To the graduate council:

I am submitting herewith a dissertation written by Robert Foster Montgomery entitled "Performance of Mathematical Models for Predicting Effects of Johnsongrass (*Sorghum halepense*) Interference and the Effects of Primisulfuron and Nicosulfuron on Corn (*Zea mays*) Yield." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant and Soil Science.

Robert M. Hayes, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the council:

Associate Vice Chancellor And
Dean of The Graduate School

PERFORMANCE OF MATHEMATICAL MODELS FOR PREDICTING EFFECTS OF JOHNSONGRASS (*SORGHUM HALEPENSE*) INTERFERENCE AND THE EFFECTS OF PRIMISULFURON AND NICOSULFURON ON CORN (*ZEA MAYS*) YIELD

A DISSERTATION
PRESENTED for the
DOCTOR OF PHILOSOPHY
DEGREE
THE UNIVERSITY of TENNESSEE, KNOXVILLE

ROBERT FOSTER MONTGOMERY
MAY, 1996

DEDICATION

I dedicate this dissertation to my wife, Amy, without whose love, support and sacrifice this would not have been possible. I sincerely hope when we reflect on the decision to pursue this course we will know that it was the right one for our family.

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ABSTRACT

Studies were conducted from 1993 to 1995 to determine models that most accurately describe the effect of johnsongrass culm density or competition on corn yield. Yield loss to competition is a key variable in calculating economic threshold for herbicide application to weeds. Studies were also conducted during these growing seasons to determine if POST application of primisulfuron or nicosulfuron to areas within corn fields that were not infested with johnsongrass should be considered in the calculation of economic thresholds.

Treatments of nicosulfuron at 17.5 g ha^{-1}, nicosulfuron at 35.0 g ha^{-1}, season long hand hoeing and no control were applied to johnsongrass infestations of similar density in johnsongrass competition studies. Herbicide treatments were made during the critical period for weed control (4 to 8 WAP). Season long control by hand hoeing was contrasted in plots with no control at similar johnsongrass density to determine potential yield loss to corn from johnsongrass competition. There were no differences among corn yield for treatments of nicosulfuron at either 17.5 g ha^{-1}, 35.0 g ha^{-1}, or season long hand hoeing and each of these treatments were different from the untreated check. Herbicide treatments did not control johnsongrass as consistently as hand hoeing, suggesting that at high densities under some environmental conditions yield loss occurs with this herbicide at both rates tested.

Yield loss was regressed on culm density using linear and nonlinear models. Linear regression of yield loss on culm density had a low corrected coefficient of determination (R^2 =0.25) and uncorrected coefficient of determination lower than the nonlinear equations ($\sim R^2$ =0.55). Nonlinear models produced some improvement in the uncorrected coefficient of determination ($\sim R^2$=0.57 to 0.58). The amount of variation explained by the models and differences among uncorrected coefficients of determination for all models was reduced by the variation in yield loss data. Models that allowed for exponential yield loss at low weed density and approached zero at high density produced the slightly higher $\sim R^2$ and yield loss estimates that were realistic at threshold weed density and over the potential range of weed densities. Linear, sigmoidal, logistic and three parameter exponential models produced similar $\sim R^2$ but projected high yield loss estimates at the y-intercept that limit the usefulness of these equations for projecting yield loss at threshold levels. The linear model had the lowest $\sim R^2$ of the models used in the study.

The rectangular hyperbola and the two parameter exponential models project the most realistic economic threshold weed density estimates. These models should allow producers to better assess the total potential yield loss from johnsongrass infestations that are highly variable in density and distribution. The two parameter exponential and the rectangular hyperbola model are applicable for projecting yield losses to corn from johnsongrass

interference over a range of weed densities and making economic decisions regarding herbicide use.

Treatments of nicosulfuron at 35 g ha $^{-1}$ and 70 g ha $^{-1}$ and primisulfuron at 40 g ha $^{-1}$ and 80 g ha $^{-1}$ (1X and 2X rates) were applied to two hybrids that are available in acetolactate synthase (ALS) -resistant and nonresistant versions in fields that were weed-free. Pioneer 3245, nonresistant genotype and Pioneer 3245IR, resistant genotype were used in 1993 and 1994. Pioneer 3394, nonresistant genotype, and Pioneer 3395, resistant genotype, was used in 1995. The untreated check received no POST herbicide. The experimental design was a split plot with hybrid as the whole plot and herbicide as the subplot. There was no difference in yield when resistant and nonresistant hybrids were contrasted in whole plot comparisons. Nicosulfuron and primisulfuron at 1X and 2X rates produced higher yields than the untreated check in the subplot comparison. These results suggest that these herbicides have no adverse effect on corn yields when applied POST at 4 to 6 WAP on these hybrids. Economic threshold levels should be lowered to compensate for increased yield rather than raised to compensate for herbicide injury if these results hold true across the genetic diversity represented by all commercially available corn hybrids.

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CHAPTER 1

INTRODUCTION

Corn production in Tennessee was 1.1 to 2.0 billion kg per year during the 10-yr period from 1982 to 1991. A major cash crop for Tennessee farmers, corn ranked second or third among the leading cash crops in the state during this period. Tennessee ranked 20th in the nation, producing 2.0 billion kg in 1992. This state produced a record crop of 8356 kg ha^{-1} during the 1992 growing season despite an estimated 25% of the state's corn acreage being infested with yield reducing johnsongrass [*Sorghum halepense* (L.) Pers.] (**5, 86**).

Johnsongrass, an important weed in the southern United States, one of the ten worst weeds in the world, ranked seventh most common weed in corn in Tennessee in 1979, is difficult and costly to control (**83**). The weed infests 30 different crops in 53 countries (**45**). A moderate infestation of eight plants per 6.1 m of 76-cm width row reduced corn yields by 25% at two locations in Tennessee in 1988 (**13**). Infestations of this level on 25% of Tennessee's corn acreage would cost farmers approximately eight million dollars annually in lost production. Corn herbicide cost ranges from 27 to 69 dollars per hectare annually to control this weed in Tennessee.

Johnsongrass control was incomplete until 1990 when only preplant and preemergence herbicides, cultivation and cultural control methods were used. Primisulfuron, {2-[[[[[4,6-bis(difluoromethoxy)-2-pyrimidinyl]carbonyl]aminosulfonyl] benzoic acid}, and nicosulfuron, {2-(((((4,6-Dimethoxypyrimidin-2-yl)aminocarbonyl))aminosulfonyl))-N,N-dimethyl-3-pyridinecarboxamide}, received full registration in 1990 for selective control of johnsongrass and other weeds (**3, 4**). Growers have more flexibility to control johnsongrass with these products, thus facilitating conservation tillage and compliance with requirements of the Food and Securities Act of 1985 to reduce soil erosion.

Efficacy and potential for corn injury with these herbicides has been studied. Primisulfuron allowed more johnsongrass regrowth and caused more corn stunting than did nicosulfuron (**13, 14**). Corn injury occured with primisulfuron at 20 g ha^{-1} for application dates ranging from 3 weeks after planting (WAP) to 8 WAP. Symptoms included stunting, chlorosis and tissue discoloration. These symptoms tended to diminish by 3 wk after application.

The importance of controlling weeds and grasses during critical periods in the life cycle of several crops, including corn, has been previously identified (**8, 11, 41, 105, 109**). There are two recognized components to the critical period of weed interference. The first is the length of time the crop must be maintained weed-free to prevent yield loss from emerging weeds. The second is the length of time weeds can remain in the crop

before they reduce crop yield. The two periods can overlap, identifying an interval (critical duration of weed interference) over which yield reduction from weed competition can be minimized by controlling weeds(**105**).

Tennessee studies (**86**) indicate the critical johnsongrass-free period for corn reflected by corn grain yield and corn stover weight was 2 to 4 wk after planting. Corn grain yield was not reduced until johnsongrass was allowed to compete for 6 wk after planting. These results suggest that the critical duration of johnsongrass interference with corn is 4 to 6 wk after planting.

Johnsongrass density studies by Brown (**13**) suggest that corn in 76 cm rows can tolerate up to one plant per 1.5 m without sustaining yield loss. The optimum period for postemergence johnsongrass control with primisulfuron or nicosulfuron was 3 to 6 wk after planting. Nicosulfuron applied 3 WAP and primisulfuron applied 6 WAP yielded less than the weed free check at one location in this study. Brown used the linear model, $Y = 6428 - 29X$ where 6428 is the weedfree yield in kg ha^{-1} for the study and X is the number of johnsongrass plants per m of 76 cm row, to predict corn grain yield at various johnsongrass densities (**15**).

Researchers have developed decision aid software for making postemergence herbicide recommendations for corn and soybean based on weed species and density (**116, 118**). The software packages, Herb® 3.0, Herb® 4.0, and Herb® 5.0 use linear and asymptotic models to estimate the

crop yield reduction due to weed interference. Maximum corn yield losses of 25.5% for seedling and 44.3% for rhizome johnsongrass are predicted by Herb® 4.0. The maximum seedling and rhizome johnsongrass corn yield loss predictions projected by Herb® 5.0 are 52.5% and 55.3%.

WEEDCAM is a weed control decision aid for irrigated corn in eastern Colorado and similar areas. This program utilizes a linear model to predict yield loss due to weed (personal communication, E. E. Schweitzer).

General Weed Management Model version 1.0 is a decision aid developed in Minnesota (**115**). This model allows the producer to select a linear, logistic or hyperbolic function to predict yield loss due to weed density. A competitive index characterizes multispecies weed infestations.

The relative accuracy of these models for making postemergence herbicide decisions for johnsongrass control in corn has not been determined. The primary objective of this research was to evaluate existing models under field conditions and modify models if necessary to explain the relationship of corn yield with johnsongrass density. The effect of nicosulfuron and primisulfuron on corn yield was determined by comparing these herbicides on imidazolinone resistant and nonresistant genotypes under weed free conditions. This information should help to predict the yield loss to corn from johnsongrass interference, to determine the johnsongrass density that reduces yields enough to justify control and to determine the lowest POST nicosulfuron rate that can be used to control johnsongrass in

corn. A model that uses early season johnsongrass plant density to accurately estimate the yield reduction to corn induced by this weed could enable users to make treatment decisions based on economic returns and reduce unwarranted herbicide use.

CHAPTER 2

LITERATURE REVIEW

Johnsongrass History and Characteristics

History

Johnsongrass occurs in all major agricultural areas of the warm regions of the world and was listed by Holm (**45**) as one the world's ten worst weeds. Johnsongrass, native to the Mediterranean region, was introduced to the United States by 1800 (**112**). Reports suggest it was growing in several southeastern states by the 1840's and was widespread in the United States by the 1900's (**70**). The United States Department of Agriculture recognized johnsongrass as one of six weeds for which they received the most complaints in 1896 (**67**).

Morphology

Johnsongrass is a perennial plant, 50 to 150-cm tall, with culms arising from an extensive, creeping and rooting scaly rhizome (**43**). Stems are usually unbalanced and 0.5 to 2.0 cm in diameter, often with basal adventitious roots and nodes, sometimes with fine hairs. Leaves often have

a waxy secretion at the base, a prominent mid-vein and membranous ligule with a hairy fringe. Leaf blades are flat, usually green to sometimes purple, ranging from 20 to 60 cm in length. Young plants of johnsongrass are similar in appearance to narrow leaved maize [*Zea mays* (L.)] plants or sudangrass (*Sorghum sudanense*) (**45**).

Examination of johnsongrass leaf surface micromorphology (**71, 72**) reveals microroughness caused by epicuticular, cell surface contours, leaf venation and trichomes. Trichomes, appendages that protrude above the epidermis, include three types of prickles, microhairs and bicellular trichomes. Bicellular trichomes exude mucilage that covers microscopic wax crystals decreasing microroughness with age. Microroughness and exudates of bicellular trichomes likely present a barrier to herbicide penetration.

Reproductive Characteristics that Affect Competitiveness

Reproduction from seed

Johnsongrass is a prolific seed producer with an average production of 28,000 seeds per plant. McWhorter (**46**) collected and studied 55 different ecotypes of johnsongrass from the United States and several foreign countries. These distinct morphological vegetative types suggested that the

weed can adapt and flourish in a broad range of environments. Control of these different ecotypes with dalapon (2,2-dichloro-propionic acid) varied from 36 to 91%. Cultivation and high fertility (**47**) tended to maximize johnsongrass variation in fields infested with several ecotypes. When the soil was not disturbed for two growing seasons, the variation in surviving ecotypes was small.

Burk (**16**) reported similar variation for johnsongrass clones depending on the environment from which they were originally selected. The rate and practical significance to adaptation have not been well defined for many weed species. The ability of weeds to adapt to new environments is suggested by the ease at which genetic variants of several species may be found (**42**).

Johnsongrass is not only a prolific seed producer but also has an inherent survival mechanism in its seed. Louisiana researchers (**100**) reported initial germination rates of 55% and 57% at harvest and viability at 1, 2 and 7.25 yr after burial in soil at depths of 7.6, 15 and 30 cm. Seed buried deeper retained higher germination rates. Seed planted 4 wk after collection (**50**) in October exhibited 30% germination as compared with 90% germination the following March. Freshly collected seed exhibited dormancy. Seed production has the greatest potential for establishment and spread of johnsongrass. Production of dormant seed may hinder the control of johnsongrass. Dormant seed maintain the reservoir of seed in the soil,

enabling reestablishment after unfavorable growing conditions. Removing the seed coat or soaking in concentrated sulfuric acid for 2 min avoided dormancy (**107**). Johnsongrass germination rates have been altered by subjecting seed to varying light intensity, period, wavelength and temperature (**62**). The consistently maintained differences in seed germination rates of vegetatively propagated johnsongrass ecotypes suggest genetic control of dormancy (**61**).

Vegetative reproduction

Once johnsongrass becomes established, rhizomes contribute to the competitive advantage while seed production facilitates its spread. The rhizome system is made up of primary, secondary and tertiary rhizomes. The initial spring growth beginning from primary rhizome buds, functions for 2 to 3 wk, and then begin to decay. Extensions from the primary rhizome become secondary rhizomes that emerge and give rise to new plants. Tertiary rhizomes grow from the base of the plant deep into the soil and produce plants the following growing season (**63**). Plants that develop from rhizomes establish crowns faster than seedlings. Rhizome johnsongrass initiates growth slowly at 20 C. The optimum temperature for rhizome sprouting is near 28 C, and at 39 C sprouting slows significantly. The maximum temperature for rhizome production is near 30 C. Rhizomes do not exhibit physiological dormancy. Apical dominance determines which bud on

the rhizome initiates growth. Growth and development of seedling and rhizome plants are similar, but seed require approximately 10 C higher temperature to germinate. Seedlings emerge later but soon attain aerial development equal to vegetatively reproduced plants (**64, 65**). Plants from seed produce between 0.3 and 1 m of total rhizome growth per day (**64**) after reaching the bloom stage. This growth aids in reproduction and makes plants more tolerant to clipping. Plants with developed rhizomes can draw on energy reserves in the rhizome.

Approximately 80% of johnsongrass rhizomes (**68**) develop in the top 7.5 cm in clay soils while 80% appear in the top 12.5 cm of silt loam soils. More plants emerge from short rhizomes but long rhizomes enable plants to emerge from greater depth. Rhizomes grow at twice the rate in sandy loams as compared to clay soils.

The sensitivity of johnsongrass to freezing is effective as a control measure in the north central United States but is of little use in the South unless the soil is tilled to expose rhizomes to temperature extremes. The drying of rhizomes effectively reduces vegetative shoots, but to totally eliminate shoot development they must be dried to 20% (**2**) of their initial weight. This control method works only under the best of drying conditions; in many cases conservation compliance constraints prohibit the practice.

Johnsongrass Competition in Corn

Numerous researchers have documented the competition of johnsongrass with other crop species (**6, 51, 69, 74, 83**), as well as competition to corn from several weed species (**48, 73, 74, 85, 86**).

