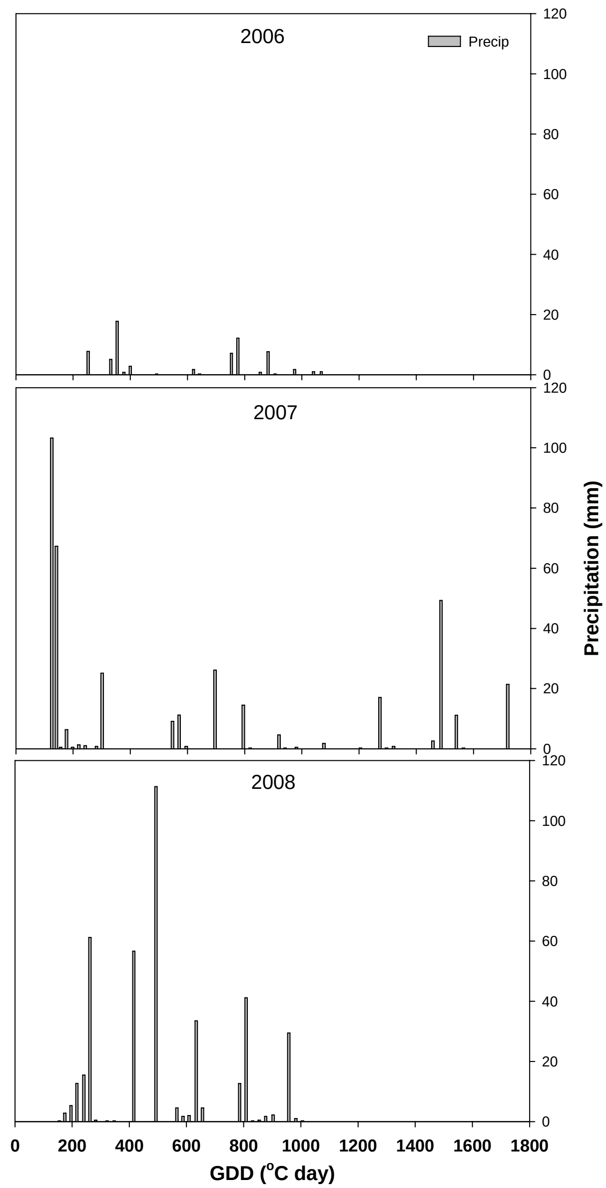

Figure 2.4 Mean number of shattercane seedlings observed (number of seedlings/0.25 m^2) during week 4 and week 5 as affected by no-crop (NC), no-residual herbicide (NH), half-rate (HR), and full-rate (FR) residual herbicide treatments in the same species patch in 2006 and 2007.

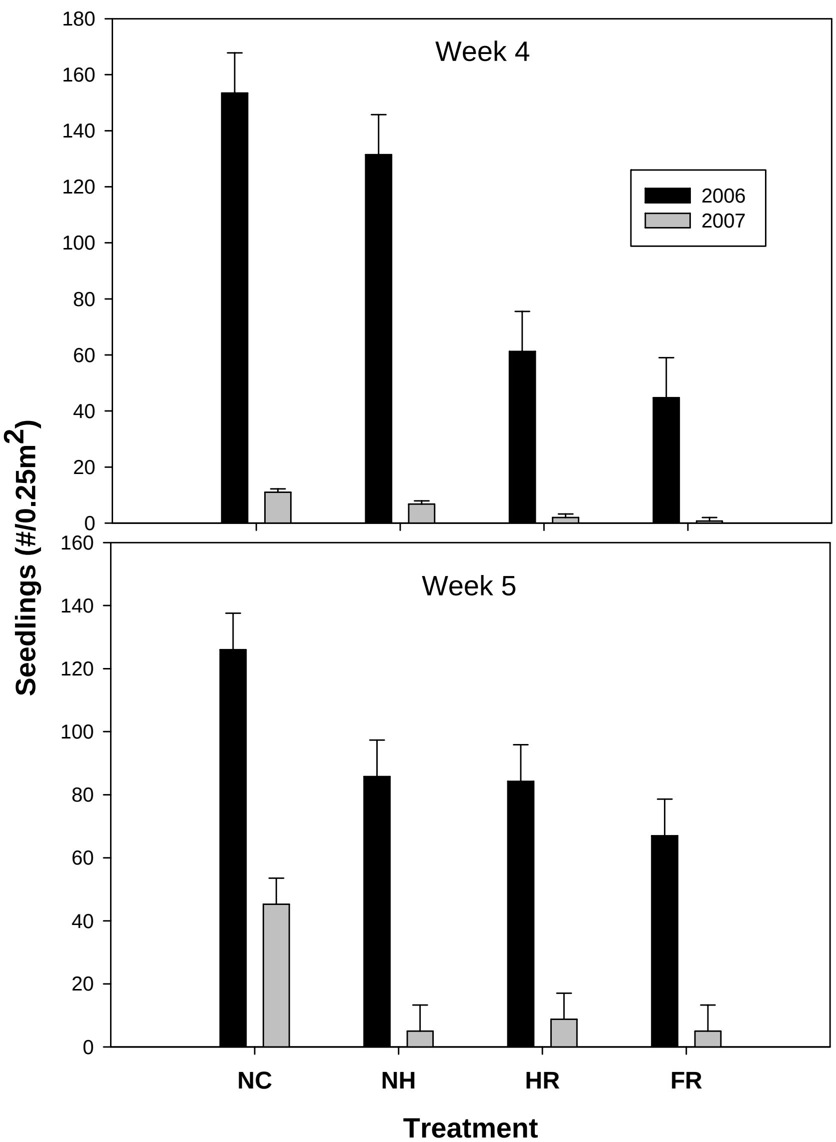

Figure 2.5 Mean number of ivyleaf morningglory seedlings observed (number of seedlings/0.25 m^2) during week 4 as affected by no-crop (NC), no-residual herbicide (NH), half-rate (HR), and full-rate (FR) residual herbicide treatments in 2006.

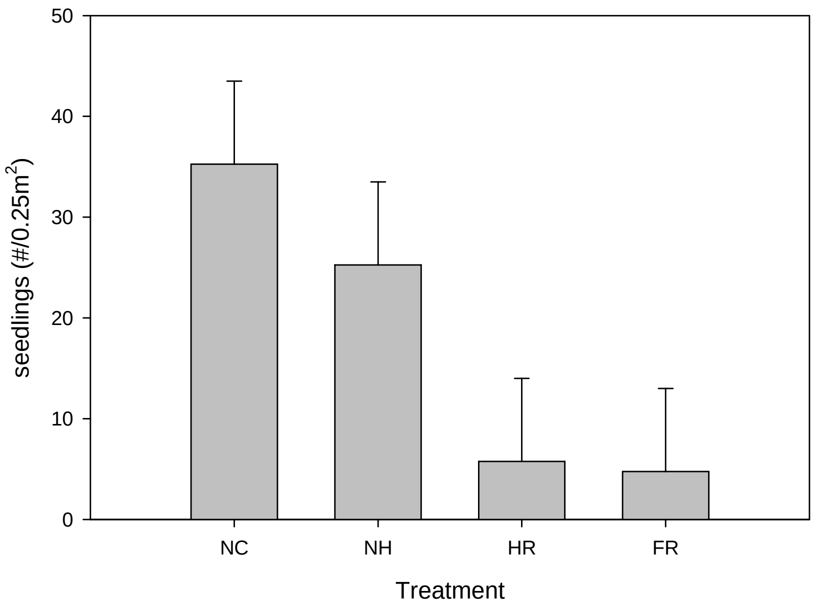

Figure 2.6 Cumulative shattercane emergence (number of seedlings/0.25 m^2) in relation to GDD, for patches initiated in 2006, 2007, and 2008. Symbols represent average emergence observed in the patch for each treatment, lines represent predicted emergence based on equation 1, and parameter estimates are in Table 2.5. Data pooled across treatments.

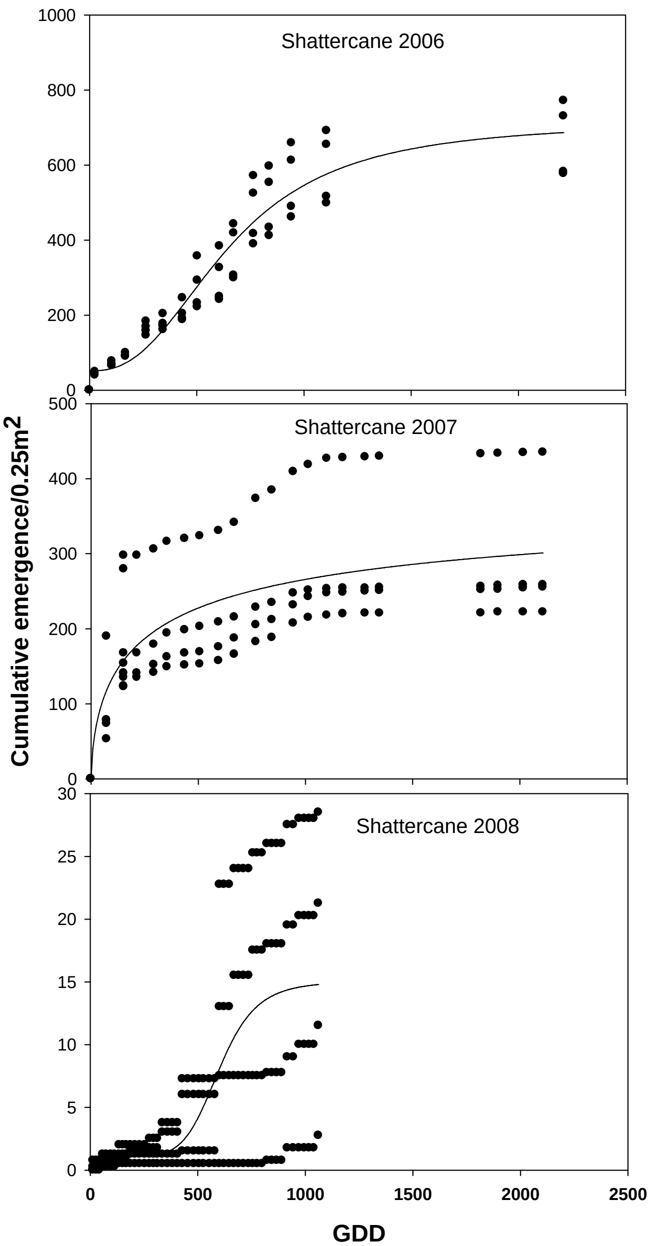

Figure 2.7 Cumulative ivyleaf morningglory emergence (number of seedlings/0.25m^2) in relation to GDD for patches initiated in 2006 (A) and followed in 2007 (C), and initiated in 2007. Symbols represent average emergence observed in the patch for each treatment, lines represent predicted emergence based on equation 1, and parameter estimates are in Table 2.4.

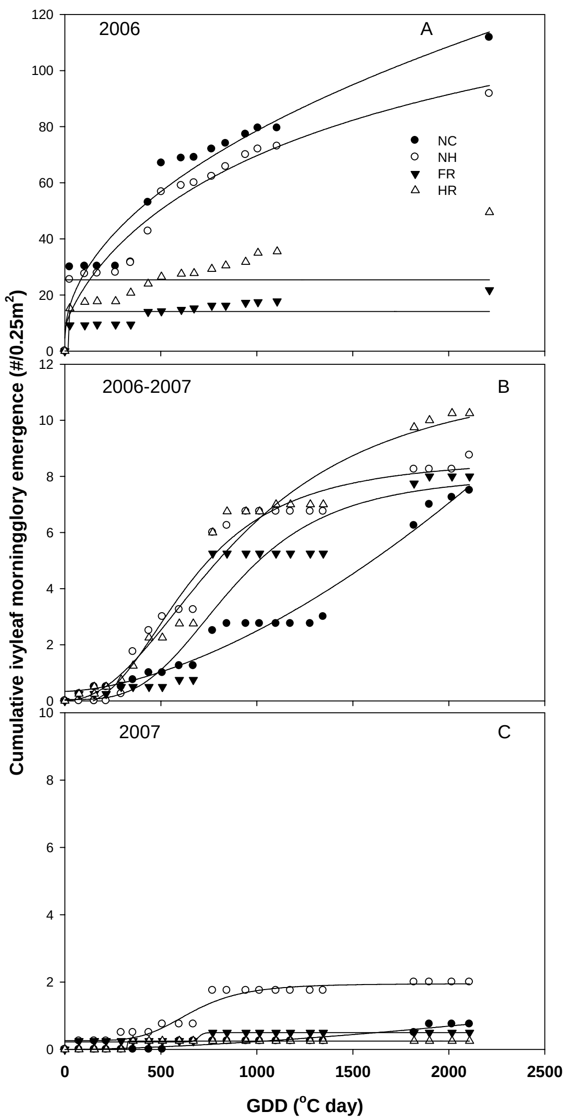

Figure 2.8 Cumulative prickly sida emergence (number of seedlings/0.25m^2) in relation to GDD for patches initiated in 2006 and 2007, with patches initiated in 2006 followed in 2007. Symbols represent average emergence observed in the patch for each treatment, lines represent predicted emergence based on equation 1, and parameters are in Table 2.5. Data pooled across treatments.

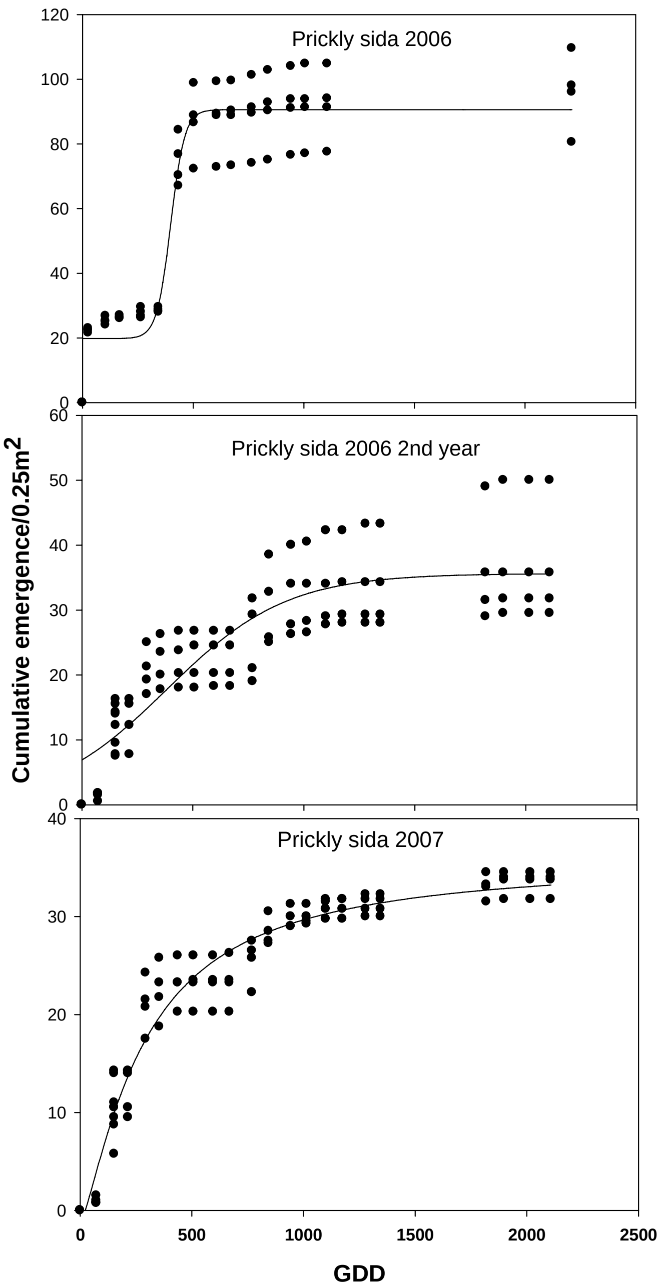

Table 2.1 Mean (± standard error) number of shattercane, ivyleaf morningglory, and prickly sida seeds recovered from five soil cores. Means within a species in columns followed by the same letter were not significantly different (P=0.05).

Year	Shattercane	Ivyleaf morningglory	Prickly sida
2006	47 (8.2) a	1 (0.387) a	12 (1.76) a
2007	16 (8.2) b	0 (0.387) a	3 (1.76) b
2008	9 (8.2) b	-----	-----

----- no data collected

Table 2.2 Total cumulative seedling emergence (number of seedlings/0.25 m^2) by the end of August in each year.

Weed species	Year of Patch initiation	Treatment	Year 1	Year 2	Year 3
			------#/0.25m^2------		
Shattercane	2006	No crop	771 a[1]	566 a	32 a
		No herbicide	730 a	204 b	20 ab
		Half rate	576 a	209 b	5 bc
		Full rate	582 a	257 b	2 c
		LSD (0.05)	327	211	17
	2007	No crop	435 a	15 a	----[2]
		No herbicide	258 a	18 a	----
		Half rate	222 a	5 b	----
		Full rate	255 a	1 b	----
		LSD (0.05)	222	9	----
	2008	No crop	24 a	----	----
		No herbicide	29 a	----	----
		Half rate	12 a	----	----
		Full rate	2 a	----	----
		LSD (0.05)	27	----	----
Ivyleaf morningglory	2006	No crop	111 a	7 a	----
		No herbicide	91 ab	8 a	----
		Half rate	49 ab	10 a	----
		Full rate	21 b	8 a	----
		LSD (0.05)	76	10	----
	2007	No crop	0.75 ab	----	----
		No herbicide	2 a	----	----
		Half rate	0.25 b	----	----
		Full rate	0.5 ab	----	----
		LSD (0.05)	1.6	----	----

Prickly sida	2006	No crop	109 a	50 a	----
		No herbicide	94 a	35 a	----
		Half rate	80 a	31 a	----
		Full rate	96 a	29 a	----
		LSD (0.05)	94	37	----
	2007	No crop	34 a	----	----
		No herbicide	34 a	----	----
		Half rate	31 a	----	----
		Full rate	33 a	----	----
		LSD (0.05)	24	----	----

[1] Means within a column for a given species and initiation date followed by the same letter were not significantly different (P=0.05).

[2] ----data not collected

Table 2.3 Cumulative GDD (°C day) to observe 10 and 90% emergence (E) and duration of emergence in days of weed seedlings in soybean with no residual herbicide treatment at Manhattan, KS for shattercane, ivyleaf morningglory and prickly sida.

	2006			2007			2008		
	10% E	90% E	Duration	10% E	90% E	Duration	10% E	90% E	Duration
Weed species	---GDD---		days	---GDD---		days	---GDD---		days
Shattercane	42	950	38	153	1410	35	484	1010	24
Ivyleaf morningglory	42	867	35	570	2280	45	----[1]	----	----
Prickly sida	42	525	21	200	1400	33	----	----	----

[1] no observation(s) in 2008

Table 2.4 Parameter estimates for ivyleaf morningglory cumulative emergence expressed as a function of cumulative growing degree days used to fit the logistic emergence model (equation 1) for each weed species.

			Year 1					Year 2				
			Parameter estimates					Parameter estimates				
Weed Species	Initiation year	Treatment	Em_h	b	GDD_m	Em_o	R^2	Em_h	b	GDD_m	Em_o	R^2
Ivyleaf	2006	No crop	----	0.52	----	----	0.93	----	----	----	----	----
Morningglory		No herbicide	161.6	-0.8	1820	7.66	0.94	8.9	-2.6	655.9	-0.2	0.97
		Half rate	1.6	-10.6	----	----	----	11.8	-2.1	925.9	0.02	0.97
		Full rate	----	95	-19	14	0.47	8.07	-3.3	880.2	0.04	0.92
	2007	No crop	----	----	----	----	----	·	·	·	·	·
		No herbicide	0.28	-57.1	969.8	0.22	0.88	·	·	·	·	·
		Half rate	----	----	----	----	----	·	·	·	·	·
		Full rate	1.7	-4.74	660.6	0.26	0.95	·	·	·	·	·

---- model couldn't give biologically meaningful estimates (Emergence numbers too low)

· no data collected

Table 2.5 Parameter estimates for cumulative emergence expressed as a function of cumulative growing degree days used to fit the logistic emergence model for weed species (data pooled).

		Parameter estimates				
Weed species	Initiation year	Em_h	b	GDD_m	Em_0	R^2
Shattercane (Pooled)	2006	665	-2.5	655	52	0.92
	2007	393	-0.6	292	-0.6	0.47
	2008	14	-6.9	-600	1	0.44
Prickly sida (Pooled)	2006	71	-13	-397	20	0.92
	2007	---	1.3	-288	35	0.95
	2006 (2nd yr)	47	-0.99	459	-1.02	0.79

CHAPTER 3 - Interaction of Herbicide Choice and Rate Based on Weed Species and Density

ABSTRACT

The use of foliar applied herbicides at high weed density could result in ‘safe sites’ for smaller plants due to overlapping leaf canopies. Plants generally are most susceptible to herbicides at early growth stages. Experiments were conducted to evaluate how grass and broadleaf weed density interacts with herbicide choice and rate as well as to evaluate the influence of velvetleaf growth stage and density on herbicide efficacy. In a field study, soybean was planted at 300,000 seed ha^{-1} in 0.76-m rows in 2006 and 2007. Within the herbicide main plot, either large crabgrass or shattercane; or Palmer amaranth or velvetleaf seed were sown in separate subplots at nine targeted densities in a 0.36 m^2 area. Clethodim or glyphosate was applied to grass species plots, while lactofen or glyphosate was applied to the broadleaf species plots at 1.0, 0.5, 0.25, 0.125, 0.0625, and 0.03125X of labeled rates. In a greenhouse study, velvetleaf was planted at densities of 5, 30, and 60 plants per pot. Glyphosate or lactofen herbicides were applied at 1.0, 0.5, 0.25, and 0.125X of the labeled rates to velvetleaf seedlings at the 2-, 4-, and 6-leaf stages. Untreated checks were included for comparisons. In the field study, as large crabgrass density increased, percent mortality decreased with clethodim while both grass species were not affected by density when treated with glyphosate. Shattercane was more susceptible than large crabgrass to both herbicides. Across densities 0.1X rate of clethodim or glyphosate reduced shattercane dry weight to 0 g while 0.5X of labeled rate of both herbicides was required for complete large crabgrass control. At all densities, the 0.5X rate of glyphosate reduced dry weight to 0 g in 2006 for broadleaf species. In the greenhouse, the 0.125X rate of glyphosate at a density of 5 seedlings per pot, achieved more than 90% mortality when applied to velvetleaf at 2-leaf stage but control dropped to 60 and 50% when applied at the 4- and 6-leaf stages, respectively. The trend was the same for velvetleaf at 30 plants per pot, which had 80, 60, and 55% mortality when applied at 2-, 4-, and 6-leaf stages, respectively. A rate of 0.1X of glyphosate reduced velvetleaf dry weight to 0 g at 5 plants per pot for all leaf stages. At a

velvetleaf density of 30 plants per pot, 0.1X rate of glyphosate reduced dry weight to 0 g for 2- and 6-leaf stages, however, 0.50X glyphosate rate was required to reduce dry weight of the same magnitude at the 4-leaf stage. Weed management outcomes are dependent on weed species, weed density, weed growth stage, herbicide choice, and herbicide rate. Therefore, improvement in weed control could be achieved if weed managers and farmers could match the herbicide choice and rate to individual weed species in patches that vary in density.

Nomenclature: glyphosate; clethodim; lactofen; large crabgrass, (*Digitaria sanguinalis* (L) Scop. DIGSA; shattercane, *Sorghum bicolor* (L.) Moench ssp. *arundinaceum* SORVU; Palmer amaranth, *Amaranthus palmeri* S. Wats AMAPA; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; Soybean, [*Glycine max* (L.) Merr. 'DKB 36-52'];

Key words: dose response, dry weight, herbicide rate, mortality, weed density

INTRODUCTION

The spatial variability of weed seedlings in agricultural fields is well documented. Weed seedlings occur in patches of varying sizes and densities and field areas may have few or no weed seedlings (Christensen and Heisel 1998; Johnson et al. 1995; Marshall 1988). Farmers and managers can exploit spatial variability of weed seedlings by employing site specific weed management (SSWM) practices such as applying herbicide only to where there are weed seedlings.

Annual weeds were controlled and residual herbicide use reduced with SSWM in corn (Donald et al. 2004). In nontransgenic and glyphosate-tolerant soybean, SSWM resulted in $105 and $96 net gain per hectare, respectively, compared to broadcast herbicide application (Medlin and Shaw 2000). Herbicide use was reduced by 39% using SSWM based on a weed seedling map and by 24% for a mature weed map relative to broadcast application, indicating that mapping weeds at an earlier stage was better than mapping later in the growing season (Koller and Lanini 2005). Compared with conventional application, atrazine usage as a preemergence herbicide in corn was decreased by 43% using SSWM; while variable rate application of dicamba as postemergence treatment reduced herbicide input by 47% relative to conventional treatment (Tredaway-Ducar et al. 2003). Variable-rate spraying based on maps created from estimating weed population density and levels of infestation just before harvest the previous year gave the best weed control (Koller and Lanini 2005). Uncontrolled velvetleaf can cause 55% yield loss in soybean (Akey et al. 1991). This shows how important weed control is in soybean. Herbicide reductions due to the use of SSWM are in the range of 40 to 60% (Stafford and Miller 1997). Even if site specific weed management had only a marginal advantage, Rider et al. (2006) indicated that it is important. Site specific weed management reduces herbicide use (Goudy et al. 2001; Johnson et al. 1995, Vogel 2005; Williams et al. 1999).

The traditional measure of herbicide efficacy, or plant response to herbicide application, is percent control capturing both reduced density and size of survivors (Mortensen and Dieleman 1998). To understand herbicide efficacy and mode of action, the relationship between herbicide rate and plant response is important (Seefeldt et al. 1995) as this will help weed managers and farmers in knowing how much herbicide to apply. Plant susceptibility to herbicide is quantified by a dose-response curve.

Plants are most susceptible to postemergence herbicides at early growth stages. Growth stage influences plant size, surface area, cuticle composition, and source to sink relationship (Chism et al. 1992). Chism et al. (1992) reported that control of southern crabgrass (*Digitaria ciliaris* L.) by quinclorac was influenced by plant growth stage. Mature crabgrass plant had higher GR_{50} values as compared to early growth stages. They used nonlinear regression to compare the influence of growth stage on herbicide efficacy. Schuster et al. (2007) found that common lambsquarters (*Chenopodium album* L.) treated with glyphosate at 1.1 kg ae ha^{-1} caused more than 80% injury to 2.5-cm plants but less than 55% injury to 7.5- and 15-cm plants. Herbicide efficacy was reduced as *Amaranthus* increase in size and growth stage (Coetzer et al. 2002, Stouggard et al. 1997).

Herbicide efficacy is also influenced by plant characteristics such as growth habit, leaf morphology and leaf orientation. Large crabgrass, shattercane, Palmer amaranth and velvetleaf are important weeds in soybean in Kansas. Large crabgrass is a prostrate plant while shattercane is an erect plant. Palmer amaranth and velvetleaf are summer annuals with erect growth habit but the leaves and stem of velvetleaf are covered with hairs while Palmer amaranth is smooth. These characteristics could lead to different abilities to retain and absorb postemergence herbicide.

Weed distribution is not uniform across a field as weeds tend to be clumped in patches of high densities along with areas of low to no weeds present (Wiles et al 1992). Percent control, as a standard method of assessing herbicide efficacy, does not take into consideration the interaction between weed density and mortality. It can be predicted for foliar-applied herbicides that high weed density could result in 'safe sites' for smaller weeds due to overlapping leaf canopies resulting in poor herbicide efficacy since small individuals can escape application (Mortensen and Dieleman 1998). Other mechanisms between density and herbicide are mode of action and competition (size, drought stress, and biomass). At high densities plants tend to be smaller as compared to low densities. Systemic herbicides do well at high densities while contact herbicides fair poorly at high densities because of coverage issues. Dieleman et al. (1999) reported that high initial velvetleaf and common sunflower (*Helianthus annuus* L.) seedling density resulted in more survivors after application of a weed management treatment compared to low seedling density. This indicates the need to match herbicide choice and rate to individual weed patches that vary in density. This would be a key step for SSWM. The objective of this study was to evaluate large crabgrass, shattercane, Palmer amaranth, and velvetleaf mortality and dry weight in response to herbicide choice and varying herbicide rates across a range of densities as well as to determine the influence of velvetleaf growth stage and density on herbicide efficacy.

MATERIALS AND METHODS

Field studies. Field studies were conducted in 2006 and 2007 at the Department of Agronomy Ashland Bottoms Research Farm near Manhattan, KS. Dekalb® soybeans (DKB 36-52) were no-till planted at 300,000 seeds ha^{-1} on May 17, 2006 and May 18, 2007. The experimental design was a split-split-split plot with herbicide choice as main plot (three soybean rows wide by 60 m long), herbicide rate as subplot (three soybean rows wide by 5.4 m), and weed densities as sub-subplots (60-cm by 60-cm). For the 2006 study, velvetleaf seeds were obtained from the University of Nebraska[1] and for 2007, they were collected from the Ashland Bottoms Research Farm. Palmer amaranth seeds were collected from the Department of Agronomy Ashland Bottoms Research Farm in 2005 and 2006. Large crabgrass and shattercane seeds were obtained from Valley Seed Service[2] in 2006 and Azlin Seed Service[3] in 2007. Within the herbicide main plots two grass weed species (large crabgrass and shattercane) or two broadleaf weed species (Palmer amaranth and velvetleaf) were sown in separate herbicide rate subplots. Herbicides were applied at fraction of labeled rates equivalent to 1.0, 0.5, 0.25, 0.125, 0.0625, and 0.03125X along with an untreated control to each herbicide rate subplot. Weed species were sown at densities of 5, 10, 20, 40, 80, 160, 320, 640, and 1200 seed in a 60-cm by 60-cm sub-subplot. A total of 63 sub-subplots for each herbicide choice by weed species combination (7 rates by 9 densities) were established and replicated three times. Weed seedlings were counted in a 30-cm by 30-cm quadrat in the center of each density sub-subplot before postemergence application.

Herbicides applied on grass weed species were clethodim (1.0X = 0.28 kg ai ha^{-1}) or glyphosate (1.0X = 1.54 kg ai ha^{-1}). Lactofen (1.0X = 0.18 kg ai ha^{-1}) or glyphosate (1.0X = 1.54 kg ai ha^{-1}) were applied to broadleaf weed species. Glyphosate spray mixture included 2% ammonium sulfate (UAN, wt wt^{-1}), while clethodim and lactofen mixtures included 1% and 0.25% crop oil concentrate (COC, vol vol^{-1}), respectively. Herbicides were applied with a CO_2 backpack sprayer using a 4-nozzle boom equipped with a half-step log sprayer controller (R & D sprayers[4]) to 15-cm tall weeds. Treatments were applied on June 21 in both years. Sprayer tips used were Tee Jet 8002 VS[5].

Four weeks after postemergence application, surviving weed seedlings in the 30-cm by 30-cm quadrat at the center of each density sub-subplot were counted and then severed at ground level, dried in an oven at 66°C for four days and aboveground biomass (g plot^{-1}) measured. Percent mortality was calculated as reduction in seedling density due to postemergence application:

$$\% \text{ mortality} = \frac{(\text{no. seedling BA} - \text{no. seedling AA})}{\text{no. seedling BA}} \times 100 \qquad [3.1]$$

where no. is the number, BA denotes before application, and AA denotes after application.

Differences in percent mortality and dry weight responses across years, herbicide choice, weed species, herbicide rate, and density were tested using Proc Mixed (SAS version 9.1 2003)[6]. Years were different and analyzed separately. Interactions among herbicide choice, weed species, herbicide rate, and weed density for percent mortality and dry weight were tested using Proc GLM (SAS version 9.1 2003). Data were presented separately if interactions were found. For each combination of herbicide choice and weed species, percent mortality data were plotted in response to weed density by herbicide rate.

Dry weight data were plotted in response to herbicide rate for each combination of herbicide choice, weed species, and weed density. Nonlinear regression analysis was used to fit the Mitscherlich model, a three parameter exponential model, to the dry weight data (Chism et al. (1992):

$$\text{Dry weight} = B_0 + B_1 * \exp(-B_2 * \text{Rate}) \qquad [3.2]$$

where dry weight is the aboveground biomass (g plot^{-1}), B_0 is the lower asymptote of aboveground biomass at high herbicide rates (g plot^{-1}), B_1 is the reduction in aboveground biomass from the upper to the lower asymptote (g plot^{-1}); B_2 is the slope or rate at which the lower asymptote is obtained (established as 1/Rate), and Rate is the fraction of herbicide applied relative to the labeled rate of 1.0X. Pseudo R^2 values were used to assess goodness-of-fit (Chism et al. 1992) and were determined for each combination of weed species, herbicide choice, and weed density by 1 - (sums of squares residual / corrected total sums of squares).

To establish if dry weight response curves were different across weed densities for a given herbicide choice and weed species, confidence intervals were calculated. If the upper and lower confidence intervals of two densities overlapped for a given entire curve fit, then they were considered not statistically different. The advantage of this approach was that the curves were based on replicate variability (Dr. Leigh Murray, Statistician, Department of Statistics, Kansas State University, personal communication).