Physiological competition

Competition among plants depends on many factors including morphology, capacity to extract nutrients and moisture, differential response to temperature and the interaction of these factors (**62**). Black et al. (**10**) suggest that growth or the ability to assimilate CO_2 and photosynthate into foliage is an important factor in competition among plants. Plants that use the C_4 pathway for photosynthesis are foremost among competitive weeds in many crops. Johnsongrass makes efficient use of water, CO_2 and sunlight through C_4 photosynthesis. Soil moisture conditions and plant species showed significant interaction in studies by Wiese (**114**). All plants did not grow the same when subjected to competition under different soil moisture levels.

Johnsongrass growth increased with greater light intensity, but rapid rate of growth occurred at relatively low light levels. This abilility to tolerate low light levels partially explains the competitiveness of johnsongrass when growing underneath crops such as soybeans and corn (**62**).

Morphological competition

Weeds tend to compensate for density by branching or tillering. Sibuga and Bandeen (**97**) observed similar dry weights and seed yields for weeds of varying densities. Similar results were reported by Moolani et al. (**79**) when comparing dry matter yields for corn infested with smooth pigweed (*Amaranthus hybridus)* and weed-free corn yields. The combined dry matter biomass for crop and weed varied less than 7% over a 3-yr period while corn yields varied 39% (**74**).

Allelopathy

Johnsongrass may increase allelopathic affects on certain plant species. Johnsongrass treated with translocated herbicides produced more allelochemicals and/or phytotoxic residue. This factor could enhance the potential for johnsongrass interference with certain crop species (**100, 38**).

Disease vector

Johnsongrass is usually infested with maize dwarf mosaic virus (MDMV) and/or maize chlorotic dwarf virus (MCDV). Johnsongrass serves as an alternate host for this disease and contributes to its spread. Corn yield reductions occur when the virus is vectored into corn by insects. Crop failure (100% yield reduction) in johnsongrass (**8**) infested corn due to johnsongrass over the course of a 5-yr study has been reported. Corn yield

loss was attributed to an interaction between weed competition and crop infection by MDMV and MCDV.

MDMV and MCDV increased in corn when johnsongrass was controlled by three methods when compared to no johnsongrass control. Corollary studies at the same site documented movement of blackfaced leafhoppers [*Graminella nigrifrons (Forbes)*], the insect vector of MCDV, following treatment of johnsongrass (**34**). Increased MDMV in POST herbicide treated plots was associated with a higher percentage of virus-infected plants rather than more severe MDMV infections (**111**).

Critical period

The critical period (**121**) of weed control is the interval between two separate components. The first, the maximum length of time that weed control efforts must be maintained to prevent crop yield loss, represents the period that crop must be maintained weed free after planting so that emerging weeds do not reduce yield. This period represents the minimum time that preplant incorporated or preemergence herbicide must remain effective. The second, the length of time that weeds can remain in a crop before they interfere with crop growth and yield, represents the amount of time that postemergence treatment could be delayed in the event a residual preplant incorporated or preemergence herbicide could not be applied or failed to control all of the competitive weeds. Both components can be

integrated to identify a single critical period of weed control, during which control produces acceptably low yield reductions induced by either component. If the two components do not overlap, weeds should be controlled prior to the point when yield losses occur due to the second component (**113**).

The Gompertz equation (**41**) has been used to describe the increasing duration of weed control on yield:

$$Y = Ae^{(-Be^{(-kT)})}$$

where Y is the yield (% of season-long weed-free corn), A is the yield asymptote (% of season-long weed-free corn), B and K are constants, and T is the time from planting in days.

The logistic equation has been used to describe the increasing duration of weed interference on corn yield:

$$Y = [1/(De^{(K(T-x))+F)+((F-1)/F)}]*100\%$$

where Y is the yield (% of season long weed-free corn), T is the time from planting in days, x is the inflection point (days), and D and F are constants. The beginning and end of the critical period were identified by setting an acceptable yield loss at 2% and solving these equations for T (days). The beginning of the critical period varied from the 3-leaf stage to the 14-leaf

stage. The end of the critical period was less variable. The average stage of growth that marked the end of yield reduction to increasing the duration of weed competition was the 14-leaf stage. Weed free requirements varied from 28 to 56 d after planting in studies conducted in Canada. Studies by Cousens (**25**) support this method of identifying a critical period by regression rather than mean separation.

Critical period studies (**105**) for white beans (*Phaselous vulgaris*) and corn indicated that yield losses decline as seedling emergence of the natural weed population was delayed. Models using weed density to predict yield loss could be improved by incorporating relative time of emergence or relative leaf area as a factor. Crop yield loss to a specific weed at a given density and among locations was a concern. Perry (**86**) recorded reductions in grain yields from johnsongrass competition with corn in Tennessee at 18 to 50%. Corn biomass yields were reduced from 37 to 67%. The critical johnsongrass free period for corn was determined to be between 2 and 4 wk after planting depending upon environmental conditions. Periods of johnsongrass interference from planting through 6 and 10-wk increased stalk lodging and delayed the onset of reproductive growth.

The critical period is difficult to define and varies with weed species, density and environment (**105, 120**). Weed interference in corn prior to herbicide application in a total postemergence (POST) program has been examined. Treatments of nicosulfuron plus bromoxynil (3, 5-dibromo-4-

hydroxybenzonitrile) were made to plots with dense natural weed populations and compared to weed-free plots. These herbicides gave near complete control of weeds when applied to canopy heights of 5, 10, and 15 cm. Weed interference did not reduce yields in plots with canopies of 5 and 10 cm. Weed interference reduced corn height and yield in plots with weed canopy of 15 cm in 1992 although weed control was nearly complete. Incomplete weed control reduced corn height and yield when applications were delayed until weed canopy reached 20 cm. This study identifies a weed canopy height that defined the time at which POST herbicides must be applied if no preemegence (PRE) herbicide had been applied to avoid yield reduction due to johnsongrass competition (**18**).

Johnsongrass Control in Corn

Methods used to control johnsongrass in corn have included cultural, biological, and chemical. Biological control has shown promise for controlling johnsongrass, but has not evolved into an effective tool for producers.

Cultural control

Cultural control and hand removal of johnsongrass were the earliest

methods used to reduce johnsongrass competition. Today cultural or mechanical methods are used efficiently in johnsongrass control systems, and cultivation of fields and rows can be an part of the total johnsongrass control program. These methods reduce populations of johnsongrass by dislodging plants that are growing in competition with corn, exposing rhizomes and seed to unfavorable environmental conditions. Preplant discing chops rhizomes into smaller sections, making plants more susceptible to diseases and herbicides; however, conservation plans that specify soil erosion limits restrict the area that can be tilled or cultivated (**91**).

Chemical control

Early chemical control measures introduced in the 1950's relied on the application of dalapon, a non-selective foliar-applied herbicide to kill underground tissue. Glyphosate, *N*-(phosphonomethyl)glycine, introduced in the 1970's, replaced dalapon. Both products must be applied to johnsongrass that has emerged before the crop is planted. Delayed planting causes corn yield loss and johnsongrass regrowth can be a problem as well. Fall-applied herbicides after corn harvest may help reduce johnsongrass plants arising from rhizomes the next year, but seedlings continue to be a problem (**44**).

Carbamothioate herbicides, EPTC (*S*-ethyl dipropyl carbamothioate) and butylate (*S*-ethyl bis(2-methylpropyl)carbamothioate), have effectively

reduced seedling and rhizome johnsongrass infestation. These soil-incorporated herbicides control 90% of seedling johnsongrass. Rhizome johnsongrass control is rated at 60 to 70% for these herbicides in Tennessee (**7**). Enough johnsongrass escapes control to replenish the seed bank in the soil and thus infestation levels remain high year after year when these herbicides are used. Effectiveness of these products has been estimated at 20 to 80% in other studies (**82, 83**). Roeth (**90**) reports control ranging from 79% to 93% using these PPI herbicides in 2 yr of a 3-yr study. All herbicides gave < 60% control in 1 yr of this study. Corn yield was highly correlated to johnsongrass control. Conservation compliance measures restrict the use of tillage that is required to incorporate these herbicides on highly erodible land.

Many PRE herbicides including pendimethalin, alachlor, acetochlor, dimethenamid and metolachlor have been used to reduce seedling johnsongrass in corn. These products do not give adequate control of johnsongrass that arises from rhizomes.

The use of cultivation, herbicide, and treatments combining mechanical and chemical weed control measures has been compared (**77**). Cultivation increased weed cover when compared to treatment combinations using only herbicides and herbicides in combination with cultivation for 3-yr and produced lower corn yields in 1 yr of 3-yr. Weeds in the row were troublesome in cultivation treatments. Control with broadcast

herbicides was similar to control methods combining cultivation with herbicides banded in the row. This approach reduced herbicide use by 67% while providing adequate weed control. The availability of labor for making timely cultivation of weeds was cited as a concern for the effectiveness of this control method and its acceptance by farmers.

Control of johnsongrass with primisulfuron and nicosulfuron

Primisulfuron and nicosulfuron were labeled for use in corn in 1990. These sulfonylurea herbicides are applied POST in corn at 18 to 105 g ha^{-1} to control emerged perennial and annual grasses and some broadleaf weeds. Preliminary field research revealed that nicosulfuron at 18 to 70 g ha^{-1} controlled 27 weed species > 80%. Corn was not injured. Very little soil residual activity has been observed at these low rates (**78**).

Nicosulfuron and primisulfuron were applied POST at rates of 35 g ha^{-1} and 30 g ha^{-1} at 3 to 6 wk after planting (**13**). Johnsongrass control with these herbicides ranged from 25% to 93% depending upon time of application and location. The highest corn yields were produced with nicosulfuron applied between 3 and 5 wk after planting.

Combinations of nicosulfuron, EPTC (S-ethyl dipropylthiocarbamate) + dichlormid, and cultivation were evaluated (**101**) to determine the effect of these treatments on johnsongrass interference with corn. Nicosulfuron

controlled 30 cm johnsongrass better than 60 cm johnsongrass. Later applications of nicosulfuron were more effective. Corn yields were improved by preplant-incorporated EPTC. Nicosulfuron treatments produced better weed control and higher yields than cultivation and/or EPTC alone.

Nicosulfuron at 40 g ha^{-1} reduced johnsongrass growth more than primisulfuron at 40 g ha^{-1} when soil applied in greenhouse studies (**20**). Both herbicides were more active when applied to foliage. Soil treatments in combination with foliar treatment did not improve johnsongrass control over foliar application alone. Two application periods, early (4 to 6 WAP) and late (6 to 8 WAP), were compared. The best weed control (> 88%) was produced by late application at full rates. Corn yields did not differ between early and late applications. A split application of primisulfuron at 20 g ha^{-1} followed by nicosulfuron at 17.5 g ha^{-1} provided the most thorough weed control 8 WAT.

These results are supported by earlier field corn, greenhouse, and laboratory studies (**81**) where johnsongrass was controlled more effectively by nicosulfuron at later growth stages (> 5 leaves) when compared to earlier growth stages (< 5 leaves). Late and split applications gave more effective control than early application because regrowth was controlled and plant emergence was more nearly complete at the late application time. Synergistic and additive results have been reported for 1:1 combinations of nicosulfuron and rimsulfuron (DPX-79406) on weed species in corn (**76**).

Primisulfuron at 20 to 40 g ha^{-1} controls approximately 35 weed species 80 to 100%. It has a short to moderate soil life; therefore, several rotation crops may be planted safely following application at 40 g ha^{-1}. Surveys in several states indicates that nicosulfuron and primisulfuron are used extensively to control weeds including johnsongrass (**37**).

Selectivity mechanism

One selectivity mechanism identified for acetolactate synthase inhibiting herbicides is differential metabolism. Corn plants metabolized 90% of the herbicide within 20 h. There was no detectable metabolism of the herbicide in johnsongrass within 24 h after application (**81**).

Models for Estimating Yield Reductions of Crop by Johnsongrass and Other Weeds

Computer aids for weed control decisions have increased recently. The two types of computer decision aids that have emerged are efficacy and population-based programs. Population based decision-aids estimate potential yield loss relative to seed bank size for selection of PRE herbicides (**52**) or estimate crop loss from emerged weed seedling density (**75**). Historical annual grass infestation requires the use of PRE grass herbicides in most Tennessee corn fields. Models that accurately predict crop yield loss

to johnsongrass could receive wide use because perennial johnsongrass and seedling johnsongrass sometime escape PRE herbicide control measures. Effective POST johnsongrass control herbicides are available to producers. Modeling the effect of johnsongrass on corn yield should increase the efficiency of POST herbicides used to control this weed.

Economic threshold

Weed management can be categorized into three strategies: eradication, prophylaxis, and containment. Eradication programs tend to be expensive in the short term and most feasible on newly introduced pests infesting small areas. Prophylactic strategy uses herbicides every year regardless of weed seed soil bank, size and population. Most PRE herbicides are applied by this strategy. Containment is an effort to maintain the weed below a specific level. A containment policy presupposes that a population of weeds can be defined and monitored. This strategy is inextricably linked with weed thresholds (**24**).

The economic threshold concept establishes parameters for a pest population allowing producers to make decisions about control options that optimize probability for economic return. The economic threshold has been defined as the density at which control measures should be applied to prevent an increasing pest population from reaching economically harmful levels. Threshold levels are always lower than economic injury levels, to

allow control measures to take effect before the pest causes economic injury that exceeds the cost of control (**102**). An economic threshold for chemical control of weeds may be defined as the weed population at which the cost of control is equal to the value of the crop yield attributable to that control (**118**). Mathematically, this economic threshold for an individual crop may be defined as:

$$t_E = (Ch + Ca)/(YPLH)$$

where t_E is the economic threshold, *Ch* is the herbicide cost, *Ca* is the application cost, *Y* is weed-free crop yield, *P* is the price per unit of crop, *L* is the proportional loss per unit weed density, and *H* is the proportional reduction in weed density by the herbicide treatment.

This model for economic threshold assumes a single pest and a linear relationship between yield loss and weed density. Thresholds have been developed that describe hyperbolic relationships, multispecies weed complexes, and herbicide efficacy. Many other factors can be accounted for in a threshold including risk aversion, visual crop appraisal or herbicide injury to the crop.

Estimates for the factors in economic threshold models that can be obtained accurately are herbicide cost, application cost and crop value per unit. Crop yield, herbicide efficacy and proportional loss per unit weed density are more difficult to predict because of environmental factors, weed

species, weed size and cropping system. Cousens et al. (**27**) suggests that a threshold may be more appropriately defined as an arbitrary, indefinite point on a smooth curve rather than a definite step in a biological or economic response.

Weed competition yield loss models

Studies of field sampling technique (**60**) reveal that precise estimates of weed density and distribution can be achieved only at high sampling intensity, at least 18 locations m^2 ha^{-1}. The mean for the weeds that occur at high densities can be more accurately determined with lower sampling intensity when compared to low density weed infestations. Low density infestations tend to be patchy rather than normally distributed throughout fields. Weed distribution as it relates to POST soybean herbicide selection has been examined (**117**). The assumption of normal weed distribution when in fact the field infestation was patchy or scattered can lead to overestimation of yield loss. Incorrect yield loss estimates lead to possible mistakes in herbicide use decisions. The potential for mistakes increases when weed complexes involve multiple species. The cost of these mistakes increases as crop value increases or crop competitiveness decreases. Assuming normal weed distribution when populations are patchy can lead to both increased or decreased POST herbicide use. Errors most frequently involve using excessive herbicides . Herbicide use in kilogram of formulation

or active ingredient per unit of area is a crude measure because activity and use rates vary widely by product. The variation in herbicide use rates increases the difficulty in making quantitative comparisons among the herbicide options for weed control. The cost of assuming regular distribution when selecting POST broadleaf herbicides was low for soybeans.