Greenhouse study. The greenhouse study was conducted to determine the influence of velvetleaf growth stage and density on herbicide efficacy. Velvetleaf seeds were sown into 14-cm diameter by 11-cm high pots filled with Metro-mix® 360[7] growing medium. Velvetleaf densities were 5, 30, and 60 plants per pot. The two herbicides investigated were lactofen and glyphosate. Herbicide rates were 1.0, 0.5, 0.25, and 0.125X of the labeled rate for each herbicide as previously listed. Herbicides were applied to velvetleaf seedlings at 2-, 4-, and 6-leaf stages. An untreated check was included for comparisons. The treatments were established as a factorial arrangement in a completely randomized design. A total of 90 pots were used for one replication. The experiment was replicated three times and repeated. Growing conditions in the greenhouse were 26/22 ± 5 ºC day/night temperatures, with a 14/10-h day/night period, and supplemental light of 240 $\mu mol^{-2}s^{-2}$ photosynthetic photon flux. Herbicides were applied with a bench-type sprayer[8] equipped with 80015LP[5] spray tip. The sprayer was calibrated to deliver 187 L ha^{-1} at 138 kPa. All lactofen treatments included COC at 1.0% vol vol^{-1}while glyphosate treatments included UAN. The untreated no herbicide controls were sprayed with water plus COC or UA. At three WAT, surviving plants were harvested at ground level in each pot, dried in an oven, and biomass measured (g pot^{-1}). Differences in repeats for percent mortality and biomass data were tested using Proc Mixed (SAS version 9.1 2003). Repeats for percent mortality were not different and the data were combined. Repeats for biomass data were different and were analyzed separately. Proc GLM (SAS version 9.1 2003) was used to test percent mortality and biomass data for significant interactions among herbicide choice, herbicide rate, growth stage, and velvetleaf density. Nonlinear regression analysis was used to fit the model (equation 3.2) to the biomass data as was done with the field study.

RESULTS AND DISCUSSION

Field study. There was a good correlation between the number of weed seed planted in a 60-cm by 60-cm plot and the actual number of seedlings that emerged and were counted in each 30-cm by 30-cm plot (data not shown).

Percent Mortality. For grass weed species, one 3-way significant interaction for percent mortality occurred among weed species, herbicide rate, and weed density in 2007. For broadleaf species in 2006 and 2007, two 3-way significant interactions were observed among herbicide choice, herbicide rate, and Palmer amaranth and velvetleaf; and among herbicide choice, weed species, and weed density; while in 2007, a significant interaction among herbicide rate, weed species, and weed density was also observed. Due to these treatment interactions, percent mortality data were presented by weed species and herbicide choice across the different weed densities for specific herbicide rates.

In 2007, 100% mortality was observed for both shattercane and large crabgrass across all densities at the 1.0X labeled rate of clethodim (Figure 3.1). For shattercane 0.5X rate was as effective as the 1.0X rate in reducing seedling densities, while 90% mortality was observed with 0.25X rate averaged across densities. For large crabgrass, percent mortality decreased as density increased with 0.5X and 0.25X rates of clethodim. Percent mortality of shattercane was not affected by density except at 0.25X rate while large crabgrass had differential responses to 0.5 and 0.25X rates of clethodim (Figure 3.1). Percent mortality of shattercane and large crabgrass in 2007 in response to all rates of glyphosate was 100% (data not shown). No density effect was observed with glyphosate for either grass species. In comparing the two herbicide choices, glyphosate application resulted in higher mortality of both species than clethodim. Shattercane was more susceptible than large crabgrass to both clethodim and glyphosate. At labeled rates for both products, percent mortality of shattercane was not affected by density. In general, shattercane had a higher mortality than large crabgrass.

In 2007, the 1.0X labeled rate of lactofen did not provide 100% mortality of velvetleaf at any density or Palmer amaranth except for a very low density of 5 seed 0.36 m^{-2} (Figure 3.2). Velvetleaf at low densities (5, 10, and 20 seed 0.36 m^{-2}) had high survivorship in response to 1.0, 0.5, and 0.25X rates of lactofen compared to high densities (640 and 1200 seed 0.36 m^{-2}) (Figure 3.2). High percent mortality was observed for Palmer amaranth at low densities, and as density increased, percent mortality decreased across the three herbicide rates (Figure 3.2). With lactofen, different effects of density were observed for velvetleaf compared to Palmer amaranth such that increasing velvetleaf density resulted in increased percent mortality while increasing Palmer amaranth density resulted in decreased percent mortality.

In 2006, the 1.0 and 0.5X rates of glyphosate achieved 100% velvetleaf mortality for densities of 5, 10, 20, and 40 seed 0.36 m^{-2}, after which percent mortality decreased as density increased from 80 to 1200 seed 0.36 m^{-2} (Figure 3.3A). In 2007, none of the glyphosate rates provided 100% mortality of velvetleaf and percent mortality decreased as density increased for 1.0 and 0.5X rates while percent mortality increased as density increased with the 0.25X rate of glyphosate (Figure 3.3B). Palmer amaranth had 100% mortality in response to the 1.0X rate of glyphosate in 2006 across all densities (Figure 3.3C). The combination of lower Palmer amaranth densities (5 to 80 seed 0.36 m^{-2}) and lower glyphosate rates of 0.5 and 0.25X resulted in at least 90% or more mortality. In 2007, as Palmer amaranth density increased, percent mortality decreased across the three glyphosate rates (Figure 3.3D). With lower glyphosate rates, percent mortality was less for both velvetleaf and Palmer amaranth as density increased. Though percent mortality of both species was affected by density when treated with glyphosate, Palmer amaranth was less influenced by density than velvetleaf. In comparing the two herbicide choices, glyphosate provided a higher overall percent mortality at high densities for velvetleaf and Palmer amaranth than lactofen in both years. Palmer amaranth had a higher percent mortality that velvetleaf.

Dry weight. Across the four weed species, as weed density increased, aboveground weed dry weight per 0.09 m^2 plot increased with no herbicide application (data not shown). Across the grass weed species, a significant 3-way interaction among herbicide rate, weed species, and weed density was observed for dry weight in 2006 and 2007, while a significant 3-way interaction among herbicide choice, herbicide rate, and weed species was observed in 2007. Due to these significant interactions, dry weight data will be presented by herbicide choice and weed species given different weed densities for each year. For broadleaf weeds, a significant 3-way interaction among herbicide choice, herbicide rate, and weed species was observed in 2006. For this part of the study, the focus will be on three densities which represent low (10), medium (160) and high (1200) densities of the seed sown per 0.36 m^{-2} plot.

Selection of an appropriate nonlinear equation requires consideration of the ability of the equation to fit the data as well as the investigator's ability to interpret the biological significance of the estimated parameters (Chism et al. 1992). The model was picked because it provides estimates of nonlinear regression parameters, a method of calculating pseudo R^2 values for goodness-of-fit, and a method of comparing between nonlinear regressions such as stages and densities. Equation 3.2 was fit to dry weight data by year, by weed species, and by herbicide choice.

The fit of equation 3.2 to the data was excellent with high pseudo R^2 (Table 3.1) The model fits in 2006 for shattercane treated with clethodim had pseudo R^2 values of 0.96, 0.95, and 0.95 for densities 10, 160, and 1200, respectively, while pseudo R^2 values of 0.87, 0.91, and 0.86 were obtained for shattercane treated with glyphosate (Table 3.1). The model fits in 2006 for large crabgrass treated with clethodim had pseudo R^2 values of 0.34, 0.64, and 0.90 for densities 10, 160, and 1200, respectively, while large crabgrass treated with glyphosate had pseudo R^2 values of 0.43, 0.47, and 0.61 for the same densities in 2006. Pseudo R^2 values were 0.53 and higher for model fits for clethodim- and glyphosate-treated shattercane in 2007. Greater than 0.80 pseudo R^2 were obtained for both clethodim and glyphosate in 2007 for large crabgrass. The model fits in 2006 for Palmer amaranth had pseudo R^2 values of 0.19 and higher when treated with lactofen while model fits in 2006 for glyphosate-treated Palmer amaranth had pseudo R^2 values of 0.43 and higher (Table 3.1). In 2007, pseudo R^2 values of 0.25 and higher were obtained for Palmer amaranth model fits across both herbicides. Model fits for velvetleaf had pseudo R^2 of 0.47 and higher when treated with either herbicide in both years.

The lower asymptote of aboveground biomass at high herbicide rates, represented by parameter B_0, was close to zero for both shattercane and large crabgrass for both herbicides and in both years (Table 3.1). This indicates that high rates of both herbicides resulted in almost no aboveground biomass for the two grass weed species at 4 WAA (Figure 3.4). Palmer amaranth and velvetleaf had B_0 values greater than zero across most herbicide and density factors (Table 3.1). This indicates that high rates of both herbicides did not completely eliminate aboveground biomass of these two weed species by 4 WAA (Figure 3.5). Standard error values are presented on Table 3.1.

The aboveground biomass reduction from the upper to lower asymptote, represented by parameter B_1, indicated the estimated amount of aboveground biomass that was controlled as herbicide rate increased from 0 to 1.0X for each weed species and herbicide choice. Shattercane had more aboveground biomass controlled in each year, weed density, and herbicide choice when compared to large crabgrass except for 2007 at low densities of 10 seed sown 0.36 m^{-2} (Table 3.1). The values for B_1 for the shattercane models were larger than that of the large crabgrass models due to the two species difference in growth habit. Figure 3.4 highlights that the amount of aboveground biomass produced by shattercane across densities is greater in comparison to large crabgrass. In 2006, the amount of aboveground biomass reduced for Palmer amaranth with lactofen ranged between 27.5 (±6.5) g and 33.2 (±7.8) g 0.09 m^{-2} and with glyphosate the aboveground biomass was reduced between 24.6 (±4.9) g to 33.8 (±5.8) g 0.09 m^{-2} across densities (Table 3.1). Aboveground biomass production by velvetleaf at the 160 seed 0.36 m^{-2} density was higher across years (Figures 3.5E-H) and thus, higher B_1 values of 47.7 (±16.6) g 0.09 m^{-2} with lactofen and 69.5 (±12.8) g 0.09 m^{-2} with glyphosate in 2006 compared to the reduction in biomass at the other densities with 19.6 (±5.6) g to 26.4 (±8.4) g 0.09 m^{-2} with lactofen and 36.6 (±4.4) g to 49.2 (±9.3) g 0.09 m^{-2} with glyphosate (Table 3.1). In 2007, both velvetleaf and Palmer amaranth had higher B_1 values when treated with glyphosate, indicating more aboveground biomass reduction compared to lactofen (Figure 3.5). The plant architecture of the two weed species seems to play a role. Shattercane has an erect growth habit, which helps in intercepting herbicide as compared to large crabgrass, with a prostrate growth habit and roots at nodes which helps the plant to re-grow after herbicide application. This could explain the 3-way interaction that was observed among species (shattercane and large crabgrass), herbicide rate, and density for a given herbicide.

Parameter B_2 represents the slope or rate at which aboveground biomass is reduced to the lower asymptote and is measured as 1/Rate. In 2006 for the low density, less clethodim for shattercane and less clethodim or glyphosate for large crabgrass were needed to reach the lower asymptote compared to the rates needed for the medium and high densities (Table 3.1). Less glyphosate was needed to reach the lower biomass asymptote for shattercane at the medium density compared to the low or high density (Figure 3.4) because of less total biomass present. In 2007, within a herbicide choice and grass weed species, no differences were observed in the rate at which the lower asymptote was reached (Figure 3.4) (SE around parameter estimates on Table 3.1). More lactofen was needed to reduce the aboveground biomass to the lower asymptote of the two broadleaf weed species compared to glyphosate across densities for each year (Table 3.1 and Figure 3.5). In general, more lactofen or glyphosate was needed to reduce velvetleaf aboveground biomass to the lower asymptote compared to Palmer amaranth across densities and years. The only exception was glyphosate in 2006 at medium and high densities of velvetleaf or Palmer amaranth because it was warm and dry. (Figure 3.5).

Shattercane dry weight was predicted to be 0 g 0.09 m^{-2} when sprayed with 0.135X or more of the clethodim labeled rate across the three densities of 10, 160 or 1200 seed 0.36 m^{-2} in 2006 (Figure 3.4A). Compared to 2007, 0.135X of clethodim labeled rate reduced the low shattercane density to 0 g but up to 0.51X is needed for the medium density and 1.0X was not sufficient to reduce shattercane biomass to 0 g 0.09 m^{-2} at the high density (Figure 3.4C). In response to glyphosate, shattercane dry weight was reduced to 0 g when 0.135X of the labeled rate was applied across densities in both years except for density 1200 (Figure 3.4B and D). In 2006, 1.0X of the glyphosate labeled rate did not reduce large crabgrass dry weight to 0 g across any of the densities while in 2007, 0.135X of the glyphosate rate reduced large crabgrass dry weight to 0 g 0.09 m^{-2} across all densities (Figure 3.4F and H).

Glyphosate-resistant soybean varieties have become a major component of soybean weed management systems. Glyphosate is a broad-spectrum, nonselective, translocated, postemergence herbicide that effectively controls many annual, biennial, and perennial weed species (Franz et al. 1997). Glyphosate inhibits the 5-enolpyruvylshikimate-3-phosphate synthase enzyme, thereby blocking the synthesis of the aromatic amino acids phenyl-alanine, tyrosine, and tryptophan (Grossbard and Atkinson 2003). The level of activity of glyphosate depends on the weed species, growth stage, and weather conditions during and after application (Vangessel et al. 2000). Clethodim is a graminicide registered for use in cotton, peanut (*Arachis hypogea* L.), and soybean (Anonymous 2001). Clethodim is a member of the cyclohexanedione family whose mode of action is the inhibition of the acetyl-CoA carboxylase enzyme and lipid synthesis, which interferes with cellular membranes production and causes the death of treated plants in two to three weeks (Rosales-Robles et al. 2001). Lactofen is a contact herbicide commonly used to control broad leaf weeds in soybean. Lactofen is a member of the diphenyl ether chemical family that is commonly used to control broad leaf weeds in soybean, potatoes, and peanuts (WSSA 2007). Lactofen targets protoporphyrinogen oxidase, which in turn causes singlet oxygen generation. Clethodim accumulates at the growing points while glyphosate is translocated throughout the plant, eventually causing plant death (WSSA 2007).

Palmer amaranth or velvetleaf dry weights were not predicted to be 0 g 0.09 m^{-2} at any density with the 1.0X rate of lactofen in either year (Figure 3.5A, C, E, and G). When treated with lactofen, both Palmer amaranth and velvetleaf dropped the treated leaves and new growth occurred from axillary buds as a compensatory response because lactofen is a contact herbicide and not translocated. Density dependent would mean that increasing the density does not necessary means that there will be an increase in biomass. In 2006, Palmer amaranth response was not density dependent; however, in 2007 the response was density dependent as the density of 160 gave the highest dry weight, far more than density 1200. Velvetleaf was density dependent in both years. These results confirmed the findings of Bussan et al. (2001) who reported that velvetleaf dry weight was density dependent. Glyphosate was predicted to reduce Palmer amaranth and velvetleaf dry weight to 0g when treated with 0.51X of the labeled rate in 2006 (Figure 3.5B and F). In 2007, 1.0X of the labeled glyphosate rate did not reduce dry weight to 0 g for the medium and high densities of Palmer amaranth or velvetleaf (Figure 3.5D and H). Irrespective of the biomass produced by plants at different densities, results indicated that at low densities, a low rate of herbicide reduced dry weight. Glyphosate controlled these broadleaf species better than lactofen. Systemic herbicides are more effective than contact herbicides on weeds at high densities. Systemic herbicide can be translocated throughout the plant while contact herbicides kill plants parts that come into contact with the herbicide.

The choice of herbicide is critical; at higher densities, systemic herbicide such as glyphosate should be used. With lactofen, low velvetleaf densities had high survivorship; while low Palmer amaranth densities had low survivorship. Before weed control measures are taken, weed species, weed densities, herbicide choice and herbicide rate should be taken into consideration. The use of lower herbicide rates should be done with caution as weed species respond differently. For large crabgrass and velvetleaf, the use of reduced herbicide rates may need to be integrated with other weed management practices. This information is of importance as growers are interested in any steps, including the use of reduced rates, without compromising crop yields or increasing future weed problems.

Greenhouse study. A significant 4-way interaction for percent mortality among herbicide choice, herbicide rate, velvetleaf density, and growth stage was observed. Thus, results were presented separately by herbicide choice, herbicide rate, growth stage, and density. Glyphosate provided greater control of velvetleaf compared to lactofen, irrespective of herbicide rates, growth stage or density (Figure 3.6A-D vs. Figure 3.6 E-H). High rates of glyphosate had high levels of percent mortality, no matter the growth stage or density. Low rates of glyphosate were much more variable, with poor percent mortality at later growth stages and higher densities

(Figure 3.6A). Low rates of lactofen provided no or very low mortality of velvetleaf across growth stages or densities. High rates increased percent mortality but only up to 30% (Figure 3.6H). Schuster et al. (2007) found that common lambsquarters (*Chenopodium album L.*) treated at 2.5, 7.5 and 15-cm heights with glyphosate at 1.1 kg ae ha^{-1} (this is 1.0X labeled rate) caused more than 80% injury to 2.5-cm plants but less than 55% injury to 7.5 and 15-cm plants. Early growth stages are more susceptible to herbicides than later stages (Coetzer et al. 2002) because herbicide efficacy is reduced as weeds increase in size (Stouggard et al. 1997). This trend was observed in this study with velvetleaf.

A significant 3-way interaction was observed for velvetleaf dry weight data among herbicide rate, growth stage and velvetleaf density. Due to that fact that the repeats were differed statistically, results were presented separately by repeats. The nonlinear regression model (equation 3.2) was fit to the velvetleaf dry weight data for each herbicide choice, herbicide rate, growth stage and density. Pseudo R^2 values were used to assess goodness-of-fit (Table 3.2 and 3.3).

In general, B_0 values were greater for lactofen across densities and growth stages compared to glyphosate, indicating that lactofen could not reduce velvetleaf dry weight as much as glyphosate (Table 3.2). Parameter B_1 describes the reduction in biomass from upper to lower asymptote and in general, glyphosate reduced velvetleaf biomass more than lactofen for a given density and growth stage. For example, a velvetleaf density of 30 plants per pot treated at the 2-leaf stage with glyphosate had its biomass reduced by 6.4 or 4.2 g per pot for each repeat, respectively, compared to only 4.1 or 2.7 g per pot when treated with lactofen (Table 3.2). As velvetleaf density increased from 5 to 60 plants per pot, more biomass was reduced with glyphosate across the growth stages and repeats. Parameter B_2 is the slope or rate at which biomass reaches the lower asymptote and B_2 values were high for the low velvetleaf density across growth stages. This indicates that a low glyphosate rate (1/Rate) was needed to reduce biomass to the lower asymptote. A higher rate of glyphosate herbicide was needed at higher velvetleaf densities (Table 3.2). The parameter estimates for lactofen generally had higher B_2 values at lower densities, indicating that lower lactofen rates would reduce velvetleaf biomass to the asymptote.

Differences in repeats for percent mortality and biomass data were tested using Proc Mixed (SAS version 9.1 2003). Repeats for percent mortality were not different and the data were combined. Repeats for biomass data were different and were analyzed separately. For all leaf stages, 0.135X of the glyphosate labeled rate reduced velvetleaf dry weight to 0 g at 5 plants per pot (Figure 3.7A). For 30 plants per pot, 0.26X of glyphosate labeled rate reduced dry weight to 0 g at the 2- and 6-leaf stages while the 0.51X rate was required to reduce dry weight to 0 g for the 4-leaf stage (Figure 3.7 C). For 60 plants per pot, the 6-leaf stage required 0.26X to reduce dry weight to 0 g while 2- and 4-leaf stages required 0.51X glyphosate rate (Figure 3.7E). Similar trends were observed for the second experimental run (Figure 3.8A, C, and E). The 1.0X rate of lactofen failed to reduce dry weight to 0g across all densities and leaf stages for both experimental repeats (Figure 3.7B, D, and F; Figure 3.8A, D, and F). Seedlings treated with glyphosate had significantly less dry weight as compared to those treated with lactofen. The 1.0X rate gave the lowest dry weight as compared to the other herbicide rates but it was similar to the 0.5X rate (Figure 3.7 and 3.8). Results indicated that glyphosate reduced velvetleaf dry weight more than lactofen.

Results of this study showed that velvetleaf was susceptible to glyphosate and lactofen at early seedling stages; however as seedling growth stage increased, tolerance to herbicide also increased. The 1X glyphosate rate controlled velvetleaf at all growth stages and densities; however, lactofen failed to achieve 100% control even at early stages and low densities. Lactofen is not a good herbicide to control velvetleaf and is now labeled only for suppression at 4-leaf stage and smaller.

Irrespective of the biomass produced by the weed seedlings at different densities, results indicated that at low densities low rate of herbicide is required to reduce dry weight by 50%. When scouting fields, weed species, weed growth stage, and weed density are of importance. Weed management outcomes (percent mortality and dry weight reduction) are dependent on weed species, weed density, weed growth stage, herbicide choice, and herbicide rate. Therefore, improvement in weed control could be achieved if weed managers and farmers could match the herbicide choice and rate to individual weed species in patches that vary in density.

SOURCES OF MATERIALS

[1] University of Nebraska-Lincoln, Lincoln, NE 68588

[2] Valley Seed Service, P.O. Box 9335, Fresno, CA 93791

[3] Azlin Seed Service, P.O. Box 914, Leland, MS 38756

[4] R and D Sprayers Inc, 419 Hwy 104, Opelousas, LA 70570

[5] Sprayer tip, TeeJet XP Spraying Systems Co., North Ave., Wheaton, IL 60188

[6] Statistical Analysis Systems, Version 9.1. 2003. Statistical Analysis Systems Institute Inc. 100 SAS Campus Drive, Cary, NC 27513-2414.

[7] Metro-mix® 360, SUN GRO Horticulture Distribution Inc., 15831 N.E. 8th street, Suite 100, Bellevue, WA 98008

[8] Research Track Sprayer SB-8. Devries Manufacturing, RR 1, Box 184, Hollandale, MN 56045.

REFERENCES

Akey, W. C., T. W. Jurik, and J. Dekker. 1991. A replacement series evaluation of competition between velvetleaf (*Abutilon theophrasti*) and soybean (*Glycine max*). Weed Res. 31:63-72.

Anonymous, 2001. Select 2EC®, Pages 2606-2614 *in* Crop Protection Reference. 17th ed. New York: C & P Press.

Bussan, A. J., C. M. Boerboom, and D. E. Stoltenberg. 2001. Response of velvetleaf demographic processes to herbicide rate. Weed Sci. 49:22-30.

Chism, W. J., J. B. Birch, and S. W. Bingham. 1992. Nonlinear regressions for analyzing growth stage and quinclorac interactions. Weed Technol. 6:898-903.

Coetzer, E., K. Al-Khatib, and D. E. Peterson. 2002. Glufosinate efficacy on *Amaranthus* species in glufosinate-resistance soybean (*Glycine max*). Weed Technol. 16:326-331.

Christensen, S. and T. Heisel. 1998. Patch spraying using historical, manual and real-time monitoring of weeds in cereals. Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz XVI, 257.

Dieleman, J. A. and D. A. Mortensen. 1999. Characterizing the spatial pattern of *Abutilon theophrasti* seedling patches. Weed Res. 39:455-467.

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 Sci. 47:81-89.

Donald, W. W., D. Archer, W. G. Johnson, and K. Nelson. 2004. Zone herbicide application controls annual weeds and reduces residual herbicide use in corn. Weed Sci. 52:821-833.

Franz, J. E., M. K. Mao, and J. A. Sikorski. 1997. Glyphosate- A Unique Global Herbicide. ACS Monograph 189. Washington, DC: American Chemical Society, 653 p.

Goudy, H. J., K. A. Bennett, R. B. Brown, and F. J. Tardif. 2001. Evaluation of site-specific weed management using a direct-injection sprayer. Weed Sci. 49:359-366.

Grossbard, E. and D. Atkinson, eds. 1985. The Herbicide Glyphosate. London: Butterworths, pp. 49-57.

Johnson, G. A., D.A. Mortensen, and A.R. Martin. 1995. A simulation of herbicide use based on weed spatial distribution. Weed Res. 35:197-205.

Koller, M. and W. T. Lanini. 2005. Site-specific herbicide applications based on weed maps provide effective control. California Agriculture 59(3):182-187.

Marshall, E.J.P. 1988. Field-scale estimates of grass population in arable land. Weed Res. 28:191-197.

Medlin, C. R. and D. R. Shaw. 2000. Economic comparison of broadcast and site-specific herbicide applications in nontransgenic and glyphosate-tolerant *Glycine max*. Weed Sci. 48:653-661.

Mortensen, D. A. and J. A. Dieleman. 1998. Why weed patches persist: dynamics of edges and density. Pages 14-19 *in* R. W. Medd and J. E. Pratley, eds. Proceedings of Precision Weed Management in Crops and Pastures, Wagga Wagga, Australia.

Mortensen, D. A., J. A. Dieleman, and G. A. Johnson. 1998. Weed spatial variation and weed management. Pages 293-309 *in* J. L. Hatfield, D. D. Buhler, and B. A. Stewart, eds. Integrated Weed and Soil Management, Chelsea, MI: Ann Arbor Press.

Rider, T. W., J. W. Vogel, J. A. Dille, K. C. Dhuyvetter, and T. L. Kastens. 2006. An economic evaluation of site-specific herbicide application. Precision Agric. 7:379-392.

Rosales-Robles, E., J. M. Chandler, S. A. Sensemam, and J.R. Salinas-Garcia. 2001. Growth Stage affects Johnsongrass [*Sorghum halepense* (L.) Pers] response to herbicides nicosulfuron and clethodim. Agrociencia 35:525-533.

Schuster, C. L., D. E. Shoup, and K. Al-Khatib. 2007. Response of common lambsquarters *Chenopodium album*) to glyphosate as affected by growth stage. Weed Sci. 55:147-151.

Seefeldt, S. S., J. E. Jensen, and E. P. Fuerst. 1995. Log-logistic analysis of herbicide dose-response relationships. Weed Technol. 9:218-227.

Stafford, J. V. and P.C.H. Miller. 1997. Spatially variable treatment of weed patches. Pages 465-473 *in* P. C. Robert, R. H. Rust, and W. E. Larson, eds. Proceedings of the 3rd International Conference on Precision Agriculture, Minneapolis, MN. Madison, WI: ASA-CSSA-SSSA.

Stouggard, R. N., B. D. Maxwell, and J. D. Harris. 1997. Influence of application timing on the efficacy of reduced rate of post emergence herbicide for wild oat (*Avena sativa*) control in spring barley (*Hordeum vulgare*). Weed Technol. 11:283-289.

Tredaway-Ducar, J., G. D. Morgan, J. B. Wilkerson, W. E. Hart, R .M. Hayes, and T. C. Mueller. 2003. Site-specific weed management in corn (*Zea mays*). Weed Technol. 17:711-717.

Vangessel, M. J., A. O. Ayeni, and B. A. Majek. 2000. Optimum glyphosate timing with or without residual herbicides in glyphosate-resistant soybean (*Glycine max*) under full-season convential tillage. Weed Technol. 14:140-149.

Vogel, J. 2005. Implementing site-specific weed management in Kansas row crops. MSc. Thesis. Kansas State University, Manhattan, KS. 194 p.

[WSSA] Weed Science Society of America. 2007. Herbicide Handbook. 9th Edition.

Williams, M. M. II, R. Gerhards, and D. A. Mortensen. 1999. Spatio-temporal outcomes of site-specific weed management in maize. Pages 897-906 *in* J. V. Stafford, ed. Precision Agriculture, Odense, Denmark. Sheffield, UK: Sheffield Academic Press.

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*). Weed Sci. 40:554-557.

Figure 3.1 Average percent mortality for shattercane and large crabgrass in response to three clethodim rates across sown densities at 4 weeks after application in 2007. Symbols represent observed field data and bars represent standard errors.

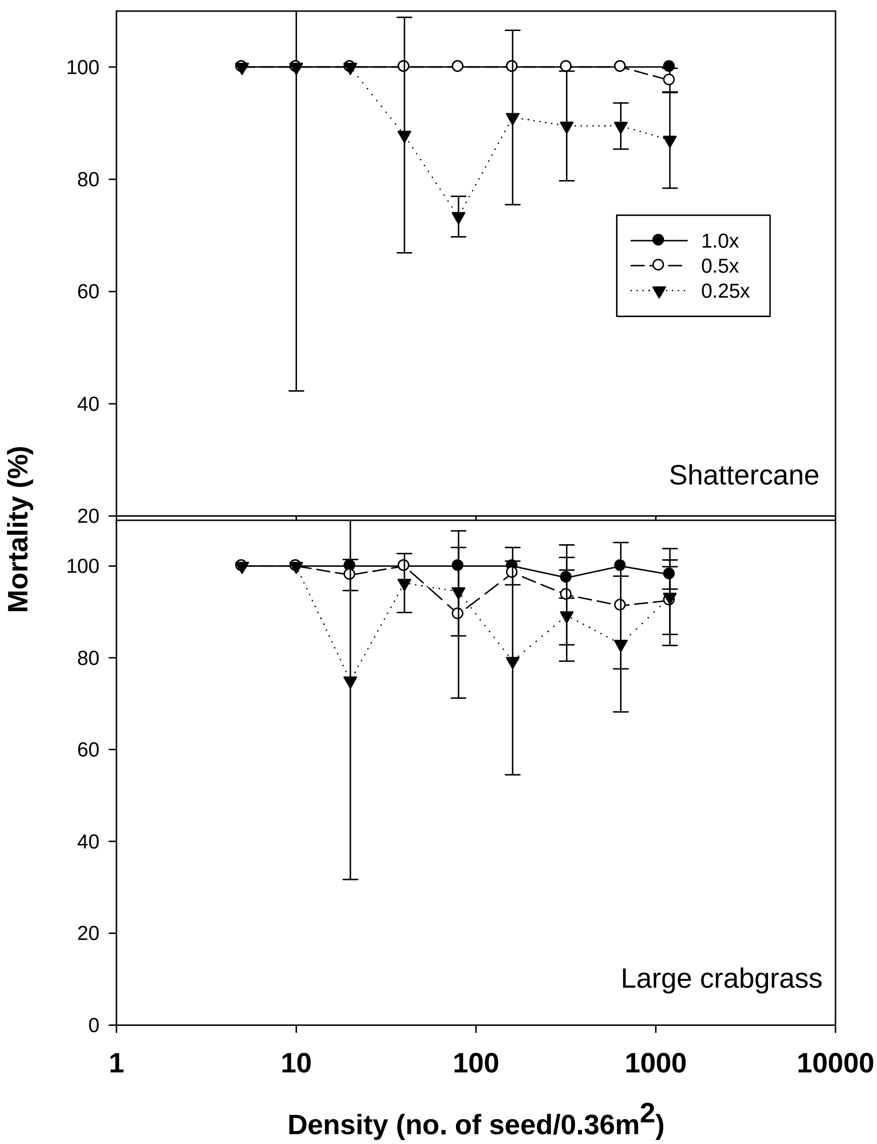

Figure 3.2 Average percent mortality for velvetleaf and Palmer amaranth in response to three lactofen rates across sown densities at 4 weeks after application in 2007. Symbols represent observed field data and bars represent standard errors.

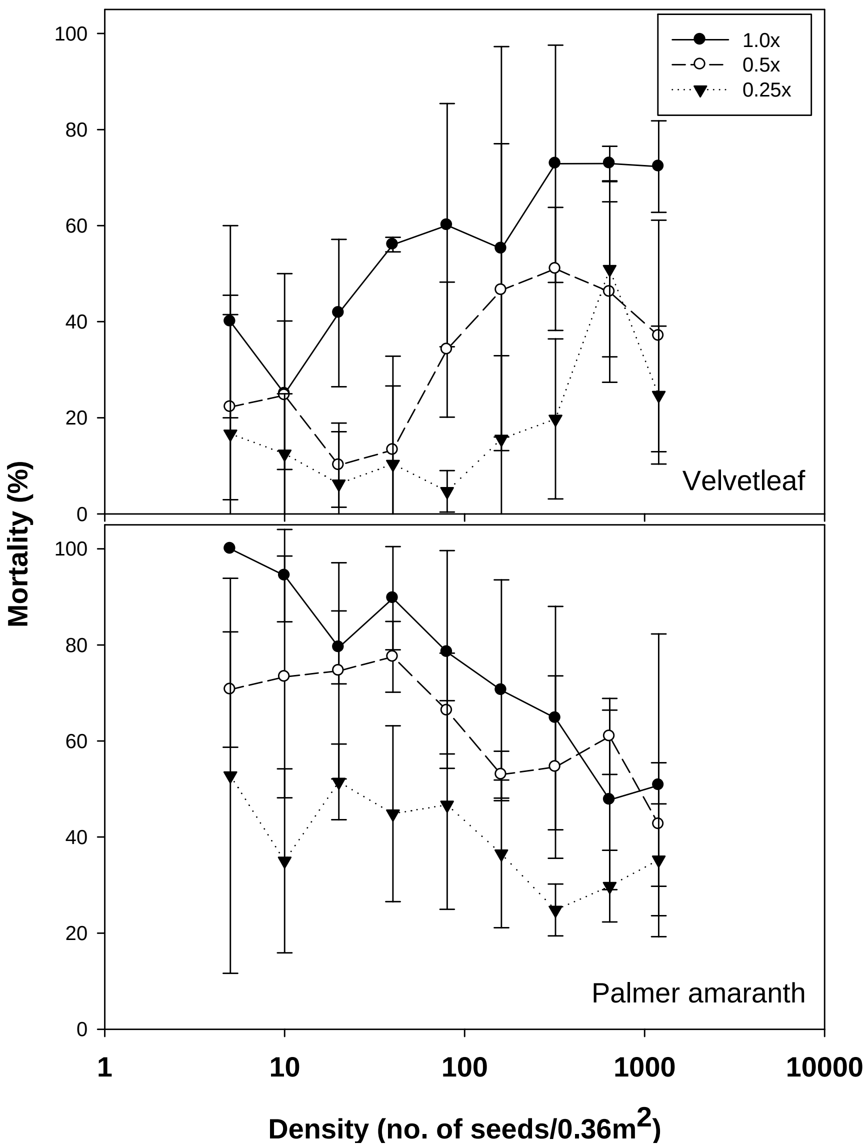

Figure 3.3 Average percent mortality for velvetleaf and Palmer amaranth in response to three glyphosate rates across sown densities 4 weeks after application in 2006 and 2007. Symbols represent observed field data and bars represent standard errors.