Linear models

Coble and Mortensen (**19**) and Cousens (**26**) suggest linear regression ($Y = a - bx$) is a plausible description of weed density on crop yield at low weed densities where areas of influence do not overlap. In this equation, a equates to crop yield in the absence of weed interference, b is the slope of the regression line, or yield loss per weed and x is the number of weeds per unit area of land. One way to examine the competitive ability of individual weed species is to examine the crop yield loss caused by an individual weed as a proportion of total yield. A competitive index (*CI*) is calculated. The number of weeds per unit area is multiplied by the respective *CI* value for that species to determine the competitive load (*CL*) for individual species. The *CL* can be summed for multispecies infestations into a total competitive load (*TCL*) *TCL* value is substituted into multispecies models for weed density (**116, 118**) The linear model was also used by Brown (**13**) to describe the johnsongrass competition in corn in Tennessee. Corn yields were equal to the check at densities up to four johnsongrass plants per 6.1

m of 76.2 cm width rows at two locations in 1988. All higher densities were significantly lower than the weed free check. The data suggest that corn can tolerate up to one plant per 1.5 m of row without sustaining yield loss or else there is a lack of statistical sensitivity for yield reduction at low infestation levels.

Brown's work (**15**) indicated that yield and johnsongrass density were correlated negatively. He reported yield reductions of up to 78% for heavy infestations in weedy check plots and yield reductions of 44% for infestations of 16 rhizome plants 6.1 m of 76 cm width row. Brown used the following linear regression model to describe the relationship between yield and rhizome johnsongrass density: $Y = 6428.1 - 29X$, where Y = predicted corn yield kg ha^{-1} and X = johnsongrass density m^{-2} row.

WEEDCAM, a decision aid (**52, 58**) that assists researchers and those making weed management decisions in irrigated corn in eastern Colorado and similar irrigated areas, establishes crop yield loss to weeds from the predicted aggregate number of weed escapes at harvest. The WEEDCAM's competitive index based on a survey of twelve weed scientists knowledgeable about corn-weed competition rated on a scale of 0 to 1 with the most competitive weed given an index of 1. The index identifies sunflower as the most competitive weed. Johnsongrass was not in the competitive index. The weighted weeds for management strategy i (WW_i) is the number of species j (N_j) per 33 m of row times the weed species

competitive index (CI_j) summed over all weed species. WW_i is described by the following equation:

$$WW_i = \sum_{j=1}^{n} N_j * CI_j$$

A linear relationship between *WW* and percent yield loss is used. The constant 0.9976747 in the equation that follows represents a slight yield loss from weeds that emerge late in the growing season and compete with the crop even when there are no projected weed escapes. Each *WW* is expected to reduce crop yield by 0.0012514%. The weedfree yield (*WFY*) is multiplied by the expected yield percentage to compute the expected yield for the i^{th} weed management strategy (Y_i). The coefficients in the following equation were estimated statistically from 4 yr of field trial data:

$$Y_i = WFY * (0.9976747 - 0.0012514 WW_i)$$

There is a constant percentage yield reduction as weed escapes increase because this equation is linear. The linear form was adopted because of its simplicity and the near linear response of the yield loss function over the weed management decision range. The function is truncated to prevent negative treatment yields for dense weed populations.

Researchers conducted studies (**110**) to decide the effect of the distribution of indigenous weed populations on the yield of irrigated corn. They evaluated early summer and mid-September weed populations for predicting final corn yield with the bioeconomic weed management model,

WEEDCAM. Determining predicted yield from weed populations 5 to 8 WAP was more highly correlated to actual yield than predicted yield from weed population determined on September 12. The following linear regression equations explain the relationship between yield and weed density for 1991 and 1992: $Y_{1991} = 9707 - 8.5X$ and $Y_{1992} = 10500 - 2.3X$, where Y_{year} = predicted corn yield kg ha^{-1} and X = weed density 30 m^{-1} of 76 cm row.

Multispecies yield loss models

Researchers at North Carolina State University have developed an approach for estimating multispecies economic thresholds for weeds in corn and soybeans. This multispecies herbicide decision aid software is available as HERB® (**118**). This software package establishes an index for comparing the competitiveness of different weed species infesting crops, using field survey information (scouting) to determine the number of weeds of each species per unit area (10 m^2). The competitive ability of individual weed species was used to determine crop yield loss caused by an individual weed as a proportion of total yield. This can be determined by dividing the slope of the regression equation by the *y* intercept. Competitive ability can be expressed as *b/a*.

An indexing system (**19**) can compare effectively the competitive abilities of different weed species. Usually, the most competitive species receives some arbitrary value (*K*), and all other weeds take a rank relative to

the most competitive species. Then, the competitive index $(CI)^3$ equation for an index based on a 0 to 10 scale may appear as follows:

$$CI_1 = \frac{(\frac{b_1}{a_1})}{(\frac{b_i}{a_i})} * K$$

where b_1 = slope linear of the linear regression for the effect of weed density of a weed species on crop yield, a_1 = the y intercept for the linear regression of yield on weed density for a weed species, b_i slope of the linear regression for the effect weed density of the most competitive weed species on crop yield, a_i = y intercept for the linear regression of yield on weed density of the most competitive weed species on crop yield, and K = a constant or in this case 10. The $K_{\text{rhizome johnsongrass}}$ is equal to 5.0 and the $K_{\text{seedling johnsongrass}}$ is equal to 3.0 in corn for the decision aid HERB® (personal communication, G. G. Wilkerson, North Carolina State Univ.). This indexing procedure allows the summation of the effects of multiple weeds on crop yield to determine the competitive load (*CL*), defined as the product of the number of weeds of a single species per unit area multiplied by the *C* value for that specie:

$$CL = CI_1 * \text{number of species per unit area}$$

This procedure is repeated for each species in the weed population. Then summing the *CL* values calculates the total competitive load $(TCL)^3$:

$$TCL = CL_1 + CL_2 + CL_3 + ... + CL_n$$

Nonlinear models

As weed populations increase, and the areas of influence of individual weeds begin to overlap, the linear function no longer provides a meaningful description. For a wide range of weed populations, Cousens (**21, 26**) determined the rectangle hyperbola to be an appropriate model:

$$Y_L = \frac{Id}{[1 + \frac{Id}{A}]}$$

where Y_L = yield loss, I = yield loss per weed as d approaches O, d = weed density, and A = yield loss as d approaches maximum. This model is used to calculate yield losses from weed competition in HERB®.

The following equation describes the effect of weed density on crop yield, Y_t (kg ha^{-1}):

$$Y_t = Y_{wf} [1 - r_{max} M_t / (1 + \gamma M_t)]$$

where Y_{wf} is the weed-free crop yield, r_{max} is the proportional yield reduction per unit weed density at low infestation levels and γ is a constant that determines the way in which proportional yield loss changes with weed density. Within the model time is measured in years and is denoted by t (**23**).

Spitters (**98**) used a similar hyperbolic model to describe the competition of barnyardgrass (*Echinochloa crus-galli)* with corn. The study points out problems of generalizing the results of a competition experiment to other experiments and the large amount of variation possible between yr.

This problem appeared in competition studies of velvetleaf in corn (**17**), where the economic threshold ranged from 0.13 velvetleaf m^{-2} to 18.2 velvetleaf m^{-2}. Variation was a combination of year and time of emergence effects. A sensitivity analysis revealed that economic threshold was extremely responsive to changes in *I*, but not to A. A 1% deviation in *I* produced a 31.3% change in economic threshold, whereas a 1% deviation in *A* changes economic threshold only 0.09%. Economic thresholds predicted using yield goal information deviated from actual thresholds (using actual yields) for a given year by -43 to 30%.

Herb® (**116**) utilizes the value 0.5 for *I* and *A* is 80 for soybeans. Because *TCL* values are derived from density values multiplied by an index, the *TCL* values may be substituted for d in the rectangular hyperbola, thus giving:

$$Y_L = \frac{0.5(TCL)}{[1 + \frac{0.5(TCL)}{80}]}$$

Values for corn of $I = 0.14$ and $A = 60$ are used in HERB® versions 3.0 and the latest version 5.0. HERB® version 4.0 uses $I = 0.1$ and $A = 80$. Values of 0.14 and 70 have been reported for *I* and *A* (**19**). The parameters of this model vary with crop, location, weed infestation and year effects.

Inputs for HERB®, considering the yield loss function and the *TCL* calculations for multispecies weed infestation, include average density of

each species per 10 m^2, size range of the weed population, soil moisture status, expected weed-free yield, expected crop selling price, and herbicide and application costs. Outputs include crop loss assessment if nothing is done, the best herbicide choice based on net return, and a ranking of all alternatives in order of net return. The crop loss function in HERB® for soybeans is a rectangular hyperbola when $TCL > 50$ and linear when $TCL \leq 50$. The program uses the rectangular hyperbola model for corn when *TCL* values > 1.0 and the linear function when *TCL* values ≤ 1.0 in HERB® 3.0 (personal communication G. G. Wilkerson). Present plans are to use the rectangular hyperbola as the yield loss function in updating HERB® due to the narrow range at low weed densities for which the linear model is appropriate in corn (personal communication H. D. Coble). Herb® adjusts for weed species, size and water stress status (**116, 117**).

Users in several states have modified HERB® to better estimate weed losses on a regional basis (Georgia, Kentucky, Arkansas, and Nebraska), more closely representing agronomic practices in those states. Validation trials conducted in North Carolina verified the crop loss function used in HERB® and suggested that it produced an accurate estimate of yield loss at low weed populations and appeared to slightly overestimate crop loss at high densities. HERB® projected crop losses that were compared to weed free checks.

The decision model HERB® adjusts herbicide efficacy, by species,

depending on soil moisture and weed size categorizing weed size as < 5 cm, 5 to 10 cm, and > 10 cm and soil moisture as normal or dry. These factors create a total of six efficacy conditions (soil moisture by weed size combinations). Weed size provides an indirect measure of relative weed emergence that can be applied in practical use (**19**).

Soybean yields produced by herbicide recommendations generated from HERB®, MSU-HERB and Soybean Weed Control (SWC) decision aids have been compared to each other, to recommendations of weed scientists, to untreated check plots and weed free check plots (**87,92, 93**). Herb® and SWC predicted yield losses within 10% of actual yield losses approximately 10% of the time in 1992 and 1993. Recommended treatments between weed scientist and decision aids were seldom similar with HERB® recommendations resulting in yield losses lower than the untreated check and similar to weed scientists' recommendations. SWC recommendations reduced yield losses when compared to the untreated check, but were not as effective as weed scientists' recommendations in reducing yield loss. Herbicide recommendations did not increase net returns above the untreated check and all produced yields lower than the weed-free check (**92**). When HERB® and MSU-HERB, a modified version designed to fit growing conditions in Mississippi, were compared in Mississippi, these decision aid herbicide recommendations agreed 56% of the time. No substantial differences in herbicide efficacy were detected when the recommendations disagreed.

Yield losses projected by these decision aids were within 10% of actual yield losses 44% of the time. Yield loss was over estimated 44% of the time by both versions.

Swinton (**106**) proposed a nonlinear competitive index for use in the rectangular hyperbolic model to explain multispecies weed competition with crop. This differs from the linear competitive index modification used in all versions of HERB. Kropff (**54, 55**) points out the difference in the effect of period between crop emergence and weed emergence on yield loss. An alternative to weed density was relative leaf area of weeds with respect to the crop, as observed shortly after crop emergence. Kropff (**54**) derived an empirical model from Cousens' hyperbolic yield density function (**21, 26**) in which relative leaf area of each species replaced plant density. Kropff's model (**54, 56**) compared favorably with Cousens' model (**25**) that related yield loss to plant density and relative time of weed emergence. Models of this type may have more application in scientific research than as a decision aid to producers due to the difficulty and time required to obtain these measurements.

Cousens' (**28**) alternative approach modifies the hyperbolic function that describes yield loss as a function of weed density to include relative time of emergence. This is done by allowing i in the rectangular hyperbola equation to decline exponentially with relative time of emergence (T):

$$i = be^{-cT}$$

where b and c are regression coefficients and e is the base of the natural logarithms, b is the value of i when $T = 0$, and c is the rate at which i decreases toward zero as T becomes large. Cousens' equation can then be expressed as:

$$y_L = \frac{be^{-cT}D}{1+be^{-cT}D/a}$$

This model avoided several undesirable, implausible properties of the multiple regression model. Cousens' hyperbolic model can extend to include crop density as a variable (**22**). This has application in experiments designed with crop density as a variable. A constant crop density that targets the maximum yield in a weed-free environment is planted in production of corn for grain. Cousens suggests that more complex models cannot be justified when weed density is the only variable (**21**).

King *et al.* (**52**) used weed densities and seed numbers, weed control practices, and grain yields in a bioeconomic model that evaluated alternative weed management strategies for continuous corn. The relationship between weed and crop density has been described as sigmoidal or quasi-sigmoidal with a biological threshold weed density below which no yield loss occurs. This suggests no competition between crop and weeds at low density,

despite plant size. This theory is a direct contrast to the rectangular hyperbola model and linear models. The hyperbolic and sigmoidal model can be seen as diametrically opposed biological interpretations, both biologically and fundamentally from a weed control decision-making point of view (**21**). Cousens dismissed the sigmoidal response curve (**26**) as a misinterpretation of multiple comparison test. At low weed densities there is no significant (= not detectable) difference between treatment and control. This is usually, incorrectly according to Cousens, interpreted as no difference and the response curve is considered horizontal. As density increases, differences become significant (=detectable) and it is argued that yield then decreases. When plotting data from an additive design experiment, varying weed density and holding crop density constant, a smooth hyperbolic/exponential-like response is evident.

In contrast to this, Williams and Hayes (**119**) reported a sigmoidal relationship for the competitive effect of johnsongrass on soybean yield. The relationship between johnsongrass density and yield for soybean row spacings of 0.25 m and 1 m was explained by the following equations:

$$Y_{0.25m\,row\,space} = 1776 + 424\, e^{-0.023x^2}$$

$$Y_{1.00m\,row\,space} = 1668 + 643\, e^{-0.004x^2}$$

Economic thresholds were established for johnsongrass control in soybeans using these equations by Roberts and Hayes (**89**). An inverse sigmoidal seed cotton yield response was observed over a range of 0 to 32 johnsongrass plants 9.8 m^{-1} of row. The sigmoidal model provided a better fit than either linear or quadratic models. Sigmoidal models provided accurate crop yield estimates at low weed densities by minimizing overestimation of losses at these densities (**12**).

The impact of total weed density on crop yield has been described by the model (**52, 37**):

$$Y_t = b_{61} / [(1.0 + e^{(b_{62} + b_{63} W_t + u_{6t})}]$$

where Y_t is corn grain yield (1000 kg ha^{-1}); W_t is the density of grass and broadleaf weeds/ha; b_{61} ,b_{62} , and b_{63} are parameters to be estimated; and u_{6t} is a stochastic disturbance term. This is a logistic specification, which allows for increasing and then decreasing yield reduction as weed density increases. The impact of weed density on potential yield is determined by b_{62} and b_{63}; b_{62} can be positive or negative, while b_{63} must be positive if crop yields decrease with increasing weed density. Authors note potential problems with bias in parameter estimates that could invalidate significance tests of parameter estimates. Weighted least squares analysis is suggested

when residuals exhibit heteroscedasticity. Lyebecker (**58**) used the following model to predict corn yield from herbicide treatments based on the number of projected weed escapes: $Y = 14.1/(1.0 + e^{(-.25344 + .0000059992W)}$, where Y = expected yield (kg ha^{-1}) with weeds, and W = the number of projected weed escapes.

Multiple regression model

O'Donovan et al. (**80**) proposed the following multiple regression equation to describe the relationship between time of emergence and density of wild oat, and yield loss of wheat and barley:

$$y_L = a + bT + c\sqrt{D}$$

where T is the time interval between weed and crop emergence (T is negative if weeds emerge before the crop), D is weed density, y_L is percent yield loss relative to no weed competition, and a, b, and c are parameters that can be estimated from the data.