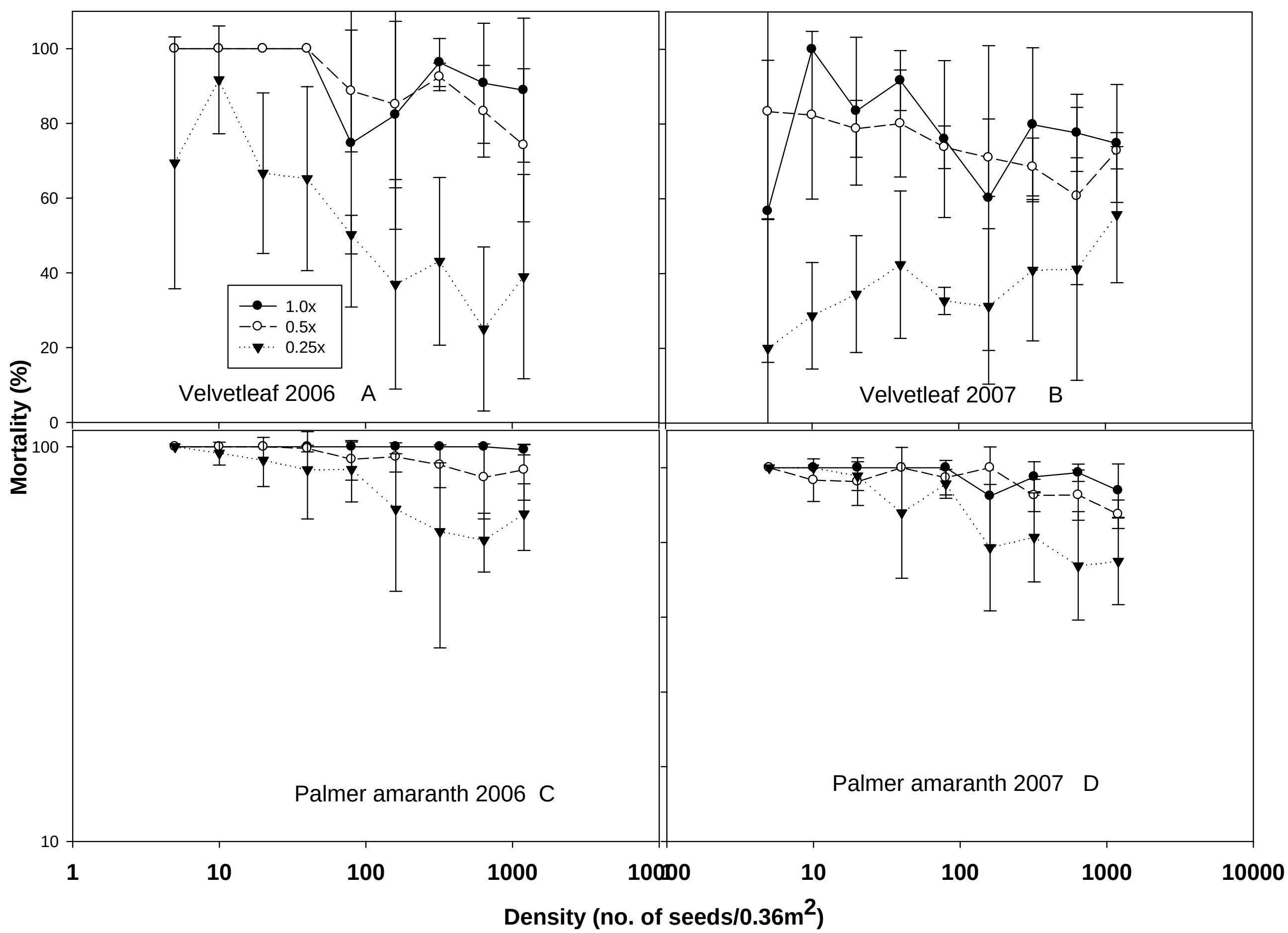

Figure 3.4 Predicted curves for shattercane and large crabgrass dry weight (g/ 0.09m^2) for three sown densities (10, 160, and 1200 seed) plotted against clethodim and glyphosate herbicide rates. Parameter estimates are in Table 3.1.

Clethodim Glyphosate

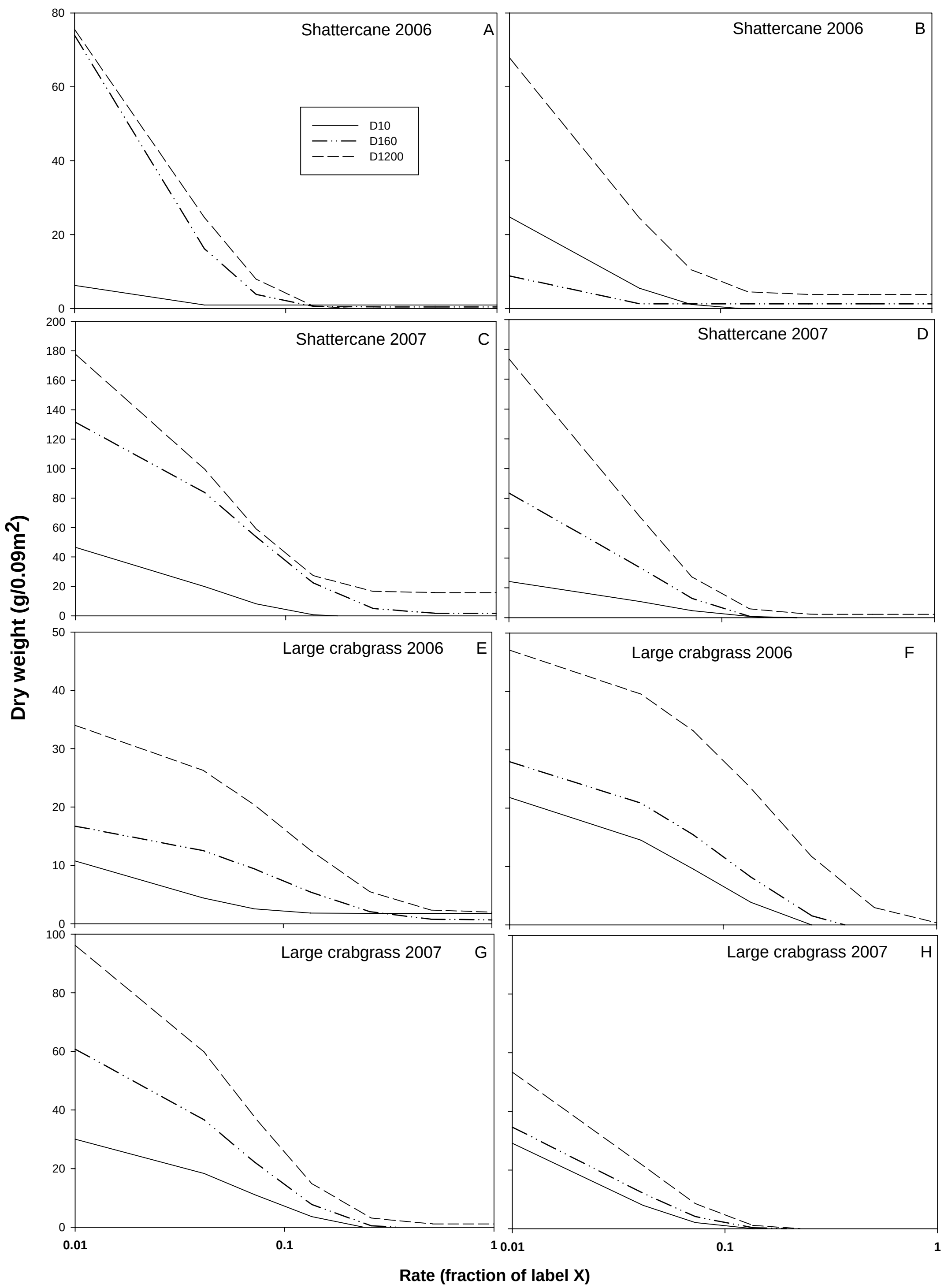

Figure 3.5 Predicted curves for Palmer amaranth and velvetleaf dry weight (g/ 0.09 m^2) for three sown densities (10, 160, and 1200 seed) plotted against lactofen and glyphosate herbicide rates. Parameter estimates are in Table 3.1.

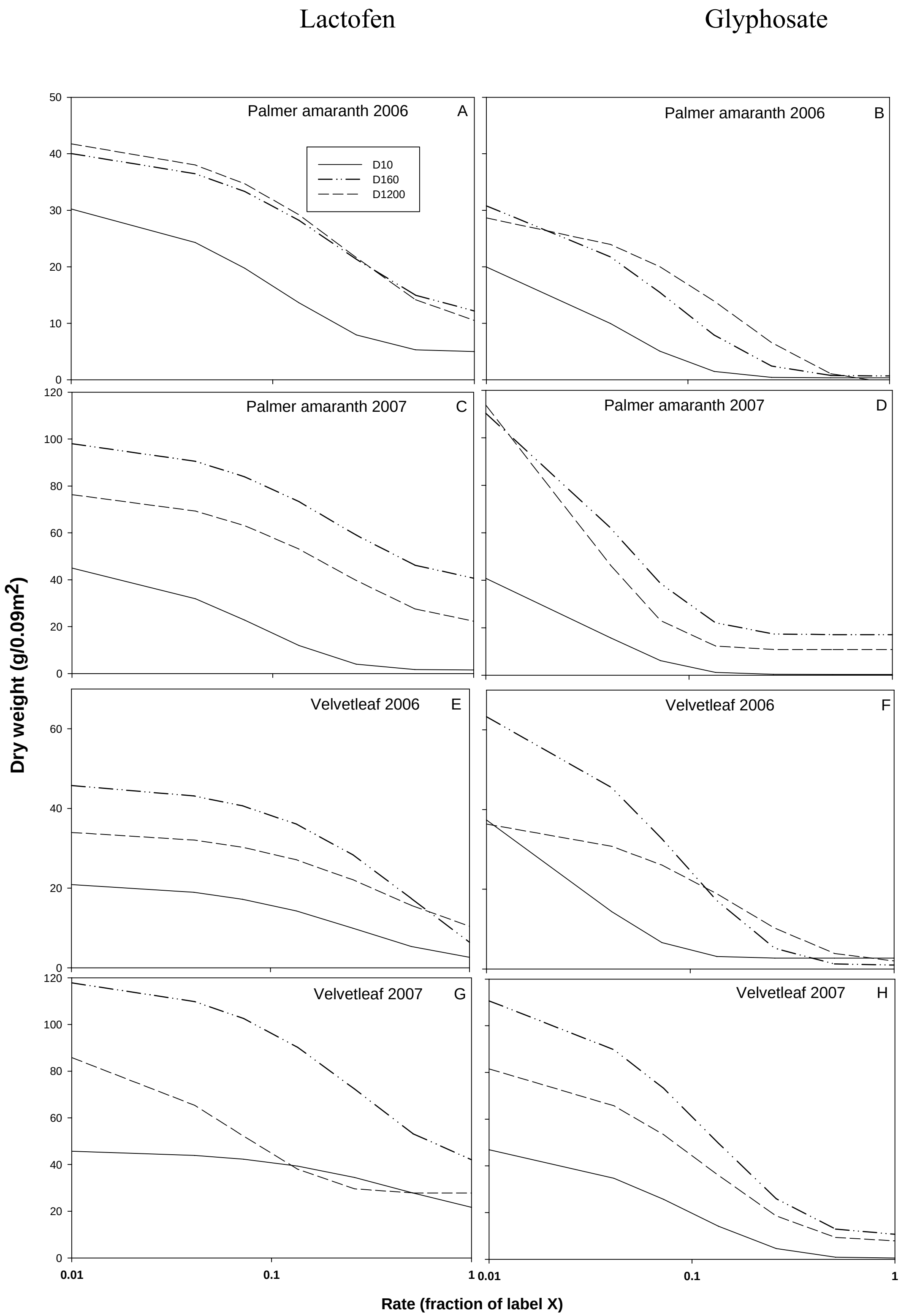

Figure 3.6 Average percent mortality of velvetleaf in response to glyphosate and lactofen at four different rates across different growth stages and weed densities at 3 weeks after treatment in the greenhouse study. Standard errors for each mean percent mortality are represented by the error bars.

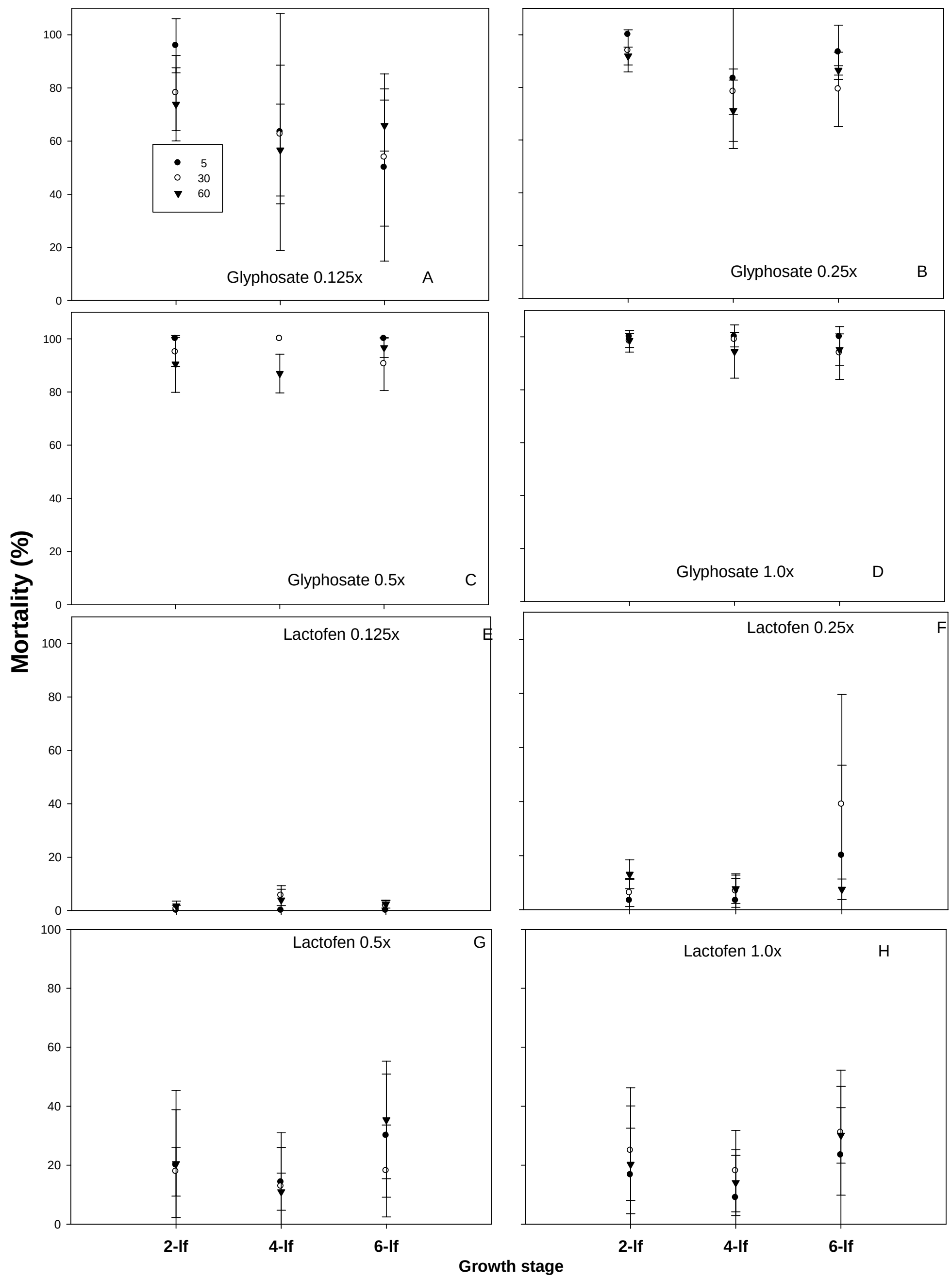

Figure 3.7 Predicted curves for velvetleaf dry weight for three densities at three growth stages (2-leaf, 4-leaf, and 6-leaf) plotted against glyphosate and lactofen rates for first repeat. Parameter estimates are in Table 3.2 and goodness of fit R^2 values are in Table 3.3.