The choice of weed densities affects the estimate of regression parameters. Geometric (n, 2n, 4n, 8n, 16n m^{-2}) and arithmetic (n, n+2, n+4, n+ 6, n+ 8, n+10 m^{-2}) series of weed densities are commonly chosen. There is no restriction to choosing one or the other of these series of

densities. In describing the entire non-linear response, for a given number of densities a geometric series is closer to optimal. An attempt should be made to choose densities to give the best description of the expected shape of response. A reasonable guide is to make sure that densities will cover the main points of interest (the Y intercept and the maximum yield loss) and to have densities near the points of inflection on the curve. This would likely include densities above those found in farmer fields. Regardless of relevance, very high densities should be included (**26**).

CHAPTER 3

PERFORMANCE OF MODELS TO PREDICT ACTUAL YIELD LOSS FROM JOHNSONGRASS (*SORGHUM HALEPENSE*) INTERFERENCE WITH CORN (*ZEA MAYS*).

Abstract

Johnsongrass escapes PRE corn herbicides used for grass and broadleaf control. This weed presently infests 25% of the state's corn acreage. Johnsongrass control of 80 to 100% has been reported for nicosulfuron and primisulfuron applied 3 to 8 WAP. Tennessee researchers have experienced corn yield loss up to 78% for heavy johnsongrass infestations.

Linear and nonlinear models have been used to describe competition between crop and weeds. Linear functions characterize low level weed competition accurately, but lack the ability to reflect changes that occur from low to high weed density. Nonlinear equations have been used to describe crop yield loss as weed density changes. Accurate models allow consultants and producers to estimate potential corn yield loss from johnsongrass competition during the critical weed control period. These models facilitate the use of economic thresholds for weed control.

Field experiments were conducted to compare nonlinear equations that describe corn yield loss to johnsongrass competition over a range of johnsongrass densities. Johnsongrass control with nicosulfuron at 17.5 g ha^{-1}, nicosulfuron at 35.0 g ha^{-1}, hand hoeing and an untreated control was contrasted. Johnsongrass culms were counted and classified into low, medium, and high densities at each location. Culm counts were made by classifications within plots: plants with < 5 culms, plants with 5 to 10 culms, and plants with > 10 culms. This experiment was replicated 12 times over 3 yr from 1993 to 1995. Treatments were replicated two to five times at each location.

Treatment means and parameter estimates were determined by combined ANOVA and linear regression using the mixed procedure SAS 6.08. Grain yields of 6600 ± 530 kg ha^{-1} were produced in the untreated control. Herbicide treatments of nicosulfuron at 17.5 g ha^{-1} and 35.0 g ha^{-1} had grain yields of 7860 ± 550 kg ha^{-1} and 7810 ± 540 kg ha^{-1}, respectively. Both herbicide treatments and hand hoeing produced yields that were different ($p < 0.001$) from the untreated check. There was no difference among means for the hand hoed and either of the herbicide treatments. Corn yields for plots treated with nicosulfuron at 17.5 g ha^{-1} and 35.0 g ha^{-1} applied 3 to 6 WAP were equal. Hand hoed treatments produced 8055 kg ha^{-1}. Linear regression predicted an average yield reduction of 1.0 ± 0.13 kg ha^{-1} ($p < 0.001$) for each johnsongrass culm 1.0 m^{-2}. Means and parameter

estimates were compared in single degree of freedom pairwise t-tests.

Five nonlinear equations and a linear equation were fit to corn yield loss data produced at varying johnsongrass densities using the procedure NLIN for the nonlinear and GLM for the linear regression in SAS 6.08 (**94**). Differences among the variation explained ($\sim R^2$) by the six models were slight, ranging from 55.1% to 58.1%. Similarity in the $\sim R^2$ for the models was likely due to variation in the yield loss data caused by biological factors other than johnsongrass density and variation due to confounding of johnsongrass density with plot and location. Yield losses predicted by equations 1, 2, and 3 were highly correlated ($r > 0.99$). The correlation among yield losses predicted by equations 1, 2, and 3 and those predicted by equations 4 and 5 ranged from $r = 0.98$ to $r = 0.95$. Corn yield losses predicted by equations 4 and 5 were highly correlated ($r > 0.99$). Yield loss estimates projected by the linear model (equation 6) were more highly correlated to those produced by equations 4 and 5 than to those produced by equations 1 and 2. Equations 1 and 3 projected yield losses that increases rapidly from low to moderate johnsongrass densities. These equations predict similiar yield loss at low weed densities where economic threshold occurs. Equations 4 and 5 allow for lower rates of increase in yield loss due to competition at low weed density, however initial predicted yield losses were high as weed infestation levels approached zero. The area of the curve for equation 4 and 5 that allows for a gradual increase in the

effect of weed density occurs at extremely low weed densities. Equations 1 and 3 produced the most realistic yield loss estimates and were the least complex of the nonlinear equations fit to these data. These equations should provide the best yield loss estimates for making economic decisions over a broad range of johnsongrass infestation levels.

Introduction

Linear and nonlinear functions have been used to explain the effect of competition between crop and weeds (**14, 15, 19, 21, 22, 23, 28, 115, 116, 117, 118**). Most crop loss functions were developed or adapted to predict yield loss induced by multispecies weed infestations. Johnsongrass often escapes PRE herbicides used to control weeds in the southern corn producing regions of the United States.

Studies with indigenous seedling and rhizome johnsongrass have reported johnsongrass control in corn with POST herbicides (**20, 37, 76, 78, 101, 108**). Nicosulfuron and primisulfuron at 17 to 40 g ha^{-1} applied 3 to 8 WAP have effectively reduced johnsongrass competition with corn. Primisulfuron and nicosulfuron exhibited superior crop tolerance to previously tested POST herbicides for corn and high levels of control (80 to 100%) of weeds, including johnsongrass (**37, 78**). Nicosulfuron controlled johnsongrass more effectively than primisulfuron in field and greenhouse studies (**20, 78**).

Linear functions characterize low level yield loss due to weed competition accurately but lack the ability to describe the change in yield loss from low to high weed densities (**13, 26, 110**). Nonlinear functions have been used to model competition. These functions reveal the changing

effect of competition on crop yield over a wide range of weed densities. Competition between crop and weeds increases initially with weed density. The increase in crop yield reduction declines at moderate to high weed density as interspecific competition gives way to intraspecific competition. Nonlinear functions model the biological crop response to weed competition more realistically than linear because they reflect intraspecific competition at high weed densities. There are conflicting reports for the effect of weed competition with crop at low densities. The type of response curve that defines the relationship between crop with a single weed species is likely to be dependent upon the weed and crop in question. Similarities in the resources needed to maximize growth for each plant, the morphology of competing plants and degree of adaptation for crop and weed to the environment are factors that affect competition models.

Various nonlinear equations have been used to describe the crop yield loss as weed densities change. Hyperbolic or exponential models project rapidly increasing yield losses at low to medium weed density. The increase in predicted crop yield loss from additional weeds approaches zero as density increases to high levels (**21, 22, 23, 28**). Sigmoidal models (**12, 119**) suggest that at some population crop and weed can coexist without competition or that low level weed competition causes slight to no crop yield loss. The amount and accuracy of data required to refute small true differences at low levels of competition with high levels of confidence is

problematic. Slight departure from optimum growing conditions, soil type or factors other than competition at low weed density induces striking yield variance. The maximum potential yield loss to weed competition is more easily and accurately measured due to the relative importance of factors influencing yield. Weed competition is the predominant factor influencing yield at high weed density, while factors other than weed competition have a more dramatic effect on yield at low weed density. Previous studies have estimated the maximum corn yield loss from johnsongrass to be 50 to 80% (**13, 116**), but these yield losses vary with the competitiveness of johnsongrass in different environments. Methods and analysis used to measure these effects influence results. One hundred percent yield loss has been reported at high johnsongrass infestation levels when corn was infected by maize dwarf mosiac virus (MCDV) and/or maize chlorotic dwarf virus (MCDV) (**8**).

The purpose of these experiments was to determine the effect of johnsongrass competition on corn yield and the response obtained from treatments with two rates of nicosulfuron on varying johnsongrass densities. Linear and nonlinear models were fit to yield loss data to determine the model that best describes johnsongrass competition with corn in this environment.

Materials and Methods

Model verification trials

Model verification trials were conducted at the West Tennessee Experiment Station in Jackson in 1993, 1994, and 1995, the Martin Experiment Station in 1994 and on farms in Obion County in 1993, 1994 and 1995. Corn was seeded in rows spaced 0.76 m apart. Plots were four rows wide and 8 or 12 m long.

Nicosulfuron at 17.5 and 35 g ha^{-1} was applied 28 to 42 d after corn emergence. Herbicide treatments at Martin and in Obion County, TN were applied in 140 L ha^{-1} with 1% COC[1]. Application was made with an ATV-mounted boom sprayer using 8002 LP[2] flat fan nozzles at 276 k Pa. Herbicide treatments at West Tennessee Experiment Station were made in 168 L ha^{-1} with 1% COC[2]. Application was made with a tractor-mounted boom sprayer using flat fan 8003 LP[3] at 276 k Pa. Johnsongrass was removed by hand hoeing initially at 4 WAP and maintained weed-free

[1]Sun-it II, methylated seed oil manufactured for American Cyanamid Company by Agsco, Inc. Grand Forks, North Dakota.

[2]Agridex, 83% paraffinic mineral oil and 17% polyethylene fatty acid ester. Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137.

[3]Teejet 8002 LP and 8003 LP nozzles. Spraying Systems Company, North Ave. and Schmale RD, Wheaton, IL60187.

season-long as regrowth occurred or allowed to compete full-season in plots that were not sprayed with herbicide. The period (3 to 8 WAP) for control of johnsongrass in corn has minimized yield reduction due to competition (**86**) and optimized POST herbicide performance in previous research (**13**). Herbicide treatments were made within this critical period.

Data collection

Treatments in a randomized block design were blocked according to johnsongrass density at each location. The study was an additive design in that corn densities were constant at each location and the johnsongrass density varied. Johnsongrass culms were counted and classified into low, medium and high density levels. Culm counts were made by three classifications within plots: number of plants with < 5 culms, number of plants with 5 to 10 culms, and number of plants with > 10 culms. Plots were selected to represent densities of no johnsongrass to extremely high densities at each location when possible. Johnsongrass populations were surveyed and treatments assigned within density levels but no measures were taken to adjust infestation levels to equal densities mechanically or chemically prior to treatment application. The experiment was conducted at a total of 12 locations over a 3-yr period from 1993 to 1995. The

experiment was conducted at six locations in 1993, four locations in 1994, and two locations in 1995. Treatments were made across different hybrids, fertilization and tillage methods, PRE herbicide treatments and planting densities. The center two rows of each four row plot were harvested to determine yield. Grain yields were determined by mechanical harvest with a plot combine at the Martin and West Tennessee Experiment Station. All on farm locations were hand harvested and later shelled with a plot combine.

Corn yield loss to interference was calculated from the corn yield of plots where johnsongrass was allowed to compete season long and predicted yield was calculated from the linear regression of corn yield on weed density within the hand hoed plots. Predicted yields for the weed-free check was calculated at a johnsongrass density equal to each weedy check plot. Weedy check actual yield was subtracted from predicted yield for weed-free check at equal johnsongrass density to obtain yield loss. Yield loss was regressed on weed density to compare models.

Statistical analysis

ANOVA was used to determine treatment differences. Linear regression was used to determine the effect of weed density on yield loss within each johnsongrass control treatment. Means reported for treatments are least square means adjusted for the effect of location and year. A mixed model analysis was used according to the mixed procedure in SAS version

6.08 (**95**), with location and year as random variables in linear comparisons. Single degree of freedom contrasts were used to determine differences among treatments and parameter estimates for the effect of weed density on yield loss.

A linear (procedure GLM SAS[1] version 6.08) and nonlinear regression analysis (procedure NLIN SAS[1] version 6.08) was performed on yield loss data. Yield loss was regressed on johnsongrass density using a linear and five nonlinear models. The coefficient of determination ($\sim R^2$) for each equation was calculated using the regression sum of squares divided by the uncorrected total sum of squares. Actual and predicted yield losses were compared in a correlation analysis (procedure CORR) in SAS[1] version 6.08.

Johnsongrass Control Treatment Linear Analysis

The natural johnsongrass densities were highly variable, ranging from 0 to 743410 culms ha^{-1} in this study. The average infestation for 213 plots was 77858 ± 110472 culms ha^{-1}. Corn plant populations ranged from 40335 to 63862 plants ha^{-1}, averaging 50448 ± 12500 plants ha^{-1} harvested.

[1]SAS is a registered trademark of the SAS Institute, Inc. SAS Circle, Box 8000, Cary NC 27512-8000.

Corn grain yields of 6600 kg ha^{-1} were produced when johnsongrass was allowed to compete season-long in untreated check plots (Table 1). The combined mean yield in hand-hoed and herbicide treated plots was 8000 $\pm$520 kg ha^{-1}. The mean for the untreated check was 1340 kg ha^{-1} (17%) less than the combined effect of the treatments that received chemical or mechanical johnsongrass control measures. Plots maintained weed free season long by hand hoeing produced the highest yield, 8060$\pm$550 kg ha^{-1}. Plots treated with nicosulfuron at 17.5 g ha^{-1} and 35 g ha^{-1} produced yields of 7860 and 7810 kg ha^{-1}, respectively. All johnsongrass control treatments, both herbicide-sprayed and hand-hoed, produced significantly ($p<0.0001$) greater yield than the untreated check (Table 1). There were no differences among the herbicide treatment least square means or between the hand hoed treatment and either of the herbicide treatments. Table 1 depicts the treatment least square means and differences among these treatments for single degree of freedom comparisons.

Mean yields produced when johnsongrass was removed by hand hoeing or either herbicide treatment differed from the untreated check. There was no difference among the means for herbicide treatments and hand hoed treatment means or between the treatment means for the herbicide treatment rates. The average yield reduction for each johnsongrass culm m^{-2} counted prior to treatment was 1.0$\pm$0.13 kg ha^{-1} ($p<0.001$) in untreated check plots (Table 2). The slope of the linear regression line for the effect

Table 1. Least squares means and standard deviation for johnsongrass control treatments.

treatment	least square means (kg ha^{-1})*
untreated check	6600 ± 530 a
nicosulfuron @ 17.5 g ha^{-1}	7860 ± 550 b
nicosulfuron @ 35.0 g ha^{-1}	7810 ± 540 b
hand hoed	8060 ± 550 b

* means followed by different letters are significantly different ($p < 0.0001$) in single degree of freedom t-test

Table 2. Linear regression slopes for the effect of johnsongrass density on corn yield among control methods.

control method	parameter est. ± std.err.	$p > \mid t \mid$
hand hoed	0.4789 ± 3.05 kg ha^{-1}	0.875
untreated check	-9.9751 ± 1.32 kg ha^{-1}	0.001
nicosulfuron @17.5 g ha^{-1}	-4.1280 ± 2.38 kg ha^{-1}	0.085
nicosulfuron @ 35.0 g ha^{-1}	-4.0854 ± 1.97 kg ha^{-1}	0.039

of johnsongrass density on corn yield (Table 3) for plots maintained weed free by hand hoeing was zero. This suggests johnsongrass density determined prior to hand hoeing did not affect corn yield. Hand hoeing provided the most complete johnsongrass control and there was no negative effect on corn yield regardless of the johnsongrass infestation level. The slope of the linear regression line for the effect of johnsongrass density on corn yield for both herbicide treatments was not equal to zero ($p<0.085$ for 17.5 g ha^{-1} and $p<0.039$ for 35 g ha^{-1} nicosulfuron). Negative slopes for johnsongrass density demonstrate a tendency for yield reduction as johnsongrass density increases in herbicide treated plots. This negative trend suggests that herbicide treatments were not as quick or thorough in eliminating johnsongrass competition as hand hoeing. It is well documented (**84**) that environmental factors readily influence herbicide performance. Competition is not eliminated immediately upon treatment with POST nicosulfuron. Nicosulfuron treated plants may continue to compete with the crop for resources for a period after treatment. Dying and dead johnsongrass plants can potentially interfere with light interception by the crop. Johnsongrass may have allelopathic effects, particularly when treated with translocated sulfonylurea herbicides capable of altering metabolic pathways (**38**) responsible for producing allelochemicals in treated plants. Phytotoxic residue from herbicide mediated alteration of phytochemical composition of plants has been report (**9, 32, 33, 59, 103, 104**).