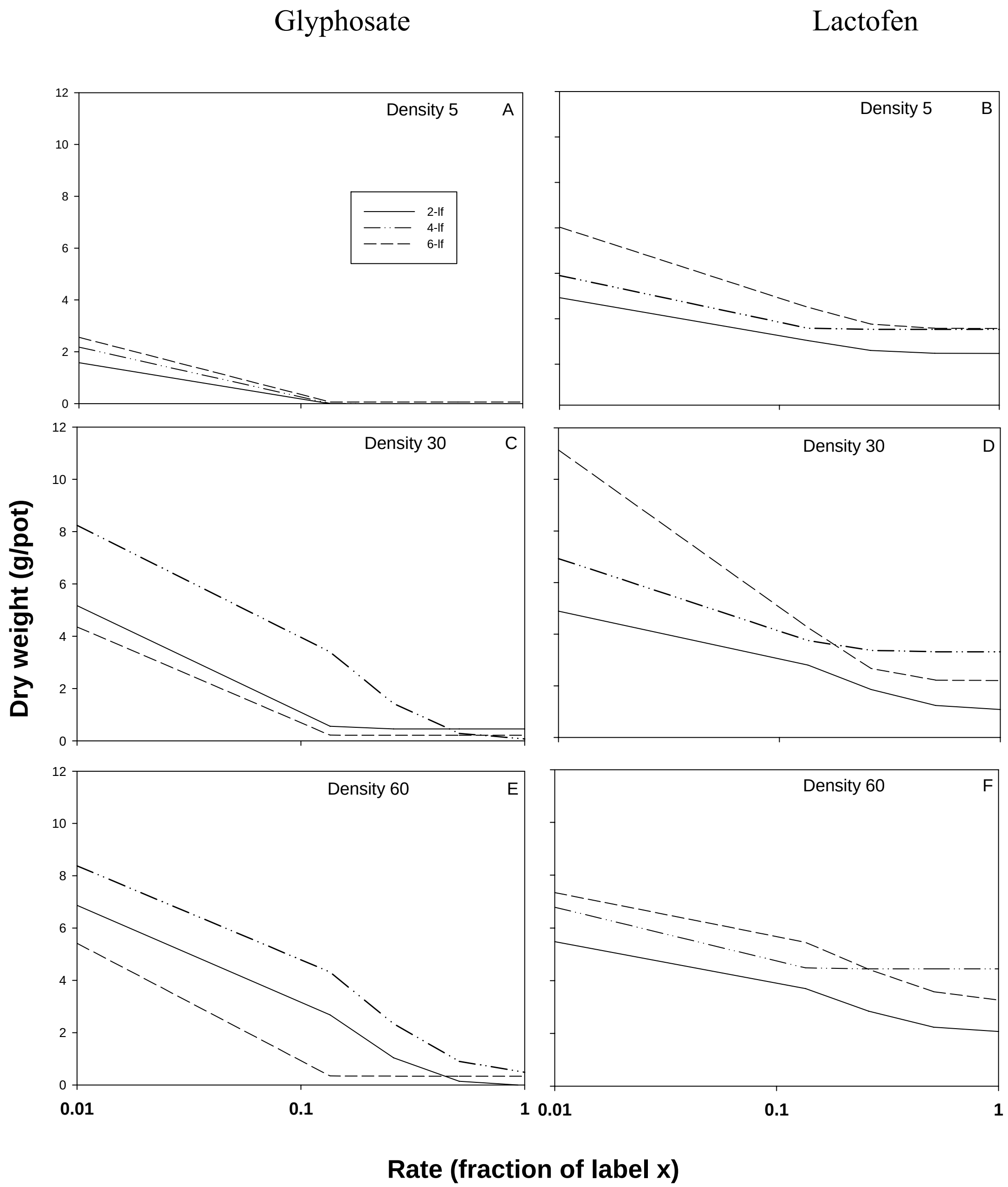

Figure 3.8 Predicted curves for velvetleaf dry weight for three densities at three growth stages (2-leaf, 4-leaf, and 6-leaf) plotted against glyphosate and lactofen rates for second repeat. Parameter estimates are in Table 3.2 and goodness-of-fit R^2 values are in Table 3.3.

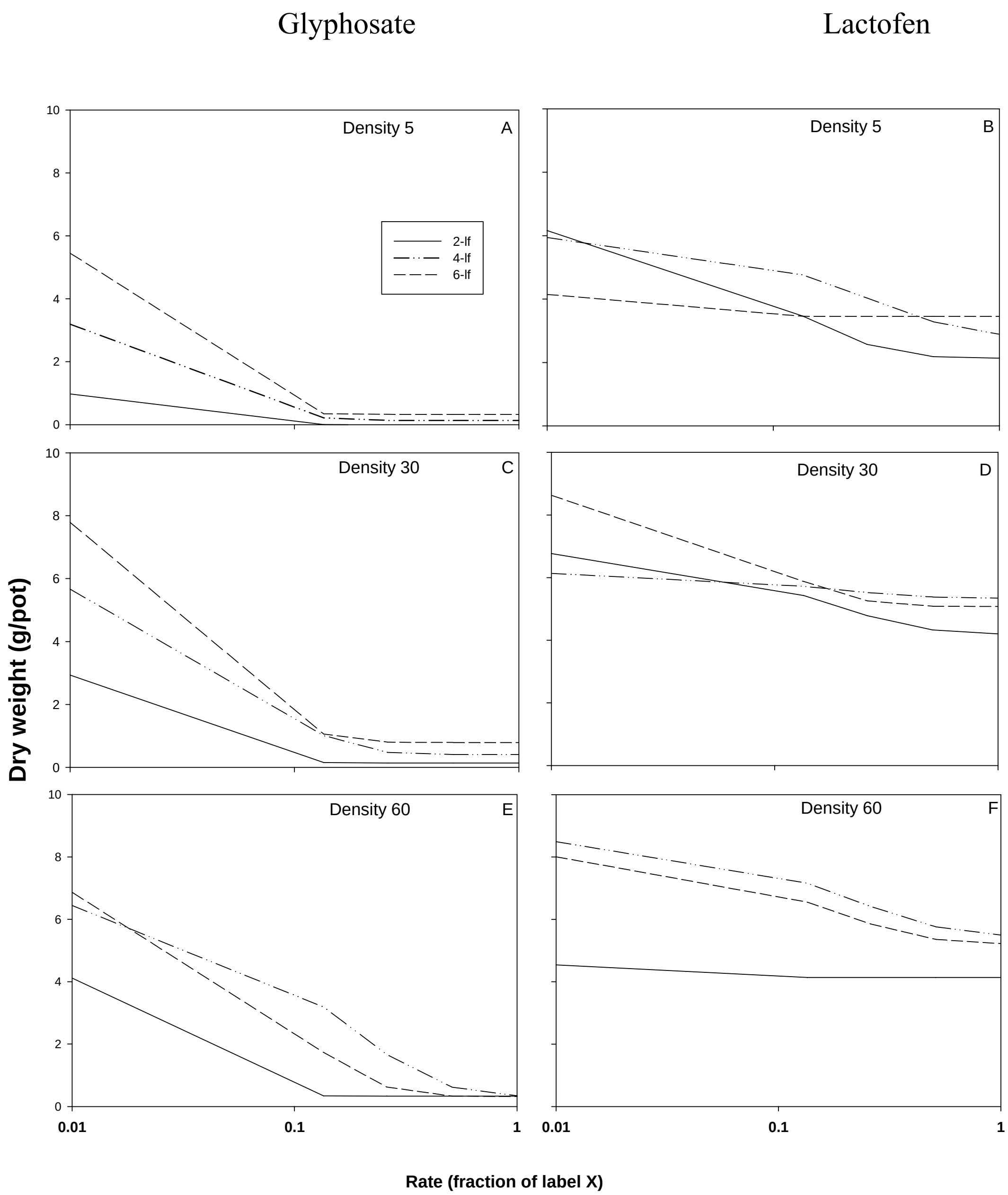

Table 3.1 Parameter estimates (B_0, B_1, *and* B_2), corresponding standard errors (±SE), and estimated rate (fraction of 1.0X) to achieve growth reduction by 50% (GR50 for 2006 and 2007) or 80% (GR80 for 2006 only) for large crabgrass, shattercane, velvetleaf, and Palmer amaranth across sown densities in field studies.

Large crabgrass 2006																	
	Clethodim								Glyphosate								
	Parameter estimates (±SE)								Parameter estimates (±SE)								
Density	B_0		B_1		B_2		**GR50**	**GR80**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**
# 0.36 m^{-2}	------------- g per plot -------------				1/Rate		Rate		----------- g per plot -----------				1/Rate		Rate	
5	1.26	(1.21)	7.62	(2.61)	33.91	(28.53)	0.020	0.033	-0.39	(1.67)	7.67	(2.36)	8.11	(6.52)	0.085	0.137
10	1.78	(1.43)	13.29	(4.33)	39.13	(32.92)	0.018	0.028	-1.08	(4.30)	25.89	(7.13)	12.27	(8.24)	0.056	0.090
20	0.77	(1.76)	17.37	(3.38)	19.66	(8.86)	0.035	0.056	-0.4	(3.04)	14.49	(4.49)	8.99	(7.16)	0.077	0.123
40	1.87	(2.47)	23.13	(5.19)	29.65	(15.84)	0.023	0.037	-1.15	(2.97)	15.94	(3.42)	4.96	(2.98)	0.140	0.223
80	1.38	(2.94)	16.24	(4.19)	8.25	(5.55)	0.084	0.134	-0.72	(3.42)	24.27	(4.83)	8.08	(4.21)	0.086	0.137
160	0.63	(2.06)	17.72	(3.13)	9.71	(4.35)	0.071	0.114	-1.76	(5.54)	32.43	(8.09)	8.76	(5.64)	0.079	0.127
320	2.61	(1.87)	23.52	(3.81)	25.62	(9.67)	0.027	0.043	-0.86	(3.37)	44.69	(5.32)	10.74	(3.19)	0.065	0.103
640	0.75	(1.99)	29.95	(3.12)	10.42	(2.72)	0.067	0.106	-0.94	(5.73)	48.92	(8.41)	8.87	(3.93)	0.078	0.125
1200	1.96	(1.89)	35.01	(2.78)	8.85	(1.82)	0.078	0.125	0.12	(7.86)	49.65	(9.54)	5.59	(2.97)	0.124	0.198

Shattercane 2006																
	Clethodim								**Glyphosate**							
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate		----------g per plot----------				1/Rate		Rate	
5	-0.06	(0.55)	50.87	(1.29)	73.32	(8.05)	0.009	0.015	-0.16	(0.95)	33.85	(2.19)	54.06	(10.97)	0.013	0.021
10	0.12	(0.90)	52.38	(2.15)	78.24	(15.18)	0.009	0.014	-0.24	(1.59)	40.10	(3.59)	47.21	(12.04)	0.015	0.023
20	-0.11	(1.58)	101.00	(3.76)	81.17	(15.10)	0.009	0.014	0.03	(1.48)	72.66	(3.57)	98.20	(33.99)	0.007	0.011
40	0.58	(1.73)	106.60	(4.08)	71.79	(11.53)	0.010	0.015	1.63	(1.93)	78.49	(4.57)	72.48	(17.96)	0.010	0.015
80	-0.21	(1.82)	101.40	(4.22)	60.67	(8.78)	0.011	0.018	0.02	(1.43)	69.26	(3.49)	160.40	(242.10)	0.004	0.007
160	0.41	(2.75)	120.40	(6.24)	49.29	(7.49)	0.014	0.022	0.05	(2.63)	87.62	(6.28)	81.92	(29.77)	0.008	0.014
320	-0.84	(3.24)	127.90	(7.12)	38.35	(5.46)	0.018	0.029	0.71	(2.73)	85.61	(6.31)	56.09	(13.37)	0.012	0.020
640	-0.02	(1.79)	130.80	(3.86)	34.47	(2.51)	0.020	0.032	0.05	(3.82)	96.30	(8.04)	29.76	(5.91)	0.023	0.037
1200	-0.26	(2.80)	108.30	(6.09)	35.65	(4.99)	0.019	0.031	3.54	(3.05)	76.83	(7.60)	31.11	(6.45)	0.022	0.036

Velvetleaf 2006																
	Lactofen								Glyphosate							
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate		----------g per plot----------				1/Rate		Rate	
5	2.04	(4.59)	16.33	(4.64)	3.93	(3.04)	0.176	0.282	1.58	(2.98)	41.51	(6.47)	35.03	(13.52)	0.020	0.032
10	2.00	(5.52)	19.55	(5.56)	3.46	(2.77)	0.200	0.320	2.69	(4.29)	49.20	(9.29)	34.90	(16.31)	0.020	0.032
20	-3.62	(38.00)	39.14	(35.37)	1.66	(3.20)	0.418	0.669	1.07	(5.11)	50.74	(10.50)	26.24	(12.67)	0.026	0.042
40	3.10	(9.96)	39.78	(10.11)	3.55	(2.54)	0.195	0.312	2.03	(6.75)	65.87	(12.42)	16.75	(7.46)	0.041	0.066
80	0.66	(9.56)	41.43	(8.96)	2.53	(1.44)	0.273	0.438	4.89	(5.83)	62.85	(12.24)	29.19	(13.47)	0.024	0.038
160	-1.02	(17.91)	47.67	(16.58)	1.86	(1.48)	0.372	0.595	0.96	(8.08)	69.45	(12.78)	10.79	(4.95)	0.064	0.103
320	1.02	(8.32)	47.41	(8.39)	3.48	(1.73)	0.199	0.319	1.28	(3.11)	48.43	(4.74)	9.73	(2.41)	0.071	0.114
640	-6.67	(15.07)	51.39	(13.97)	1.78	(1.07)	0.390	0.624	5.21	(4.21)	48.77	(6.88)	11.78	(4.08)	0.059	0.094
1200	8.18	(8.95)	26.43	(8.36)	2.48	(2.04)	0.280	0.448	1.83	(3.64)	36.55	(4.44)	5.66	(1.90)	0.122	0.196

Palmer amaranth 2006																	
	Lactofen								Glyphosate								
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**GR80**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate		----------g per plot----------				1/Rate		Rate	
5	3.00	(3.21)	25.75	(6.54)	25.34	(14.97)	0.027	0.044	-0.05	(1.66)	10.72	(2.69)	11.52	(7.13)	0.060	0.096
10	4.97	(7.65)	27.50	(11.07)	8.56	(8.94)	0.081	0.129	0.35	(2.51)	24.62	(4.99)	22.79	(10.68)	0.030	0.049
20	0.96	(5.61)	27.55	(6.43)	4.88	(3.19)	0.142	0.227	-0.43	(1.27)	17.19	(2.09)	11.98	(3.57)	0.058	0.093
40	5.16	(7.34)	38.97	(9.00)	5.74	(3.65)	0.121	0.193	2.23	(6.26)	54.40	(13.76)	38.45	(24.93)	0.018	0.029
80	5.34	(15.00)	28.78	(14.66)	3.13	(4.43)	0.221	0.354	0.30	(3.20)	33.73	(6.01)	18.17	(7.53)	0.038	0.061
160	11.74	(13.93)	29.56	(15.23)	4.33	(6.30)	0.160	0.256	0.61	(3.59)	33.76	(5.79)	11.40	(4.83)	0.061	0.097
320	15.03	(7.23)	37.51	(11.10)	9.95	(7.44)	0.070	0.111	1.35	(3.71)	47.45	(6.63)	15.41	(5.09)	0.045	0.072
640	10.36	(9.50)	37.65	(11.40)	5.46	(4.58)	0.127	0.203	-0.03	(4.74)	45.89	(7.22)	9.74	(3.89)	0.071	0.114
1200	9.84	(7.44)	33.22	(7.88)	4.00	(2.68)	0.173	0.277	-0.74	(3.87)	31.08	(4.69)	5.57	(2.32)	0.124	0.199

Large crabgrass 2007														
	Clethodim							Glyphosate						
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate	----------g per plot----------				1/Rate		Rate
5	-1.47	(3.99)	26.86	(6.63)	9.97	(4.74)	0.070	0.27	(0.38)	31.70	(0.87)	53.29	(4.81)	0.013
10	-1.22	(2.35)	36.33	(4.36)	14.97	(3.55)	0.046	-0.17	(1.69)	44.23	(3.77)	41.14	(9.08)	0.017
20	-1.48	(3.93)	29.75	(6.63)	10.54	(4.58)	0.066	-0.63	(3.09)	39.45	(6.40)	24.76	(8.55)	0.028
40	-1.24	(2.22)	55.71	(4.27)	17.92	(2.84)	0.039	0.65	(4.08)	55.18	(8.92)	44.34	(21.79)	0.016
80	-1.36	(3.25)	71.41	(5.95)	15.01	(2.64)	0.046	-0.36	(2.01)	48.28	(4.27)	29.81	(6.07)	0.023
160	-0.66	(2.70)	72.02	(4.95)	15.95	(2.45)	0.043	-0.24	(2.67)	48.68	(5.77)	33.35	(9.47)	0.021
320	-0.81	(3.94)	86.94	(7.54)	17.86	(3.30)	0.039	-1.29	(4.58)	71.87	(9.46)	24.22	(6.69)	0.029
640	0.51	(2.90)	95.82	(5.44)	18.28	(2.44)	0.038	0.52	(2.32)	76.91	(4.17)	46.84	(9.43)	0.015
1200	1.06	(3.53)	111.00	(6.31)	15.44	(2.08)	0.045	-0.34	(2.81)	71.65	(5.90)	28.80	(5.56)	0.024