Table 3. Single degree of freedom comparisons of linear regression slopes for the effect of johnsongrass density on corn yield within treatment methods.

comparison	p > t
untreated check vs hand hoed	0.0006
nicosulfuron @ 17.5 g ha^{-1} vs untreated check	0.0167
nicosulfuron @ 35.0 g ha^{-1} vs untreated check	0.0047
nicosulfuron @ 17.5 g ha^{-1} vs hand hoed	0.1581
nicosulfuron @ 35.0 g ha^{-1} vs hand hoed	0.1820
nicosulfuron @ 17.5 g ha^{-1} vs nicosulfuron @ 35.0 g ha^{-1}	0.9875

Linear regression does not allow for change in slope of the regression line as weed densities change. The slope of the linear regression in herbicide treated plots suggests that johnsongrass density has a negative effect on corn yield at higher densities or under some environmental conditions. This is not the case in hand hoed treatments if the researcher is diligent in the johnsongrass removal effort. Negative trends for corn yield in herbicide treated plots suggest johnsongrass escaped control and continued to compete with corn after herbicide application, perhaps because of lack of coverage or differential susceptibility. Competition from johnsongrass regrowth can be a problem in herbicide treatments at high densities under

certain environmental conditions. Competition from johnsongrass not physically contacted by herbicide during application may have induced differences between slopes for the effect of johnsongrass density on corn yield when hand hoed and herbicide treatments were contrasted.

Negative trends in herbicide treatment slopes indicated that yield reductions for these treatments did not occur in all instances ($p<0.08$ and $p<0.04$). Single degree of freedom comparisons for johnsongrass density slopes in plots hand hoed and both herbicide treatments were not different . Similarity of herbicide treatment means with means for hand hoed johnsongrass control and lack of difference in single degree of freedom comparisons for the effect of johnsongrass density on corn yield among the hand hoed and herbicide treatments indicates that chemical control and hand hoeing johnsongrass produced similar crop yields over a broad range of johnsongrass densities.

Increasing the rate of nicosulfuron from 17.5 to 35.0 g ha $^{-1}$ did not reduce johnsongrass competition to the point that yields increased. The slopes for the effect of johnsongrass density at both herbicide rates were negative and were not different from each other in single degree of freedom comparisons. Differences were observed in the amount of johnsongrass present at harvest in the plots treated with 17.5 to 35.0 g ha $^{-1}$ nicosulfuron. Johnsongrass that was not controlled initially or produced regrowth failed to produce yield differences in these experiments. Some densities,

environmental conditions and long term weed control strategies likely justify use of the higher rate. Nicosulfuron applied at 35.0 g ha^{-1} did not increase yields over the 17.5 g ha^{-1} rate when compared across densities, locations and years in this study.

This study suggests the 17.5 g ha^{-1} rate of nicosulfuron and the 35 g ha^{-1} rate of nicosulfuron are equally effective at reducing corn yield loss to johnsongrass competition. The 17.5 g ha^{-1} offers potential for more economical johnsongrass control over the range of johnsongrass densities and environmental conditions encountered in these experiments.

Analysis of Yield Loss Functions

Regression equations have been used by researchers to model crop yield loss over a wide range of weed densities (Table 4). Some of these equations were developed by simplifying more complex models when parameters failed to improve the model's fit on these data (Table 5). The nonlinear equations are displayed graphically in Figures 1 through 5. Figure 6 is a graphic representation of the linear regression of corn yield loss on johnsongrass culm density.

A yield loss of 11.25 ± 2.5 kg ha^{-1} for each johnsongrass culm per 10 m^2 was projected by the linear regression of yield on weed density. The linear regression of yield loss on weed density produced an $R^2 = 0.25$ and

Table 4. Nonlinear equations used to describe corn yield loss to johnsongrass competition.

equation $y = f(x)^*$	name	equation number
$y = (b0*b1*wd)/(b0+b1*wd)$	hyperbola	1
$y = b0(e^{(-b1*wd)}) + b2$	exponential	2
$y = b0 * (1- e^{(-b1*wd)})$	exponential	3
$y = b0 / (1 + e^{(b1 + b2*wd)})$	logistic	4
$y = b0 * (e^{(-b1*wd*wd)}) + b2$	sigmoidal	5
$y = b0 + b1*wd$	linear	6

*wd = johnsongrass culms 10 m^{-2}

*b(n) = parameters

Table 5. Nonlinear equations with parameter estimates

equation $y = f(x)^*$	equation number
$y = 9990*62*wd/(9990+62*wd)$	1
$y = -7920*(e^{(-0.005wd)})+8465$	2
$y = 8100*(e^{(-0.006456*wd)})$	3
$y = 8290/(1+e^{(1.713233-0.012918*wd)})$	4
$y = -6710*(e^{(-0.000027*wd*wd)}+8270$	5
$y = 1625 + 11.5*wd$	6

* wd = johnsongrass culms 10 m^{-2}

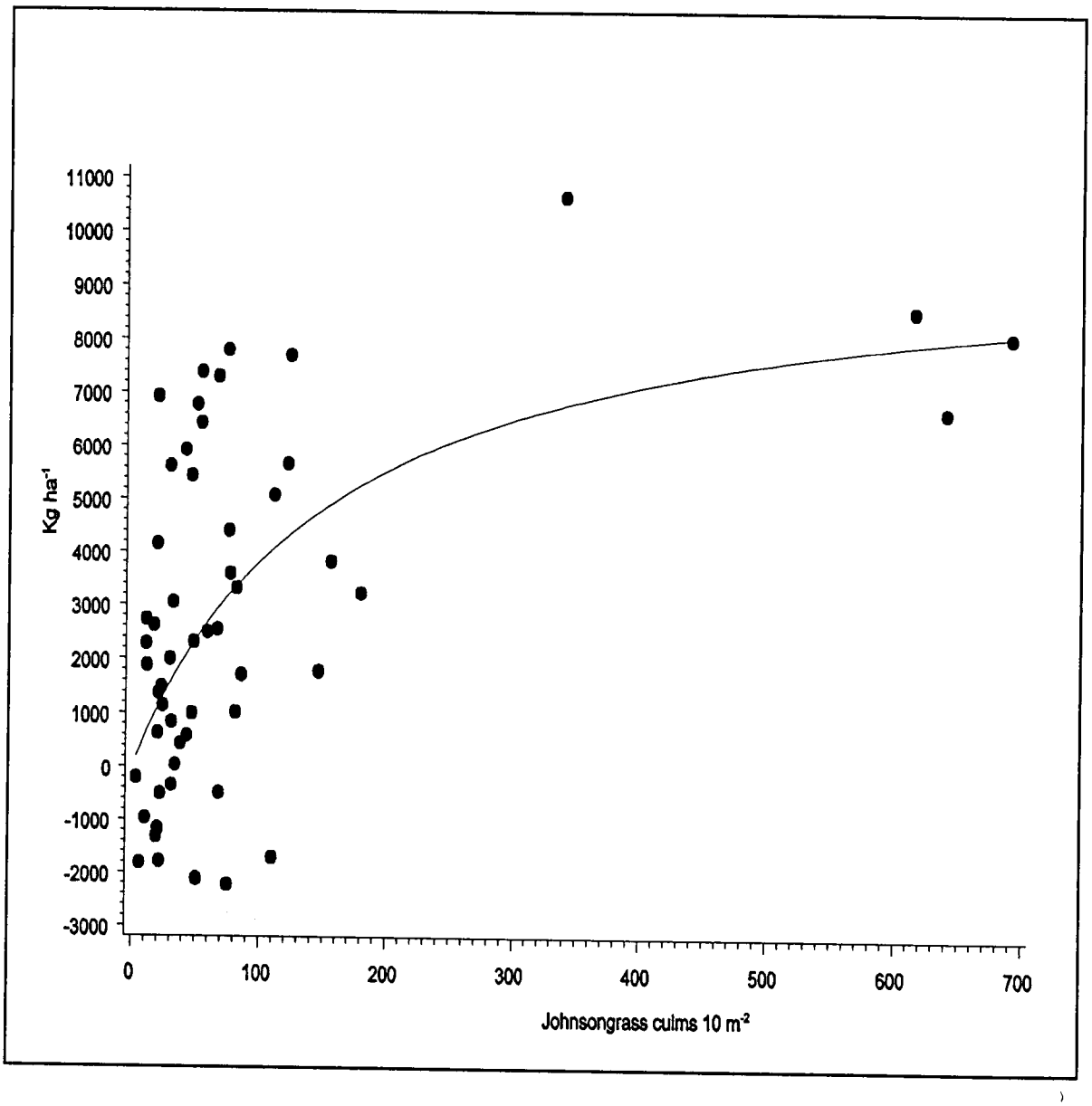


Figure 1. Actual yield loss (●) at varying johnsongrass culm densities. The line is a graphic representation of the nonlinear regression of corn yield loss (y-axis) on johnsongrass density (x-axis) with the equation

y = 9990*62*weed density/(9990+62*weed density).

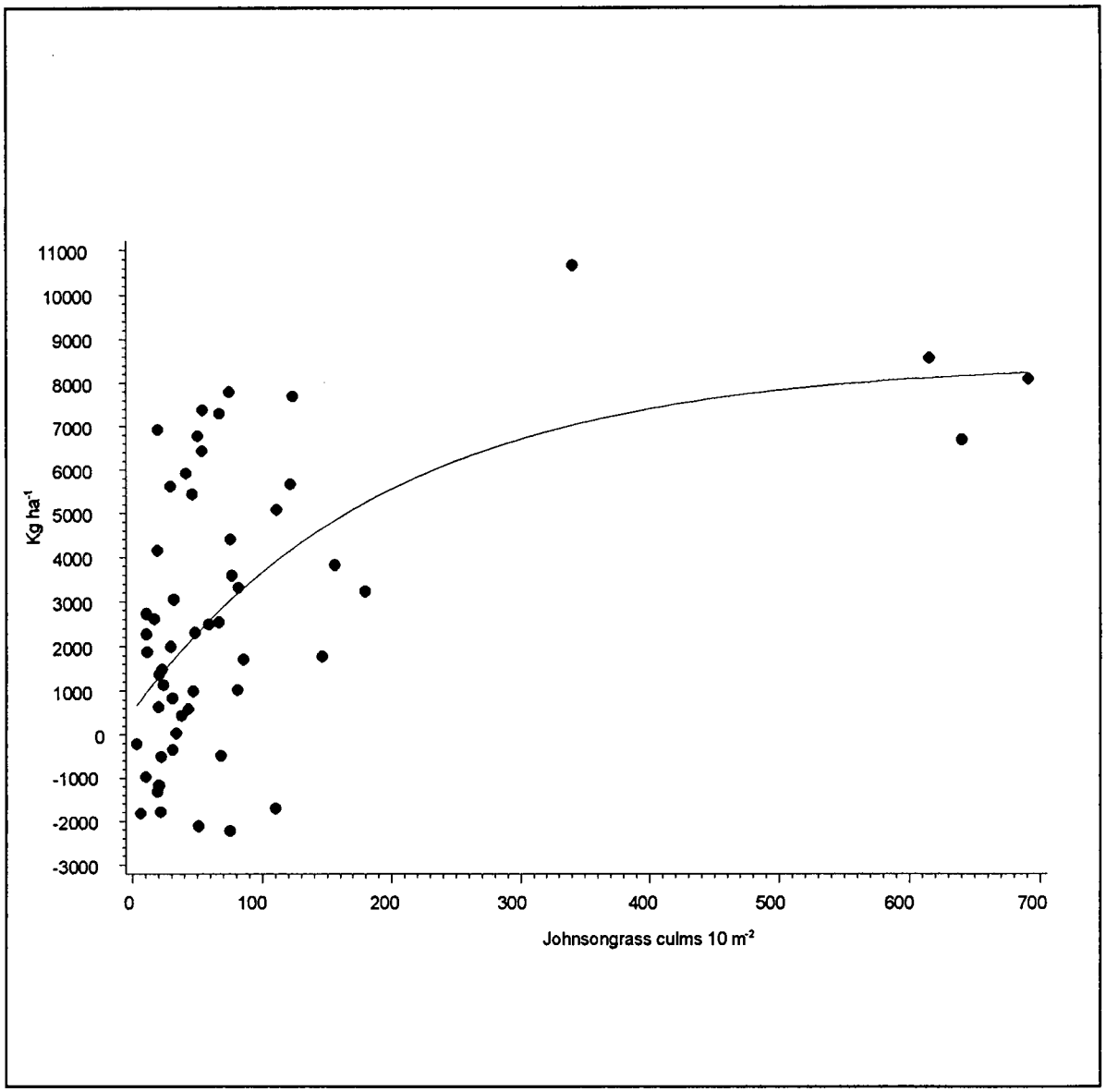


Figure 2. Actual yield loss (●) at varying johnsongrass culm densities. The line is a graphic representation of the nonlinear regression of corn yield loss (y-axis) on johnsongrass density (x-axis) with the equation

$y = -7920*(e^{(-0.005\text{weed density})}) + 8465.$

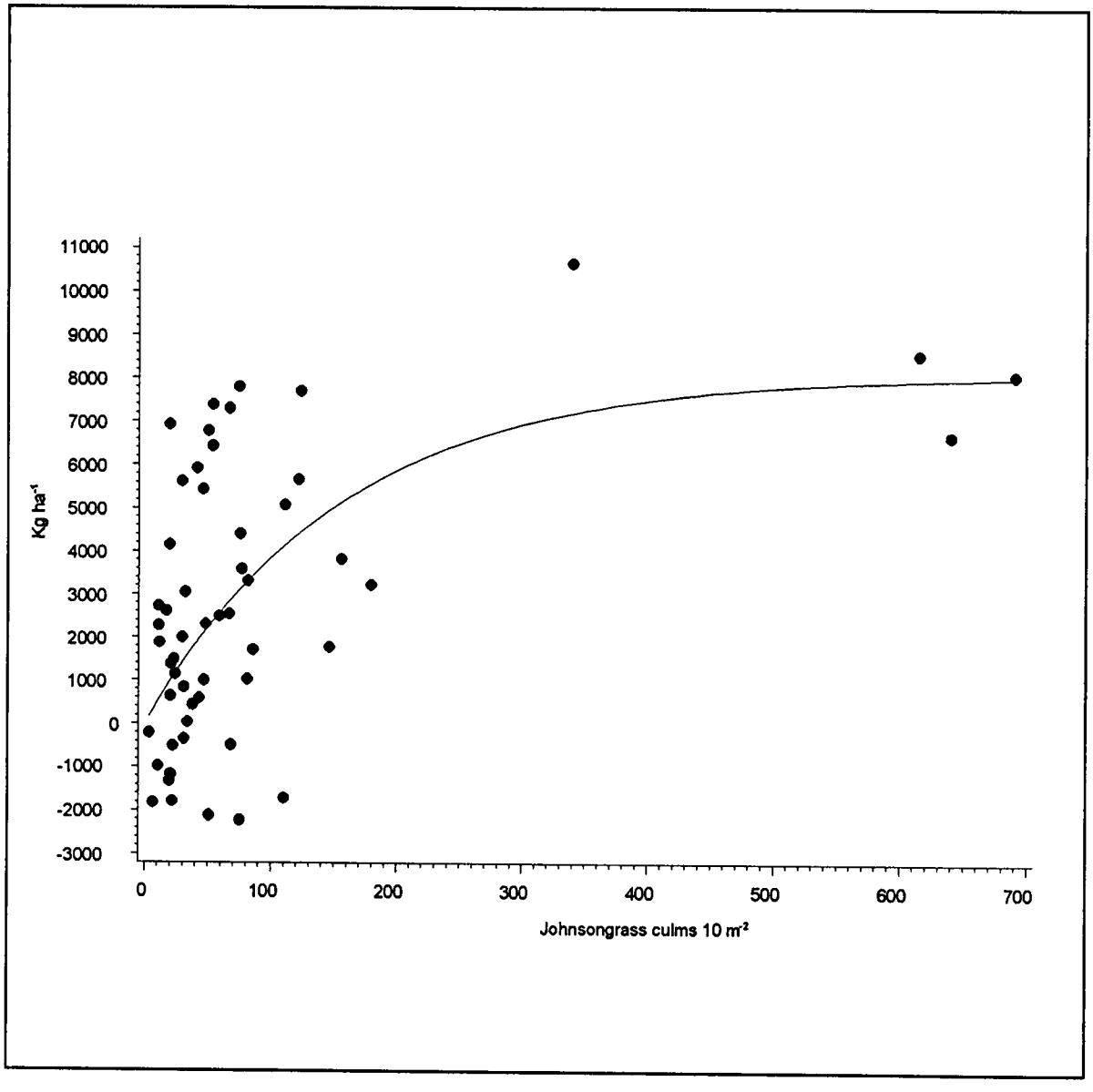


Figure 3. Actual yield loss (●) at varying johnsongrass culm densities. The line is a graphic representation of the nonlinear regression of corn yield loss (y-axis) on johnsongrass density (x-axis) with the equation

$y = 8100*(e^{(-0.006456*\text{weed density})})$.

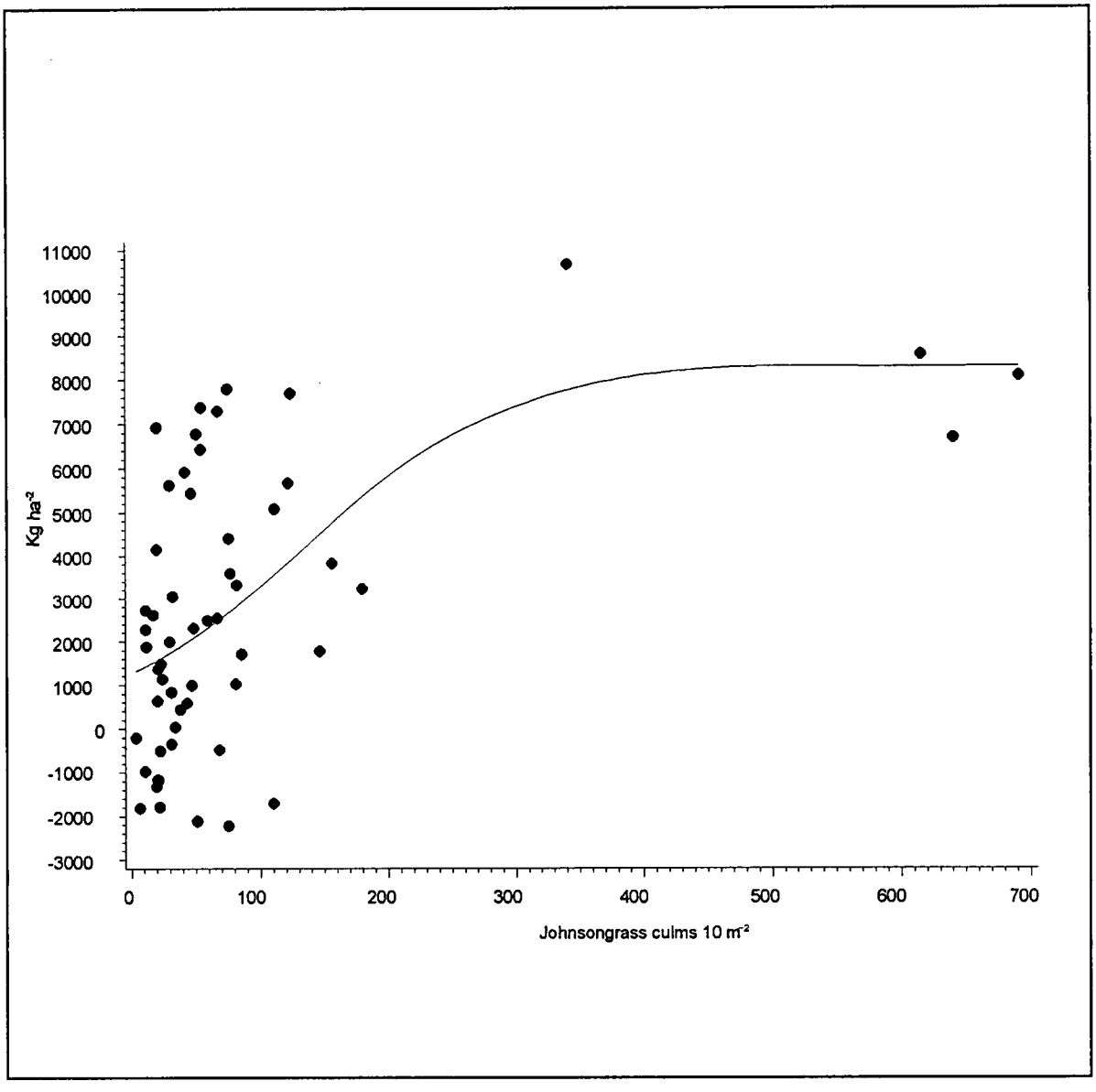


Figure 4. Actual yield loss (●) at varying johnsongrass culm densities. The line is a graphic representation of the nonlinear regression of corn yield loss (y-axis) on johnsongrass density (x-axis) with the equation

$y = 8290/(1 + e^{(1.713233-0.012918*\text{weed density})})$.

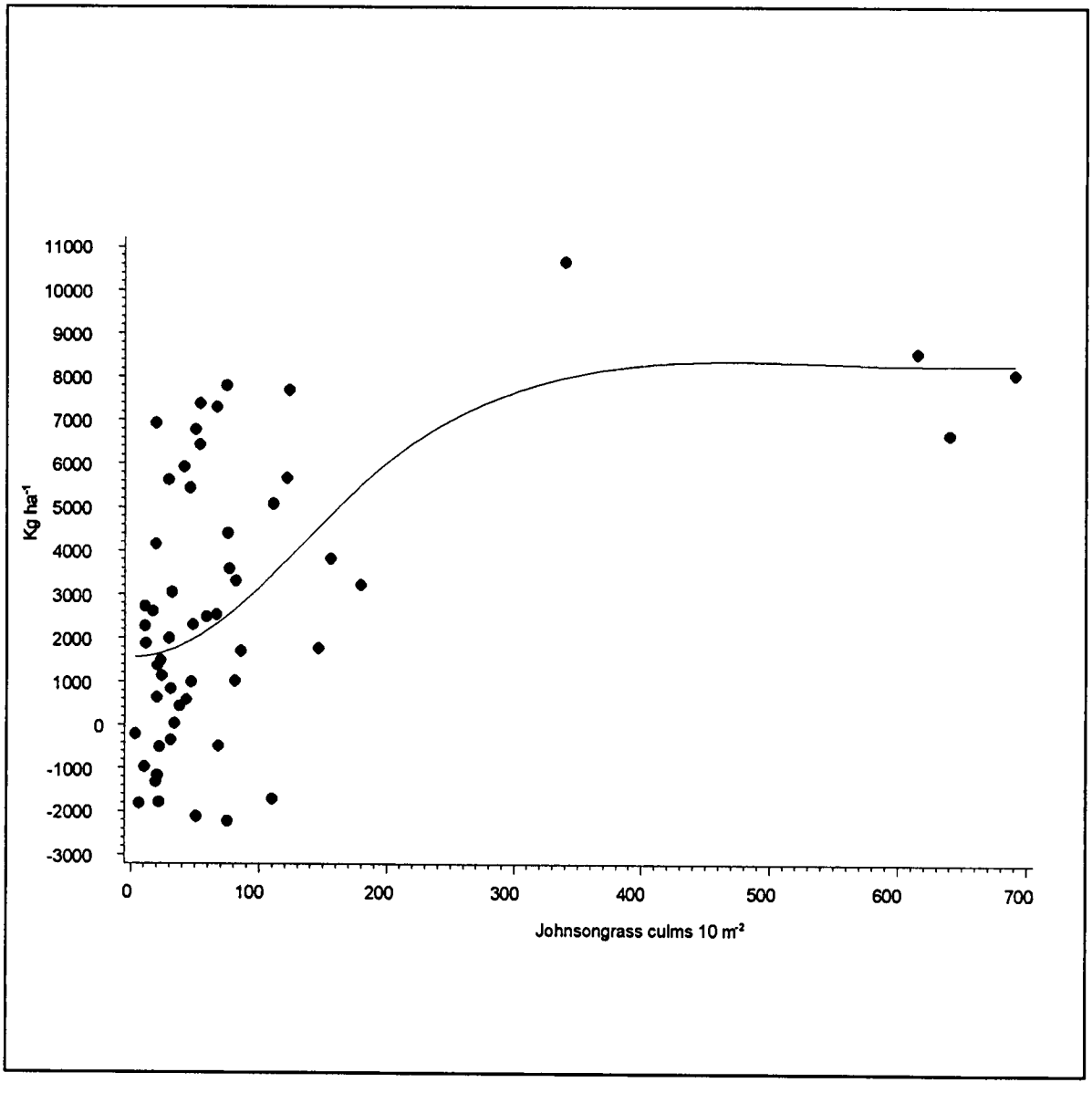


Figure 5. Actual yield loss (●) at varying johnsongrass culm densities. The line is a graphic representation of the nonlinear regression of corn yield loss (y-axis) on johnsongrass density (x-axis) with the equation

$y = -6710*(e^{(-0.000027*\text{weed density}*\text{weed density})} + 8270.$

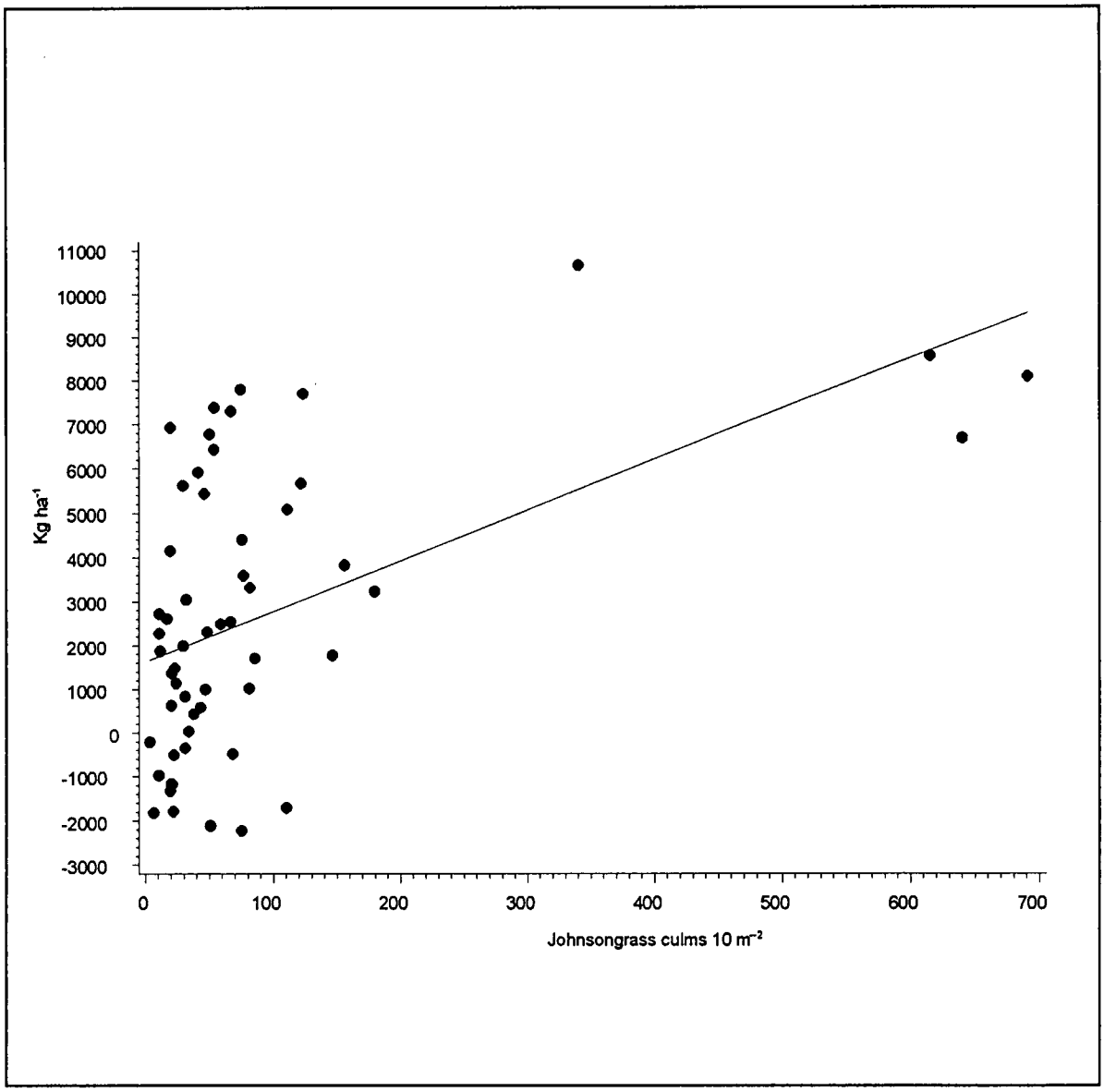


Figure 6. Actual yield loss (●) at varying johnsongrass culm densities. The line is a graphic representation of the linear regression of yield loss (y-axis) on johnsongrass density (x-axis) with the equation

y = 1625 + 11.5*weed density.

$\sim R^2$ = 0.55 (uncorrected coefficient of determination). The linear regression model overestimated yield loss at the Y-intercept and underestimated the effect of each additional weed at low weed densities. The broad range of johnsongrass densities in this study are not well suited for linear modeling.

The regression analysis within treatments suggests a strong relationship ($p<0.001$) between corn yield and johnsongrass density in untreated check plots in this study. Models used in this study produced similar $\sim R^2$ values when corn yield loss data was regressed on weed density (Table 6). Yield loss data produced in this study was variable. Some yield loss variation was introduced by environmental factors other than density that affect johnsongrass interference with corn. Some yield loss variation resulted from variation among location and plots within locations that could not be controlled without effecting the competitiveness of johnsongrass. The $\sim R^2$ for all models fit to the data was affected by this variation in the data. The ability of these models to explain only 0.55 to 0.58 of the variation in yield loss using weed density was attributable to both factors. True johnsongrass interference effects not explained by density including time of emergence, seedling and rhizome differences, interaction of virus diseases or other factors that can only be explained by adding terms for these effects. The effects of location, plots and other random variables must be controlled by experimental design. Controlling the random variation in yield loss data would likely have resulted in greater differences in $\sim R^2$ for

Table 6. Sum of squares and $\sim R^2$ for nonlinear yield loss models.

equation	regression ss	corrected total ss	uncorrected total ss	$\sim R^2$ uncorrected total ss
1	579164310	600652162	998123803	0.580
2	580546625	600652162	998123803	0.581
3	577042784	600652162	998123803	0.578
4	576840548	600652162	998123803	0.578
5	571421980	600652162	998123803	0.572
6	550156343	600652162	998123804	0.551

models used in this study. Controlling random variation without adversely impacting true interference would aid in ascertaining the need to include terms for effects other than density in models that describe interference of johnsongrass with corn.

Variation in yield loss data does not adversely effect the parameters of the models used in this study if there is no bias in the data. These experiments were conducted under a broad range of production practices and environmental conditions at different locations. These factors introduced variability into the data, reduced $\sim R^2$ and concealed $\sim R^2$ differences but at the same time make equation parameters more applicable under the diverse conditions encountered in field situations. Some of the equations projected yield losses that are not biologically feasible at certain johnsongrass densities. These models can be compared by examining the predicted yield loss estimates. The variability of the yield loss data does not invalidate the model. The models that predict practical yield loss estimates based on these parameters should produce yield loss estimates that allow more economical herbicide use decisions.