Shattercane 2007														
	Clethodim							Glyphosate						
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate	----------g per plot----------				1/Rate		Rate
5	-0.29	(4.41)	35.12	(8.41)	19.49	(10.94)	0.036	0.04	(0.44)	3.08	(0.89)	31.51	(25.96)	0.022
10	-1.07	(3.63)	61.94	(7.64)	26.37	(6.86)	0.026	-0.24	(3.43)	31.66	(7.04)	25.64	(13.00)	0.027
20	2.59	(4.98)	116.90	(10.90)	38.31	(9.30)	0.018	2.20	(4.46)	84.36	(10.63)	75.80	(42.05)	0.009
40	3.92	(5.38)	125.40	(12.01)	45.55	(12.66)	0.015	5.03	(6.89)	69.13	(16.14)	59.47	(45.39)	0.012
80	0.36	(7.37)	127.20	(12.79)	13.58	(3.17)	0.051	-0.27	(5.36)	111.30	(12.14)	46.67	(14.20)	0.015
160	1.57	(6.74)	150.50	(11.91)	14.69	(2.73)	0.047	-1.80	(66.12)	113.20	(13.04)	28.19	(6.95)	0.025
320	11.60	(17.22)	228.10	(31.25)	20.44	(7.98)	0.034	-0.65	(5.62)	188.10	(12.53)	40.93	(7.03)	0.017
640	8.67	(9.50)	221.30	(17.72)	18.61	(3.62)	0.037	3.59	(4.56)	190.20	(9.78)	38.45	(5.57)	0.018
1200	15.77	(9.42)	200.10	(17.73)	21.14	(4.92)	0.033	2.16	(12.14)	233.40	(24.90)	30.77	(8.85)	0.023

Velvetleaf 2007														
	Lactofen							**Glyphosate**						
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate	----------g per plot----------				1/Rate		Rate
5	9.66	(6.05)	26.18	(8.07)	5.60	(3.80)	0.124	7.37	(4.13)	77.62	(8.66)	46.29	(18.80)	0.015
10	18.23	(15.79)	28.04	(14.63)	2.11	(2.67)	0.328	0.58	(4.85)	51.13	(7.33)	9.84	(3.67)	0.070
20	51.59	(13.03)	13.36	(19.25)	5.16	(10.17)	0.134	1.96	(5.18)	73.32	(7.12)	7.70	(2.02)	0.090
40	44.52	(13.90)	69.22	(17.70)	4.58	(2.44)	0.151	-0.32	(5.66)	93.92	(7.57)	6.64	(1.36)	0.104
80	45.17	(13.86)	74.01	(17.50)	5.22	(2.95)	0.133	7.01	(3.62)	100.20	(5.23)	7.97	(1.02)	0.087
160	39.41	(23.46)	81.19	(25.33)	3.47	(2.67)	0.199	10.58	(5.76)	107.90	(7.86)	7.51	(1.47)	0.092
320	36.69	(8.62)	93.27	(12.67)	8.13	(2.61)	0.085	8.79	(4.86)	126.70	(7.18)	8.95	(1.30)	0.077
640	18.72	(6.00)	76.15	(7.79)	5.93	(1.51)	0.117	0.07	(6.68)	80.40	(8.10)	5.43	(1.48)	0.128
1200	27.74	(6.40)	66.73	(10.49)	13.89	(6.12)	0.050	7.80	(4.75)	79.63	(6.68)	7.72	(1.65)	0.090

Palmer amaranth 2007														
	Lactofen							Glyphosate						
Density	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**	**B0**	**SE**	**B1**	**SE**	**B2**	**SE**	**GR50**
# 0.36 m^{-2}	----------g per plot----------				1/Rate		Rate	----------g per plot----------				1/Rate		Rate
5	1.92	(30.99)	35.55	(24.01)	3.06	(8.11)	0.227	0.10	(2.53)	38.97	(5.74)	48.73	(20.84)	0.014
10	1.55	(9.80)	48.70	(16.47)	11.45	(8.56)	0.061	0.33	(2.51)	55.30	(5.32)	31.10	(7.28)	0.022
20	14.54	(12.10)	67.16	(17.93)	9.90	(7.30)	0.070	-1.67	(9.03)	95.21	(17.75)	19.57	(7.63)	0.035
40	-12.16	(39.47)	85.52	(37.81)	2.15	(2.19)	0.322	1.42	(16.10)	161.20	(35.31)	41.39	(25.34)	0.017
80	7.48	(56.68)	67.78	(50.25)	2.31	(4.71)	0.300	0.96	(4.90)	109.40	(9.85)	25.40	(5.60)	0.027
160	39.85	(25.42)	60.81	(23.14)	4.43	(6.57)	0.156	17.07	(9.28)	117.90	(19.06)	23.45	(7.94)	0.030
320	51.79	(18.17)	106.70	(31.80)	15.27	(11.43)	0.045	4.21	(6.61)	138.10	(12.72)	20.22	(4.37)	0.034
640	49.66	(18.52)	44.15	(25.06)	4.91	(5.18)	0.141	3.05	(7.76)	148.20	(13.69)	16.09	(3.81)	0.043
1200	43.92	(21.53)	57.24	(24.57)	4.42	(4.98)	0.157	10.80	(8.86)	144.90	(18.60)	34.13	(11.93)	0.020

Table 3.2 Parameter estimates (*B_0*, *B_1*, and *B_2*) for the dose-response model (Equation 3.2) for velvetleaf dry weight for each herbicide, repeat, density, and growth stage for the greenhouse study.

				Parameters						
				B_0	*SE*	B_1	*SE*	B_2	SE	
Herbicide	Repeat	Growth stage	Density (Plant pot^{-1})	-----g per plot-----		1/Rate		Rate		R^2
Glyphosate	1	2-leaf	5	-7.76E-6	(0.12)	4.5	(0.26)	105.6	(176)	0.96
			30	0.45	(0.31)	6.4	(0.68)	30.9	(.)	0.87
			60	-0.02	(0.35)	7.4	(0.55)	7.5	(1.39)	0.94
		4-leaf	5	-2.66E-6	(0.23)	6.2	(0.49)	103.7	(192)	0.93
			30	0.06	(0.41)	8.8	(0.64)	7.2	(1.23)	0.94
			60	0.45	(0.74)	8.4	(0.99)	5.7	(1.86)	0.86
		6-leaf	5	0.06	(0.09)	4.9	(0.22)	66.8	(-)	0.98
			30	0.21	(0.24)	7.7	(0.54)	61.9	(-)	0.94
			60	0.34	(0.27)	8.8	(0.61)	54.4	(-)	0.94
	2	2-leaf	5	-6.97E-7	(1.11)	2.9	(2.61)	109.4	(-)	0.26
			30	0.14	(0.17)	4.2	(0.39)	41.1	(-)	0.90
			60	0.33	(0.15)	6.5	(0.34)	54.6	(-)	0.97
		4-leaf	5	0.13	(0.33)	4.1	(0.07)	29.3	(-)	0.99
			30	0.41	(0.15)	6.3	(0.33)	17.3	(-)	0.97
			60	0.32	(0.32)	6.5	(0.46)	6.5	(1.11)	0.95

		6-leaf	5	0.33	(0.21)	8.1	(0.48)	46.2	(.)	0.96
			30	0.79	(0.20)	9.01	(0.45)	26.1	(-)	0.97
			60	0.32	(0.26)	7.4	(0.45)	12.3	(2.25)	0.96
Lactofen	1	2-leaf	5	0.47	(0.79)	2.8	(1.05)	11.7	(8.29)	0.61
			30	1.07	(0.44)	4.1	(0.87)	6.3	(-)	0.43
			60	2.06	(0.51)	3.6	(1.15)	5.9	(-)	0.26
		4-leaf	5	1.54	(0.59)	3.3	(0.78)	33.3	(1.85)	0.61
			30	3.32	(1.03)	4.3	(2.04)	17.01	(-)	0.01
			60	4.44	(1.02)	3.3	(1.47)	32.98	(4.21)	0.29
		6-leaf	5	1.56	(0.38)	5.1	(0.86)	12.5	(-)	0.40
			30	2.19	(0.51)	10.1	(0.94)	11.8	(7.28)	0.61
			60	3.23	(0.35)	4.3	(0.68)	4.9	(-)	0.59
	2	2-leaf	5	2.14	(0.16)	4.4	(0.35)	8.9	(-)	0.83
			30	4.2	(0.27)	2.7	(0.37)	5.9	(1.56)	0.91
			60	4.1	(0.35)	2.4	(0.69)	176	(-)	0.67
		4-leaf	5	2.8	(0.19)	3.3	(0.39)	3.8	(60.34)	0.86
			30	5.3	(0.29)	4.0	(0.55)	5.9	(9.14)	0.84
			60	5.5	(0.31)	3.2	(0.62)	4.6	(91.96)	0.71
		6-leaf	5	3.5	(0.22)	3.6	(0.42)	165	(2.67)	0.93
			30	5.1	(1.25)	0.84	(2.27)	11.9	(6.99)	0.63
			60	5.2	(0.49)	2.96	(0.67)	5.9	(1.81)	0.79

CHAPTER 4 - CONCLUSIONS

This research investigated the interaction of weed emergence, weed density, and herbicide choice and rate in soybean. Previous research conducted on weed emergence patterns used weed seeds that have been put in the soil. In our study, emergence patterns of weeds were studied using natural occurring weed seed populations that were in the field. This study provided information to explain why weed persist even though weed control measures are in place (Chapter 1). The other field study evaluated the interaction of herbicide choice and herbicide rate based on weed species and density (Chapter 3). The information obtained provided a better understanding on which herbicide to use for a given species at a given density and how herbicide rates perform at varying densities.

Chapter 2

In this study we observed reduction in seedbank and emergence over the two or three years in the same species patch. The results of this study showed that shattercane, ivyleaf morningglory, and prickly sida have extended emergence, allowing these species to avoid post emergence herbicide application aimed at preventing early season weed competition. A single application of non-residual herbicide is unlikely to control these weed species adequately. Our results showed that precipitation play an important role in the emergence patterns of these weed species. All weed species studied emerge in mid-May which coincides with soybean planting. Shattercane had extended emergence when the moisture was low in 2006 while ivyleaf morningglory and prickly sida had extended emergence when the moisture was high in 2007. Applying residual herbicides decreases weed emergence, thus giving the crop a competitive advantage. More seedlings were observed in the no-crop treatment followed by the no-herbicide treatment, with the residual treatments similar. The duration of shattercane emergence was 38, 35, and 24 days in 2006, 2007, and 2008, respectively. Ivyleaf morningglory duration of emergence was 35 days in 2006 and 45 days in 2007. The duration of prickly sida emergence was 21 and 33 days in 2006 and 2007, respectively.

Chapter 3

The results of this study showed that there was an interaction among weed species, weed density, herbicide rate in both the mortality and the dry weight data. For % mortality, no density effect was observed with glyphosate for both species. Glyphosate application resulted in higher mortality of both species than clethodim. The labeled rate of lactofen did not provide 100% velvetleaf mortality across all densities. The use of lower rates should be done with caution as weed species respond differently. For large crabgrass and velvetleaf, the use of reduced herbicide rates may need to be integrated with other weed management practices. Systemic herbicides such as glyphosate and clethodim are more effective on weeds at high densities than contact herbicides. Irrespective of the biomass produced by the weeds at varying densities, results showed that at low densities low rate of herbicide is required to reduce dry weight by 50%. Glyphosate controlled broadleaf weed better than lactofen. Our greenhouse study showed that velvetleaf was susceptible to glyphosate and lactofen at early growth stages, however, as seedlings growth stage increased, tolerance to herbicide increased. It was clear in this study that the weed management outcomes are dependent on weed species, weed density, weed growth stage, herbicide choice, and herbicide rate.

Appendix A - CHAPTER 2

Figure A.1 Cumulative growing degree days (GDD) near Manhattan, KS in relation to days of the year (DOY) in 2006, 2007 and 2008.

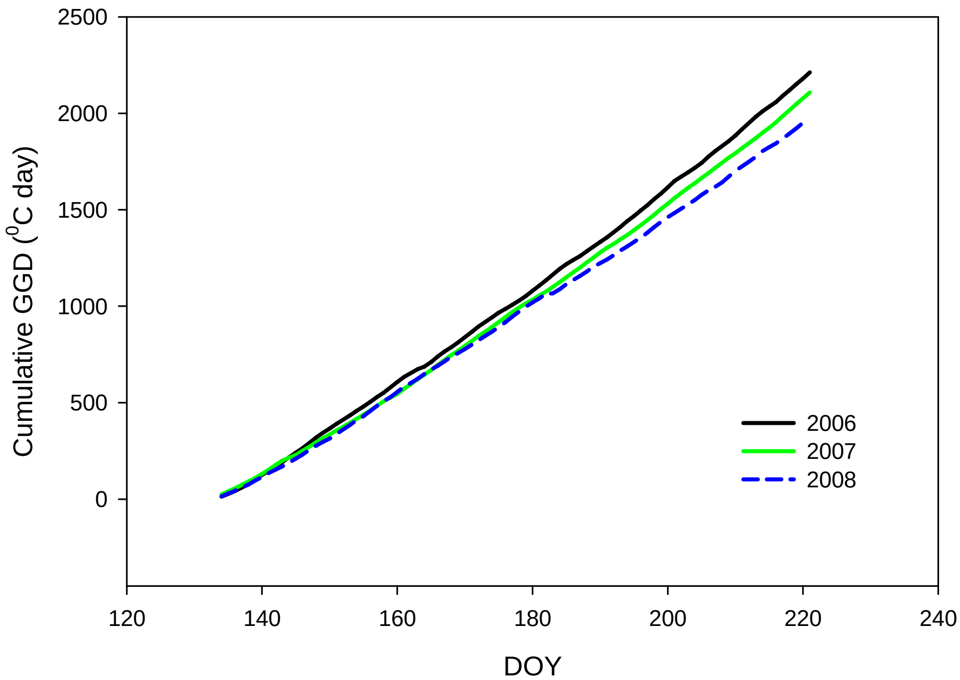

Figure A.2 Average 30-year maximum and minimum temperatures and precipitation near Manhattan, KS in relation to cumulative growing degree days (GDD) across the growing season (April to September).

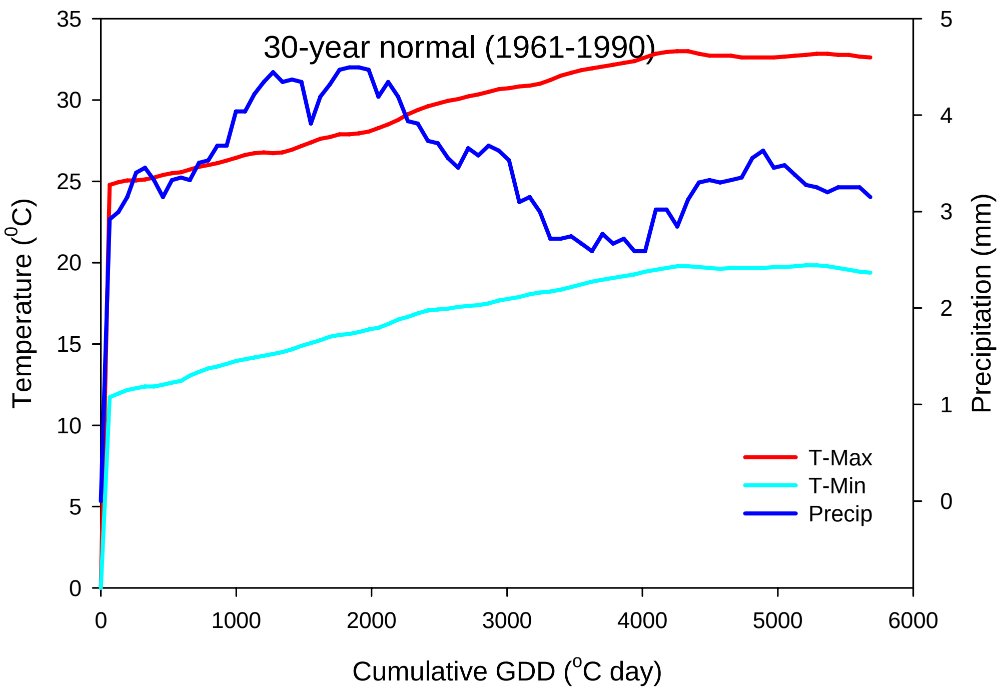

Table A.3 Cumulative growing degree days (Cum GDD), day of the year (DOY), and precipitation (mm) for Manhattan KS, in 2006, 2007, and 2008.

2006			2007			2008		
Date	DOY	Cum GDD	Date	DOY	Cum GDD	Date	DOY	Cum GDD
5/13/2006	134	14.6	5/13/2007	134	24.5	5/11/2008	132	14.3
5/14/2006	135	26.7	5/14/2007	135	40.6	5/12/2008	133	29.5
5/15/2006	136	41	5/15/2007	136	56.6	5/13/2008	134	43.2
5/16/2006	137	56.25	5/16/2007	137	73.7	5/14/2008	135	58.75
5/17/2006	138	74.9	5/17/2007	138	91.75	5/15/2008	136	75.9
5/18/2006	139	93.25	5/18/2007	139	110.25	5/16/2008	137	96.7
5/19/2006	140	118.9	5/19/2007	140	130.65	5/17/2008	138	114.4
5/20/2006	141	139.9	5/20/2007	141	153.1	5/18/2008	139	135.65
5/21/2006	142	161.05	5/21/2007	142	176.45	5/19/2008	140	153.05
5/22/2006	143	183.6	5/22/2007	143	199.15	5/20/2008	141	169.7
5/23/2006	144	206.2	5/23/2007	144	215.35	5/21/2008	142	188.85
5/24/2006	145	231.7	5/24/2007	145	230.15	5/22/2008	143	210.3
5/25/2006	146	255.3	5/25/2007	146	250.55	5/23/2008	144	230.85
5/26/2006	147	279.2	5/26/2007	147	271.6	5/24/2008	145	255.05
5/27/2006	148	305.55	5/27/2007	148	293.65	5/25/2008	146	276.8
5/28/2006	149	333.9	5/28/2007	149	315.75	5/26/2008	147	296.65
5/29/2006	150	358.5	5/29/2007	150	335.9	5/27/2008	148	313.8
5/30/2006	151	380.65	5/30/2007	151	355.35	5/28/2008	149	336.6
5/31/2006	152	404.15	5/31/2007	152	375.45	5/29/2008	150	361.4
6/1/2006	153	426.5	6/1/2007	153	394.7	5/30/2008	151	384.7
6/2/2006	154	449.05	6/2/2007	154	415.75	5/31/2008	152	407.65
6/3/2006	155	471.7	6/3/2007	155	438.05	6/1/2008	153	430.05
6/4/2006	156	494.75	6/4/2007	156	459.05	6/2/2008	154	456.25
6/5/2006	157	518.5	6/5/2007	157	483.3	6/3/2008	155	483.85
6/6/2006	158	543.55	6/6/2007	158	508.35	6/4/2008	156	507.5
6/7/2006	159	567.3	6/7/2007	159	526.35	6/5/2008	157	528.6
6/8/2006	160	593.75	6/8/2007	160	545.9	6/6/2008	158	555.85
6/9/2006	161	621.65	6/9/2007	161	571.8	6/7/2008	159	580.9
6/10/2006	162	647.75	6/10/2007	162	596.05	6/8/2008	160	601.95
6/11/2006	163	668.4	6/11/2007	163	621.25	6/9/2008	161	623.2
6/12/2006	164	688.1	6/12/2007	164	644.45	6/10/2008	162	648.3
6/13/2006	165	701	6/13/2007	165	669.3	6/11/2008	163	670.25
6/14/2006	166	725.3	6/14/2007	166	695.75	6/12/2008	164	691.95
6/15/2006	167	753.9	6/15/2007	167	721.15	6/13/2008	165	714.15
6/16/2006	168	780.25	6/16/2007	168	747.4	6/14/2008	166	738.55
6/17/2006	169	802.6	6/17/2007	169	770.05	6/15/2008	167	757.7
6/18/2006	170	826.75	6/18/2007	170	794.2	6/16/2008	168	777.5
6/19/2006	171	853.55	6/19/2007	171	819.95	6/17/2008	169	800.15
6/20/2006	172	881.15	6/20/2007	172	844.6	6/18/2008	170	823
6/21/2006	173	908.6	6/21/2007	173	868.85	6/19/2008	171	845.9

6/22/2006	174	933.2	6/22/2007	174	892.7	6/20/2008	172	868.5
6/23/2006	175	956.95	6/23/2007	175	917.85	6/21/2008	173	891.45
6/24/2006	176	980.9	6/24/2007	176	943.85	6/22/2008	174	917.65
6/25/2006	177	1001.35	6/25/2007	177	969.6	6/24/2008	175	945.55
6/26/2006	178	1021.5	6/26/2007	178	993.45	6/25/2008	176	971.9
6/27/2006	179	1043.05	6/27/2007	179	1014.8	6/26/2008	177	996.65
6/28/2006	180	1067.25	6/28/2007	180	1034.3	6/27/2008	178	1019.5
6/29/2006	181	1094.45	6/29/2007	181	1054.6	6/28/2008	179	1040.85
6/30/2006	182	1120.95	6/30/2007	182	1077.1	6/29/2008	180	1061.85
7/1/2006	183	1149.6	7/1/2007	183	1100.3	6/30/2008	181	1085.5
7/2/2006	184	1178.15	7/2/2007	184	1124.45	7/1/2008	182	1112.8
7/3/2006	185	1207.6	7/3/2007	185	1150.45	7/2/2008	183	1133.6
7/4/2006	186	1232.55	7/4/2007	186	1175.3	7/3/2008	184	1154.5
7/5/2006	187	1254.3	7/5/2007	187	1199.75	7/4/2008	185	1176.95
7/6/2006	188	1274.6	7/6/2007	188	1225.95	7/5/2008	186	1206.15
7/7/2006	189	1298.6	7/7/2007	189	1252.3	7/6/2008	187	1236.2
7/8/2006	190	1324.2	7/8/2007	190	1278.65	7/7/2008	188	1260.25
7/9/2006	191	1346.75	7/9/2007	191	1302.45	7/8/2008	189	1284.55
7/10/2006	192	1371.45	7/10/2007	192	1323.2	7/9/2008	190	1309.6
7/11/2006	193	1398.6	7/11/2007	193	1346.5	7/10/2008	191	1339.05
7/12/2006	194	1425.3	7/12/2007	194	1369.7	7/11/2008	192	1359.8
7/13/2006	195	1455.5	7/13/2007	195	1394.55	7/12/2008	193	1380.35
7/14/2006	196	1482.7	7/14/2007	196	1419.55	7/13/2008	194	1403.7
7/15/2006	197	1510.15	7/15/2007	197	1446.5	7/14/2008	195	1430.3
7/16/2006	198	1539.1	7/16/2007	198	1474.9	7/15/2008	196	1456.8
7/17/2006	199	1570.05	7/17/2007	199	1504	7/16/2008	197	1485.4
7/18/2006	200	1598.95	7/18/2007	200	1531.75	7/17/2008	198	1510.25
7/19/2006	201	1631.1	7/19/2007	201	1560.35	7/18/2008	199	1537.2
7/20/2006	202	1664.15	7/20/2007	202	1587.45	7/19/2008	200	1566.95
7/21/2006	203	1686.65	7/21/2007	203	1613.9	7/20/2008	201	1596.65
7/22/2006	204	1709.1	7/22/2007	204	1638.65	7/21/2008	202	1623.05
7/23/2006	205	1732.3	7/23/2007	205	1664.2	7/22/2008	203	1650.9
7/24/2006	206	1757.6	7/24/2007	206	1689.95	7/23/2008	204	1680.6
7/25/2006	207	1789.25	7/25/2007	207	1716.35	7/24/2008	205	1708.45
7/26/2006	208	1818.95	7/26/2007	208	1743.9	7/25/2008	206	1735.05
7/27/2006	209	1843.7	7/27/2007	209	1770.1	7/26/2008	207	1763.8
7/28/2006	210	1870.45	7/28/2007	210	1793.6	7/27/2008	208	1787.5
7/29/2006	211	1899.7	7/29/2007	211	1819.15	7/28/2008	209	1809.9
7/30/2006	212	1932.9	7/30/2007	212	1845.7	7/29/2008	210	1833.8
7/31/2006	213	1964.45	7/31/2007	213	1871.85	7/30/2008	211	1859.25
8/1/2006	214	1996.6	8/1/2007	214	1899.05	7/31/2008	212	1885.4
8/2/2006	215	2024.6	8/2/2007	215	1925.05	8/1/2008	213	1916.8
8/3/2006	216	2049.05	8/3/2007	216	1954.1	8/2/2008	214	1947.2
8/4/2006	217	2073.45	8/4/2007	217	1985.2	8/3/2008	215	1978.95
8/5/2006	218	2104.2	8/5/2007	218	2016.7	8/4/2008	216	2006.9
8/6/2006	219	2135.15	8/6/2007	219	2047.55	8/5/2008	217	2031.55
8/7/2006	220	2165.45	8/7/2007	220	2078.3	8/6/2008	218	2053.95
8/8/2006	221	2195.05	8/8/2007	221	2108.2	8/7/2008	219	2075.7
8/9/2006	222	2227	8/9/2007	222	2137.25	8/8/2008	220	2095.95
8/10/2006	223	2256.5	8/10/2007	223	2165.55	8/9/2008	221	2119.6

8/11/2006	224	2282.9	8/11/2007	224	2195.25	8/10/2008	222	2143.2
8/12/2006	225	2312	8/12/2007	225	2225.15	8/11/2008	223	2166.5
8/13/2006	226	2341.7	8/13/2007	226	2254.65	8/12/2008	224	2191.1
8/14/2006	227	2364.05	8/14/2007	227	2285.45	8/13/2008	225	2213.4
8/15/2006	228	2385.2	8/15/2007	228	2316.75	8/14/2008	226	2235.1
8/16/2006	229	2410.3	8/16/2007	229	2346.65	8/16/2008	227	2254.85
8/17/2006	230	2439.5	8/17/2007	230	2373.65	8/17/2008	228	2275.35
8/18/2006	231	2465.55	8/18/2007	231	2401.2	8/18/2008	229	2296.65
8/19/2006	232	2488.95	8/19/2007	232	2430.9	8/19/2008	230	2319.15
8/20/2006	233	2511.9	8/20/2007	233	2459.45	8/21/2008	231	2346.55
8/21/2006	234	2535.55	8/21/2007	234	2488.25	8/22/2008	232	2370.4
8/22/2006	235	2558.6	8/22/2007	235	2516.7	8/23/2008	233	2391
8/23/2006	236	2585.45	8/23/2007	236	2540.8	8/24/2008	234	2410.7
8/24/2006	237	2613.85	8/24/2007	237	2562.95	8/25/2008	235	2430.2
8/25/2006	238	2640.25	8/25/2007	238	2589.55	8/26/2008	236	2454.85
8/26/2006	239	2662.65	8/26/2007	239	2618.65	8/27/2008	237	2482.1
8/27/2006	240	2686.3	8/27/2007	240	2647.35	8/28/2008	238	2503.35
8/28/2006	241	2707.1	8/28/2007	241	2670.75	8/29/2008	239	2524.15
8/29/2006	242	2728.2	8/29/2007	242	2693.55	8/30/2008	240	2549.6
8/30/2006	243	2748.7	8/30/2007	243	2715.65	8/31/2008	241	2574.75
8/31/2006	244	2770.75	8/31/2007	244	2737.55			

Table A.4 Day of the year (DOY) and precipitation (mm) in 2006, 2007, 2008 and 30-year average for Manhattan, KS.

Date	DOY	2006	2007	2008	30 yr Av
		---------------------mm-------------------			
5/1	122	0	2.03	0	2.3876
5/2	123	14.73	12.46	0	2.2352
5/3	124	5.08	0.25	0	2.3876
5/4	125	4.57	8.64	0.25	2.3622
5/5	126	0	128.8	1.27	2.3876
5/6	127	0	11.17	3.56	2.4638
5/7	128	0	0	2.03	2.54
5/8	129	17.02	0.76	11.07	2.8702
5/9	130	0.25	0	3.73	2.8702
5/10	131	0	0	0	2.7686
5/11	132	0	0	0	2.6416
5/12	133	0	0	0	2.4384
5/13	134	0	0	0	2.413
5/14	135	0	13.21	0	2.4638
5/15	136	0	0	0	2.921
5/16	137	0	0	0	2.9972
5/17	138	0	0	0	3.1496
5/18	139	0	0	0	3.4036
5/19	140	0	0	0	3.4544
5/20	141	0	0	0.25	3.3274
5/21	142	0	0	2.79	3.1496
5/22	143	0	103.3	5.33	3.3274
5/23	144	0	67.28	12.7	3.3528
5/24	145	0	0.5	15.49	3.3274
5/25	146	0	6.35	61.21	3.5052
5/26	147	7.76	0.5	0.5	3.5306
5/27	148	0	1.27	0	3.683
5/28	149	0	1.01	0.25	3.683
5/29	150	5.08	0	0.25	4.0386
5/30	151	17.78	0.76	0	4.0386
5/31	152	0.76	25.15	0	4.2164
6/1	153	2.79	0	56.64	4.3434
6/2	154	0	0	0	4.445
6/3	155	0	0	0	4.3434
6/4	156	0	0	111.3	4.3688
6/5	157	0.25	0	0	4.3434
6/6	158	0	0	0	3.9116
6/7	159	0	0	4.57	4.191
6/8	160	0	0	1.78	4.318
6/9	161	0	0	2.02	4.4704
6/10	162	1.77	0	33.53	4.4958
6/11	163	0.25	9.14	4.57	4.4958

6/12	164	0	11.18	0	4.4704
6/13	165	0	0.76	0	4.191
6/14	166	0	0	0	4.3434
6/15	167	0	0	0	4.191
6/16	168	7.11	0	0	3.937
6/17	169	12.19	26.16	12.62	3.9116
6/18	170	0	0	41.15	3.7338
6/19	171	0	0	0.25	3.7084
6/20	172	0.76	0	0.5	3.556
6/21	173	7.62	14.49	1.77	3.4544
6/22	174	0.25	0.25	2.2	3.6576
6/23	175	0	0	0	3.5814
6/24	176	0	0	29.46	3.683
6/25	177	1.77	0	1.01	3.6322
6/26	178	0	4.59	0.25	3.5306
6/27	179	0	0.25	0	3.0988
6/28	180	1.01	0	0	3.1496
6/29	181	1.01	0.5	0	2.9972
6/30	182	0	0	6.1	2.7178
7/1	183	0	0	1.01	2.7178
7/2	184	0	0	0	2.7432
7/3	185	33.03	1.77	4.82	2.667
7/4	186	0.25	0	0	2.5908
7/5	187	0	0	0	2.7686
7/6	188	0	0	14.24	2.667
7/7	189	0	0	0	2.7178
7/8	190	0	0.25	0	2.5908
7/9	191	32.26	0	0	2.5908
7/10	192	8.63	0	9.91	3.0226
7/11	193	0.5	17.02	0	3.0226
7/12	194	0	0.25	0	2.8448
7/13	195	0	0.76	0	3.1242
7/14	196	0	0	0	3.302
7/15	197	0	0	0	3.3274
7/16	198	0	0	55.24	3.302
7/17	199	0	0	0	3.3274
7/18	200	0	2.54	0	3.3528
7/19	201	0	49.29	0	3.556
7/20	202	0	0	2.79	3.6322
7/21	203	18.29	11.16	0	3.4544
7/22	204	0	0.25	0	3.4798
7/23	205	0	0	0	3.3782
7/24	206	0	0	0.25	3.2766
7/25	207	0	0	0	3.2512
7/26	208	0	0	29.13	3.2004
7/27	209	1.27	0	5.33	3.2512
7/28	210	0	21.42	0.25	3.2512
7/29	211	0	0	0	3.2512
7/30	212	0	0	0.25	3.1496
7/31	213	0	0.5	0	3.2766

8/1	214	0	8.89	0	3.2258
8/2	215	17.02	0.25	0	3.2512
8/3	216	0	0	0	3.048
8/4	217	0	3.04	0.76	3.0988
8/5	218	0	0	0.5	3.0734
8/6	219	0	0	0	3.0734
8/7	220	0	0	84.67	3.2004
8/8	221	0	0.25	0	2.7686
8/9	222	0	0	0	2.6924
8/10	223	12.46	0	0.25	2.9972
8/11	224	0.25	0	0	2.4384
8/12	225	0	0	0.5	2.3114
8/13	226	28.19	0	0	2.286
8/14	227	25.91	0	0	2.3622
8/15	228	0.25	0	0	2.3622
8/16	229	0.25	0	0	2.413
8/17	230	15.3	0.25	0	2.159
8/18	231	86.93	0.25	0	2.2098
8/19	232	5.08	0	29.72	2.2606
8/20	233	0	0	0.25	2.1844
8/21	234	0	0	0	2.5654
8/22	235	0	0	0	2.667
8/23	236	0	41.48	0	2.667
8/24	237	0	0	0	2.7178
8/25	238	36.32	0	0	2.667
8/26	239	46.48	0	0	2.6416
8/27	240	7.62	0	0	2.8448
8/28	241	1.01	0	0	2.8448
8/29	242	0	0	0	2.6924
8/30	243	0	0	0	3.048
8/31	244	0	0	0	3.048
Total		**487.11**	**610.38**	**670.27**	**391.5156**