Four of the five nonlinear equations estimate between 80 and 84% as the maximum corn grain yield loss to johnsongrass competition. This calculation could not be determined for the hyperbolic model in this study. The hyperbolic yield loss function (eq.1) gave the second highest $\sim R^2$ (Table 6) of the equations used to describe the effect of increasing johnsongrass

density on yield loss. This equation projects yield losses that differ at two fixed points, the maximum and minimum yield loss, from a point P(x, y) by a constant. The $\sim R^2$ for the hyperbolic equation was 58%. Predicted yield losses at densities studied with this equation ranged from 200 kg ha $^{-1}$ to 8100 kg ha $^{-1}$ with a mean of 2590 $\pm$ 1870 kg ha $^{-1}$. The parameters for this equation suggest that low level johnsongrass infestations reduced yields initially by 62 $\pm$ 17 kg ha $^{-1}$ for each johnsongrass culm per 10 m^2 or 0.6 % of total potential yield loss. Corn yield losses to increased johnsongrass density reaches a maximum at 9990 $\pm$ 2240 kg ha $^{-1}$ with this equation and parameters.

The exponential function (eq. 2) that used three parameters fit the data in a manner similar to the hyperbolic function. Equation 2 explained 58.1%, the highest $\sim R^2$, of the total yield loss due to johnsongrass competition. Predicted yield losses ranged from 675 kg ha^{-1} to 8215 kg ha^{-1} with a mean of 2640 $\pm$ 1800 kg ha $^{-1}$.

The three-parameter exponential yield loss function (eq.2) was simplified to a two-parameter equation (eq.3). This equation described 57.8% of the total variation. There was little gain in the amount of variation explained by the additional parameter in equation 2 when compared to equation 3. Equation 3 predicted yield losses that ranged from 170 kg ha $^{-1}$ to 8000 kg ha $^{-1}$ with a mean predicted yield loss of 2530 $\pm$ 1635 kg ha $^{-1}$. Similar in shape, equation 4 and 5 explained slightly less variation than the

three previously mentioned functions. Equation 5 explained 57.2% of the variation in corn yield loss with varying johnsongrass density. Yield losses to weed competition that gradually increase initially, then increase exponentially to a point of inflection and finally approach a maximum of zero at high weed density are best explained by equation 4 and 5. Cell growth and plant growth are explained by functions of this type. The predicted yield loss for equation 4 ranged from 1300 to 8300 kg ha^{-1} with a mean predicted yield loss of 2650 ± 1750 kg ha^{-1}. Predicted yield loss for equation 5 ranged from 1560 kg ha^{-1} to 8270 kg ha^{-1} with a mean of 2640 ± 1750 kg ha^{-1}.

Actual yield loss to johnsongrass competition ranged from -2222 to 10660 kg ha^{-1} in this 3 yr study that produced an average yield of 8055 ± 550 in the weed-free check. Negative yield loss resulted when untreated check plots with low to medium johnsongrass densities produced higher yields than the predicted yield for hoed check plots. Yield loss was determined by comparing the yield of plots that received no johnsongrass control measures to the predicted yield of hand hoed plots for each year at equal johnsongrass densities. Natural infestations of johnsongrass were chosen for this study. Plots must be spatially separated to compare natural johnsongrass infestations at equal or near equal weed densities. Plots that are spatially separated in the field potentially allow more crop yield variance than plots adjusted to equal densities in side by side comparisons. This could explain variation in actual yield loss at medium to low weed densities.

Plots adjusted to equal densities side by side may not represent typical competition from native johnsongrass populations. Rhizomes affect the competitiveness of the culms left to compete after adjusting the johnsongrass population by hand hoeing and compete directly with corn below the soil surface. Adjusting johnsongrass culm population with POST herbicides also affects the competitiveness of rhizomes that arise from the same rhizome. The researcher induces or encounters variation with either approach that obscures the true response of competition on crop yield at low densities, a critical area along the response curve. Differences in yield loss projected with these nonlinear equations are similar over a broad range of johnsongrass densities. The greatest difference in these equations for predicting yield loss to competition occurs at low johnsongrass densities. The effect of johnsongrass at relatively low densities is critical to economic threshold determination. The models that best fit these data (eqs.1, 2, & 3) suggest that johnsongrass competition with corn increases exponentially at low densities and that high yield loss at extremely low densities are error rather than a biological response. Sigmoidal shaped functions (eqs. 4 and 5) best explain an alternative hypothesis that yield loss is gradual at low johnsongrass densities. The y-intercept that results from fitting equations 2, 4, 5 and 6 to these data suggests that weeds affect corn when they are in fact not present. This can only be interpreted as error. Equation 1 and 3 produce more realistic yield loss estimates at low johnsongrass density

resulting in a more acceptable economic threshold estimate.

Variation in johnsongrass density determination or accuracy of the weed survey among plots and locations introduces variation into the relationship between yield loss and culm count. There is more error in the survey at high weed densities, however accuracy of the survey is more critical to model performance at low to medium densities due to the relative change in corn yield due to additional competition.

The size of culms counted in these plots was not considered. It is well documented (**54,55**) that size or relative time of emergence affects the crop-weed competition relationship. Measuring weed size or relative emergence time is extremely time consuming and may not be practical or cost effective for farmers or consultants surveying the weed population in production corn fields. This approach may be more suited to research than practical application.

Natural populations of johnsongrass were selected for this study. Culm counts did not differentiate between culms arising from seedling and rhizome plants. Rhizome plants tend to emerge sooner in the growing season and compete more vigorously with corn when compared with seedling plants. Differentiating between seedling and rhizome plants complicates the weed surveying process but could increase the accuracy of prediction equations.

The models that explain these data best, based on realistic yield loss

values and slight $\sim R^2$ differences, allow for a rapid increase in the rate of yield loss due to johnsongrass competition (eq.1, 2, and 3) initially at low density rather than allowing for a gradual rate of increase for yield reduction at low densities. Corn produces high biomass and grain yield per unit of area. Fertilizer recommendations required to maximize silage or grain yield are higher than most crops. Crops with lower nutrient demands may be more tolerant to weed competition at low densities or in early growth stages when compared to corn. Johnsongrass is similar to corn morphologically, physiologically and genetically. Corn and johnsongrass plants tend to emerge simultaneously, are adapted to similar growing conditions and have comparable nutrient requirements. Crop and weed species that are not as similar in these respects could possibly coexist in the same micro-environment without competing immediately. Multispecies weed infestations would be more likely to compete at low density than a single weed species with different growth requirement than the crop. These are some plausible explanations for differences predicted by these models for yield loss at low weed density.

Correlation among predicted yield losses with the six different equations was high (0.883 to 0.998). Correlation of actual yield loss with predicted yield loss calculated with the six different yield loss models ranged from 0.50 to 0.55. Table 7 illustrates the correlation coefficients among predicted and actual yield loss to corn due to johnsongrass competition.

Table 7. Pearson correlation coefficients for actual and predicted yield loss of corn from johnsongrass competition

	predicted yield loss eq. 1	predicted yield loss eq. 2	predicted yield loss eq. 3	predicted yield loss eq. 4	predicted yield loss eq. 5	predicted yield loss eq. 6
actual yield loss	0.550	0.552	0.549	0.546	0.538	0.504
predicted yield loss eq. 1		0.996	0.998	0.968	0.951	0.894
predicted yield loss eq. 2			0.995	0.986	0.974	0.922
predicted yield loss eq. 3				0.970	0.955	0.883
predicted yield loss eq. 4					0.997	0.950
predicted yield loss eq. 5						0.945

Correlation coefficients among predicted yield losses and the amount of variation explained by the models suggests that equation 1, 2, and 3 are generating analogous information. Equation 1 and 3 explain the data with fewer parameters and produce the most highly correlated predicted values. Equation 4 and 5 predicted values which are the least correlated with actual yield loss and have lower correlation with the predicted yield losses of the hyperbolic or exponential functions (eq.1, 2, and 3).

Nonlinear models used in this study provided more realistic description of the effect of johnsongrass over a broad range of densities on corn yield than linear regression. The linear regression model (eq. 6) overestimated the yield loss at the y-intercept and underestimated the effect of each additional weed at low weed densities. Three of the nonlinear models (eq. 2, 4, and 5) also predicted yield loss above economic threshold levels at the y-intercept (zero weed density). Four of the nonlinear models (eq. 2, 3, 4, and 5) predicted maximum yield loss in a range from 8100 to 8500 kg ha^{-1}. The rectangular hyperbola (eq. 1) projected the highest maximum yield loss (10000 kg ha^{-1}) to johnsongrass competition of the nonlinear models. The two parameter exponential model and the rectangular hyperbola (eq. 1 and 3) projected realistic yield loss estimates at the y-intercept, similar threshold weed densities and highly correlated yield losses over a broad range of johnsongrass. These models produced the most realistic yield loss estimates at the y-intercept, threshold weed density and a broad range of weed

densities. The rectangular hyperbola and two parameter exponential models appear to have the most general practical application of the models compared in this study. Models capable of projecting weed loss at a range of densities will become more important as herbicide rates and selection can be varied during application within fields to coincide with the spectrum, density, location and potential yield loss projections. This application depends upon the development of technology to differentiate among weed species, weed density and target herbicides to weeds during herbicide application.

Yield Loss Prediction at Threshold Johnsongrass Density

Results from this study suggest that corn yields produced when nicosulfuron was applied at 35 g ha^{-1} 4 to 6 WAP were equal to corn yields produced with season-long johnsongrass control. Economic threshold can be calculated by determining the weed density at which total herbicide, adjuvant and application cost equal the cost of corn yield reduction to weed competition.

For the purpose of comparison, herbicide cost were fixed at \$46.75 ha^{-1}, adjuvant cost at \$1.25 ha^{-1} and application cost at \$8.75 ha^{-1}. The total retail treatment cost for the 1996 growing season is near \$56.75 ha^{-1}. Corn price was fixed at \$0.128 dollar kg^{-1} for this comparison.

The three equations compared at economic threshold weed density were the rectangular hyperbola (equation 1), the two parameter exponential model (equation 3) and the linear regression model (15) proposed by Brown et al. Equation 1 and equation 3 were selected based on performance on the data from this study. Brown's linear regression model was developed in earlier johnsongrass studies in Tennessee.

Brown's linear regression model projected an economic threshold at the lowest weed density of 5.4 plants per 10 m^2. Economic threshold was predicted by the nonlinear equations at 7.5 culms per 10 m^2 with equation 1 and 8.7 culms per 10 m^2 for equation 3.

Brown's study, also conducted in West Tennessee, was conducted by planting rhizomes at four treatment densities and comparing yields to plots maintained weed-free. These rhizome plants likely produced multiple culms by herbicide application growth stage. All three of these models predicted threshold johnsongrass densities within 3.3 plants per 10 m^2. The linear and nonlinear models would likely have produced more similar results if plant density had been determined in the same manner in both studies.

CHAPTER 4

CORN (*ZEA MAYS*) RESPONSE TO NICOSULFURON AND PRIMISULFURON IN THE ABSENCE OF JOHNSONGRASS (*SORGHUM HALEPENSE*)

Abstract

Corn hybrids; Pioneer 3245IR and Pioneer 3395, resistant to the ALS-inhibiting herbicides and Pioneer 3245 and Pioneer 3395, without resistant to these herbicides, were treated with 1X and 2X rates of nicosulfuron and primisulfuron. Yields for the resistant forms of the hybrid were compared to the non-resistant form to detect potential for herbicide-induced yield reduction. The experiment was a split plot design with hybrid as the whole plot treatment and herbicide treatments as the subplot treatments. Subplot treatments included nicosulfuron at 35 g ha^{-1} and nicosulfuron at 70 g ha^{-1}, primisulfuron at 40 g ha^{-1} and 80 g ha^{-1}, and an untreated check. All plots were maintained weed-free.

There was no difference in the yield of the hybrids in the whole plot comparison. Nonresistant hybrids produced yields of 9150 kg ha^{-1} while resistant hybrids produced yields of 9140 kg ha^{-1}. This suggests that the

nonresistant hybrids experienced no yield reduction from nicosulfuron and primisulfuron when compared to resistant hybrids.

Corn treated with nicosulfuron and primisulfuron produced higher yields ($P<0.02$) than the untreated check. The average yield was 9230 kg ha^{-1} for herbicide treatment compared to 8795 kg ha^{-1} for the untreated check.

Whole plot and subplot comparisons support the hypothesis that POST application of herbicides did not reduce corn yield. Subplot comparisons suggest that a yield increase occurred when corn was treated POST with nicosulfuron and primisulfuron in the absence of weed competition.

Introduction

Crop tolerance to a herbicide can be dependent upon the activity of a detoxifying/metabolizing enzyme. Tolerance by this definition describes a gradual tolerance that can range from high to low. Resistance is more pronounced and is usually defined by insensitive target site enzyme (**31**). Corn has a relatively high tolerance for the acetolactate synthase (EC 4.1.3.18) (ALS)[1] inhibiting herbicides, nicosulfuron and primisulfuron, used

[1]Abbreviation: ALS, acetolactate synthase EC 4.1.3.18 also referred to as aceto hydroxyacid-synthase.

for POST control of johnsongrass in corn. Five and 10-fold sensitivity margins have been reported for nonresistant hybrids, depending on stage of growth and environment (**3, 81**).

The gene, referred to as XA17 (**30,79**), coding for a resistant form of ALS was isolated from corn (**36**). This gene has enhanced the tolerance of commercially altered hybrids to imidazolinone herbicides to a level associated with herbicide resistance. This gene was selected for its resistance to imidazolinone herbicides, but confers sulfonylurea herbicide cross resistance (**57**) to the hybrids used in this study. Resistance was attributed to a single gene. The *in vitro* selected line was not suitable for use in producing commercial hybrids due to agronomic deficiencies. The gene was introduced to over 100 commercial maize inbred lines by backcrossing procedures prior to 1989. Commercial hybrids resistant to ALS inhibiting herbicides have been available since 1992. Corn hybrids can vary in sensitivity from 1 to 40 thousand fold their response to primisulfuron through the interplay of herbicide uptake, metabolism, interaction of metabolism and translocation, and this commercial modification of the ALS enzyme active site (**79, 96**).

Researchers reported herbicide injury to non-resistant corn that was treated with nicosulfuron and primisulfuron (**29, 38, 81**). Injury is worse when primisulfuron or nicosulfuron is applied to corn treated in furrow with terbufos {S -[[(1,1-dimethylethyl)thio]methy]l0,0-diethyl phosphorodithioaate} insecticide and certain herbicides due to impaired

metabolism (**13, 14, 35, 40, 49, 66, 99**).

Studies of nicosulfuron confirm occasional herbicide injury that likely results from a combination of foliar herbicide uptake, leaching, root-transfer and altered allelopathic effect of nicosulfuron-killed johnsongrass residue (**20, 37, 39, 49**). It is not clear whether any of these factors can individually produce a negative yield response.

Studies of POST herbicide rate, timing, method of application (**8, 13, 14, 15, 18, 20, 37, 81, 86, 101**) and widespread acceptance of nicosulfuron and primisulfuron by corn producers suggests injury to corn is insignificant when compared to yield reductions induced when johnsongrass is allowed to compete with corn.

Timing and the number of applications of nicosulfuron affect level and duration of johnsongrass control (**78, 88**). Researchers report (**81**) that larger, more mature plants intercept more nicosulfuron and are controlled better than younger, smaller plants. Herbicide interception considerations raise the possibility for corn injury from POST herbicide application at later growth stages.

Interactions of POST herbicides or mechanical methods of johnsongrass control with maize dwarf mosaic virus (MDMV) and maize chlorotic dwarf virus (MCDV) that increase corn yield reduction have been reported. Virus resistant hybrids are recommended where johnsongrass is present (**8, 34, 111,**).

Johnsongrass and other weed infestations tend to be sporadic rather than uniformly distributed in corn fields (**60, 117**). Present technology typically constrains POST herbicide application to broadcast treatment. Spray booms may be activated as needed but the application of herbicide is constant across the treated area rather than weed specific. Many fields require application of POST herbicide to areas not infested with johnsongrass. Crop injury from herbicides in johnsongrass free areas could affect the economic threshold for POST herbicide application to corn.

The purpose of this study is to measure the effect of the POST herbicides, nicosulfuron and primisulfuron, on corn. The study was conducted in the absence of johnsongrass and other weeds to remove any potential effect of johnsongrass competition or interaction with MDMV/MCDV on corn yield. None of the insecticides that interact with these herbicides were applied. This study used the principle of herbicide resistance and the traditional untreated check to test for significant yield reductions from POST applications of nicosulfuron and primisulfuron to corn in the absence johnsongrass.

Materials and Methods

Field experiments

Eleven field experiments were conducted from 1993 to 1995. Locations at which experiments were conducted included: West Tennessee Experiment Station, Jackson; Milan Experiment Station, Milan; and Pioneer Research Station, Union City, in 1993 and 1994. The experiment was conducted on one farm in Obion County, TN in 1993. The study was repeated only at the Pioneer Research Station, Union City, during 1995. The purpose of this experiment was to detect any crop response to herbicide application that might occur independent of the increased crop yield that occurs with reduction of johnsongrass competition. One selectivity mechanism of corn to acetolactate synthase (ALS) inhibiting herbicides, including nicosulfuron, is enhanced metabolism (**81**). The imidazolinone resistant hybrids, Pioneer 3245IR and Pioneer 3395, produce an altered ALS enzyme that reduces the binding rate of the ALS inhibiting herbicides at the active site. These hybrids are considered resistant rather than tolerant to the herbicides used in this study. The imidazolinone resistant version of 3394 was marketed as 3395 rather than the IR designation to the original hybrid number (personal communication, Joe Anderson[1], Pioneer Hi-bred International, Inc.). Non-resistant versions of these hybrids, Pioneer 3245

[1]Corn breeder and station manager, Pioneer Research Station-Union City,TN.

and Pioneer 3394, were used to make the whole plot comparison.

Fields selected for this study were not infested with rhizome johnsongrass and seedling johnsongrass was controlled. PRE herbicides were applied for annual grass and broadleaf weed control. Corn was planted in four row plots (3.9 m or 4.7 m wide by 11.81 m long). The center two of four rows were harvested to determine yield. The experimental design was a split plot with corn hybrid (Pioneer 3245 or 3245IR in 1993 and 1994 and Pioneer 3394 or 3395 in 1995) as the whole plot treatment and two POST herbicides at 1X and 2X rates plus an untreated check as the subplot treatment (five total subplot treatments).

Subplot herbicide treatments included nicosulfuron at 35 g ha^{-1} and 70 g ha^{-1} , and primisulfuron at 40 g ha^{-1} and 80 g ha^{-1} applied 21 to 42 d after corn emergence. Herbicide treatments were made in 140 L ha^{-1} with 1% COC[1] at the Pioneer Research Station and on farm in Obion County in 1993 and 1994. Application was made with an ATV-mounted boom sprayer using 8002LP[2] flat fan nozzles at 276 kPa.

[1]Sun-it II, methylated seed oil manufactured for American Cyanamid Company by Agsco, Inc. Grand Forks, North Dakota.

[2]Teejet 8002 LP nozzles. Spraying Systems Company, North Ave. and Schmale RD, Wheaton, IL 60187.

Herbicide treatments at the Milan and West Tennessee Experiment Stations were made in 170 L ha^{-1} with 1% COC[1]. Applications were made with a tractor-mounted CO_2-pressurized boom sprayer using 8003LP[1] flat fan nozzles at 276 kPa at both experiment stations.

Herbicide treatments at the Pioneer Research Station in 1995 were made in 93 L ha^{-1} plus 1% COC[2] with a backpack CO_2 pressurized sprayer and boom using 8002 LP at 276 kPa.

Data collection

Plots were observed for stunting or other visual injury symptoms weekly through 4 WAT. Ears were examined at harvest for any unusual development. Corn grain yield was determined by mechanically harvesting the center two rows of each plot with a plot combine at all location except in Obion County in 1993 where the center two rows were hand harvested and later shelled with a plot combine.

[1]Teejet 8003 LP nozzles. Spraying Systems Company, North Ave. and Schmale RD, Wheaton, IL 60187.

[2]Agridex, 83% paraffinic mineral oil and 17% polyethylene fatty acid ester. Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137.

Statistical analysis

The interaction for year and location with treatments was not significant. Data from these experiments were pooled by location and year. Analysis of variance for split plot model was done using the mixed procedure in SAS version 6.08 (**94**). Location and year were analyzed as random variables. The difference among treatment least square means was determined by F-test in ANOVA. Single degree of freedom contrasts were used to determine least square mean treatment differences.

Results and Discussion

The yield of hybrids with no resistance to nicosulfuron and primisulfuron was 9150 kg ha^{-1} (Table 8). Hybrids with resistance to these herbicides produced 9140 kg ha^{-1}. The lack of difference between non-resistant and resistant versions of these hybrids suggests that the herbicides induced no yield reduction detectable by comparing herbicide resistant and non-resistant hybrids.

Yields of 9170 and 9200 kg ha^{-1} were produced for 35 g ha^{-1} and 70 g ha^{-1} rate of nicosulfuron. Primisulfuron treatment of 40 g ha^{-1} and 80 g ha^{-1} produced yields of 9280 kg ha^{-1} and 9270 kg ha^{-1}. There were no

differences among yields of these herbicide treatments in single degree of freedom contrasts. Pairwise t-test revealed no yield difference among herbicide treatment least square means.

A yield of 8790 kg ha^{-1} was produced in untreated check plots. Yield of the untreated check plot was significantly less ($P<0.02$) than all of the herbicide treatments (Table 9). This response was contrary to results reported in other studies (**20, 37, 39, 49**). There was no delay in tassel emergence or difference in pollination period observed for the herbicide-treated and untreated check plots that could be associated with the yield difference.

Table 8. Least square mean yields for hybrid and herbicide treatment main effects and hybrid by herbicide treatment interaction.

treatment		least squares mean ± std. err. kg ha^{-1}
nonresistant hybrid	(whole plot)	9150 ± 425
resistant hybrid	(whole plot)	9140 ± 425
35 g ha^{-1} nicosulfuron	(subplot)	9170 ± 430
70 g ha^{-1} nicosulfuron	(subplot)	9200 ± 430
40 g ha^{-1} primisulfuron	(subplot)	9280 ± 430
80 g ha^{-1} primisulfuron	(subplot)	9275 ± 430
untreated check	(subplot)	8795 ± 430
nonresistant hybrid 35 g ha^{-1} nicosulfuron		9290 ± 445
nonresistant hybrid 70 g ha^{-1} nicosulfuron		9160 ± 445
nonresistant hybrid 40 g ha^{-1} primisulfuron		9420 ± 445
nonresistant hybrid 80 g ha^{-1} primisulfuron		9230 ± 445
nonresistant hybrid untreated check		8640 ± 450
resistant hybrid 35 g ha^{-1} nicosulfuron		9060 ± 445
resistant hybrid 70 g ha^{-1} nicosulfuron		9240 ± 445
resistant hybrid 40 g ha^{-1} primisulfuron		9150 ± 445
resistant hybrid 80 g ha^{-1} primisulfuron		9320 ± 445
resistant hybrid untreated check		8950 ± 445

Table 9. Single degree of freedom treatment comparisons for crop injury study.

comparison	p>t
nonresistant vs resistant hybrid	0.9784
nicosulfuron @ 35 g ha^{-1} vs nicosulfuron@ 70 g ha^{-1}	0.8524
nicosulfuron @ 35 g ha^{-1} vs primisulfuron@ 40 g ha^{-1}	0.4747
nicosulfuron @ 35 g ha^{-1} vs primisulfuron@ 80 g ha^{-1}	0.5023
nicosulfuron @ 35 g ha^{-1} vs untreated check	0.0149
nicosulfuron @ 70 g ha^{-1} vs primisulfuron@ 40 g ha^{-1}	0.5941
nicosulfuron @ 70 g ha^{-1} vs primisulfuron@ 80 g ha^{-1}	0.6230
nicosulfuron @ 70 g ha^{-1} vs untreated check	0.0081
primisulfuron @ 40 g ha^{-1} vs primisulfuron@80 g ha^{-1}	0.9625
primisulfuron @ 40 g ha^{-1} vs untreated check	0.0016
primisulfuron @ 80 g ha^{-1} vs untreated check	0.0018

Plots treated with herbicides produced an average of 437 kg ha^{-1} higher yields than the untreated check plots. This suggests that concerns for herbicide induced yield reductions in areas of the field where there is no johnsongrass are invalid. The study indicates that herbicide treatments actually increased yields significantly when compared to treatments that were not sprayed when johnsongrass was not present. This study was conducted over three growing seasons and a broad range of environments; however, variation in environmental conditions at the time of application could interact with herbicide uptake and induce injury. Hybrid-specific crop damage is another plausible explanation for herbicide injury results from other research that conflict with this study. This study used four different hybrids. The genotypes of the two resistant and two nonresistant hybrids differ slightly. This narrows further the genetic diversity of the hybrids tested. Further testing would be required to determine if this effect would be sustained across a genetically diverse group of hybrids.

This herbicide injury study differs from most that compare herbicide treatments to johnsongrass infested and johnsongrass free plots within the same field. The presence of johnsongrass in the field introduces potential variability from virus infection. MCDV/MDMV can potentially inflict yield reductions in treated and untreated check plots. It seems unlikely; however, the potential remains for the level of the virus infestation to differ between herbicide treated and untreated plots (vector attracted to treated plots).

Another possibility for differing results in fields infested with johnsongrass is that MCDV/MDMV could interact with the metabolic breakdown of the herbicide or herbicide metabolism could reduce the plant's metabolic viral defense mechanisms. Either case would result in higher injury levels for herbicide treated plots when MCDV/MDMV is present. Studies report higher incidence of MCDV/MDMV in johnsongrass infested plots treated with POST herbicides or other means of johnsongrass control. This response has been attributed to the movement of insect vectors from dying johnsongrass to healthy corn plants, increased severity of the disease and a greater number of infected plants in johnsongrass treated plots (**8, 34, 111**). MCDV/MDMV and its movement related to POST herbicide treatment potentially obscures independent herbicide effects on crop yield in many studies.

The focus of most POST johnsongrass herbicide studies in corn has been weed competition. The presence of johnsongrass in competition studies confounds yield increase due to reduced weed competition with potential herbicide effect on crop yield. Studies rarely include two johnsongrass-free check plots, one that is sprayed with herbicide treated and one that is not sprayed with herbicide. This obscures any positive yield from herbicide treatment with the yield response from reduced weed competition.

These results remained consistent in 11 experimental locations over the course of 3 yr. The hybrids used during 1993 and 1994 were Pioneer 3245 and Pioneer 3245IR at all locations. The experiment was conducted at

one location in 1995 using Pioneer 3394 and Pioneer 3395IR. There were no yield inconsistencies (significant interaction) for herbicide treatments among hybrids, locations or years for this effect. There was low probability ($p > 0.0984$) of a slight yield reduction (6.5%) when comparing the yield of imidazolinone resistant hybrid version Pioneer 3395IR to Pioneer 3394 in 1995. The process of cell culture can lead to unpredictable genetic changes known as somaclonal variation. *In vitro* selection usually prolongs the length of time in culture and leads to deleterious changes to a crop strain even though selection for the desired trait was successful (**36**). Pleomorphism was not detected when yields of Pioneer 3245 and Pioneer 3245IR, used in 1993 and 1994, were contrasted. Pioneer hybrids 3245 and 3245IR exhibited no yield difference ($p > 0.58$).

The whole plot and subplot treatment comparison support the conclusion that yield reduction from these herbicides is unlikely in areas of the field that are not johnsongrass infested. This studies do not rule out the possibility that yield reduction due to allelopathic affects from nicosulfuron-killed johnsongrass or johnsongrass residue or interaction of herbicide with MCDV/MDMV since johnsongrass was virtually non-existent in fields where these studies were conducted. It seems that under environmental conditions experienced, at plant growth stages from 4 to 6 WAP and with the herbicides and herbicide rates studied that foliar uptake, leaching, and root transfer experienced were insufficient to reduce corn yield.

Chapter 5

General Summary

The objectives of this study were to determine: (1) the relative accuracy of models for making postemergence herbicide decision for johnsongrass control in corn and (2) the effect of nicosulfuron and primisulfuron on corn yield under weed free conditions. The primary objective was to evaluate existing models under field conditions and modify models if necessary to explain the relationship of corn yield with johnsongrass density.

Five nonlinear and a linear model were fit to corn yield loss data produced over a wide range of johnsongrass densities. Uncorrected coefficients of determination ($\sim R^2$) for all models were similar (0.55 to 0.58) due to variation in yield loss data. The linear model overestimated yield loss at the y-intercept and underestimated the effect of each additional weed at low weed density near the true economic threshold weed density. Three of the nonlinear models (equations 2, 4, and 5) also overestimated yield loss at the y-intercept. The rectangular hyperbola and the two parameter exponential model (equations 1 and 3) projected realistic yield loss estimates at low johnsongrass densities. Four of the nonlinear models predicted a

maximum yield loss to johnsongrass interference in a range from 8100 to 8500 kg ha^{-1}. The rectangular hyperbola projected the highest maximum yield loss, 10000 kg ha^{-1}. Equations 1 and 3 projected the most realistic yield loss estimates at the y-intercept, similar johnsongrass threshold densities, and highly correlated yield loss estimates over a broad range of johnsongrass densities. These models produce the most practical yield loss estimates over the range of johnsongrass densities included in this study and should be the most useful models for making herbicide-use decisions based on economic threshold.

Primisulfuron and nicosulfuron did not reduce corn yield at up to twice the rate recommended for johnsongrass control when Pioneer 3245 IR and Pioneer 3395 (herbicide resistant genotypes) were compared to Pioneer 3245 and 3394, similar genotypes without herbicide resistance. Herbicide treatment produced a positive yield response when treated plots were compared to the untreated check. This response could be specific to the limited number of hybrids tested. Herbicide injury trials suggest that there is no need to adjust economic thresholds for crop injury due to POST application of primisulfuron or nicosulfuron. Herbicide cost and economic threshold weed density could be reduced by using 17.5 g ha^{-1} rather than the 35.0 g ha^{-1} labeled rate of nicosulfuron for controlling johnsongrass in corn. The hyperbolic model and the exponential model that used two parameters to explain this data produced the most realistic yield loss

estimates and were consistent with the linear model developed to explain corn yield loss to johnsongrass competition at threshold densities in previous Tennessee studies.

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VITA

Robert Foster Montgomery, son of Harry Dodds Montgomery, Sr. and Brownie Foster Montgomery, was born in Trenton, Tennessee on March 11, 1953. He attended Peabody High School and graduated in 1971. He received a Bachelor of Science degree in Animal Science from the University of Tennessee at Martin in June of 1976. He then attended the University of Tennessee, Knoxville, in September of 1976 and completed a Master of Science degree in Animal Science in August of 1978. He was employed by the University of Tennessee Agricultural Extension Service in October of 1978 as an assistant extension agent, 4-H Agriculture, in Obion County, Tennessee. He has worked there from 1978 to present as a 4-H agent (1978-1983), extension leader (1983-1995) and extension agent-area agronomist (1995-present). He enrolled in the University of Tennessee on educational leave in August of 1992 to pursue a Doctor of Philosophy in Plant and Soil Science with emphasis on chemical weed control. He received this degree in August of 1996 and continued his Extension assignment.

He has four children Garret, Hope, and Megan Montgomery and Dana Fuqua. He is married to Amy Henderson Montgomery. He and his family live near Union City, Tennessee in Obion County.