Influence of Velvetleaf (Abutilon theophrasti) and Common Sunflower (Helianthus annuus) Density Variation on Weed Management Outcomes

Author(s): J. Anita Dieleman, David A. Mortensen and Alex R. Martin

Source: *Weed Science*, Vol. 47, No. 1 (Jan. - Feb., 1999), pp. 81-89
Published by: Cambridge University Press on behalf of the Weed Science Society of America
Stable URL: https://www.jstor.org/stable/4046240

Weed Science, 47:81–89. 1999

Influence of velvetleaf (*Abutilon theophrasti*) and common sunflower (*Helianthus annuus*) density variation on weed management outcomes

J. Anita Dieleman
Corresponding author. Department of Agronomy, University of Nebraska, Lincoln, NE 68583-0915; Jdielema@unlnotes.unl.edu

David A. Mortensen
Alex R. Martin
Department of Agronomy, University of Nebraska, Lincoln, NE 68583-0915

Interactions between initial weed seedling density and postemergence herbicide and mechanical weed control were studied in two field experiments conducted between 1994 and 1996. Increasing seedbank densities of velvetleaf (0 to 500 seed m^{-2}) in soybean or common sunflower (250 to 2,500 seed 1.3 m^{-2}) in corn or soybean were established at Lincoln and Mead, NE, respectively. Emerged seedlings were treated with increasing intensities of weed control from none to bentazon alone or with interrow cultivation. A positive linear relationship between initial seedling density and density of surviving seedlings was consistently observed. As initial seedling density increased, more survivors were present after treatment. As intensity of weed control increased, the number of seedling survivors decreased. Resulting reproductive fitness decreased with increasing management intensity but remained positive when regressed against surviving seedling densities. Weed management outcomes were dependent on initial seedling density, such that the absolute number of survivors increased, while proportion of survivors appeared constant within the density ranges studied. These research findings emphasize the need to account for weed infestation level when assessing efficacy of weed management systems and provide evidence that patchy weed distributions may persist in part because of the need for considerably higher management intensities in high density patch centers.

Nomenclature: Bentazon; velvetleaf, *Abutilon theophrasti* Medikus. ABUTH; common sunflower, *Helianthus annuus* L. HELAN; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.

Key words: Infestation level, patches, seed production, seedling density, survivorship, weed management intensity, ABUTH, HELAN.

Weed management is usually the application of one or more practices to reduce weed population size and minimize crop losses (Mortensen et al. 1998; Swanton and Weise 1991). The outcome of a weed control practice is often measured as percentage weed control (Martin et al. 1994), and that expected control level is extrapolated to individual grower's fields. Growers adapt weed control practices to conditions of individual fields after characterization of weed species composition, weed growth stage, and soil characteristics. However, average weed infestation levels vary considerably from field to field (Andreasen et al. 1991) and within individual fields (Cardina et al. 1995; Johnson et al. 1995, 1996; Mortensen et al. 1993, 1995).

Numerically, most weed seedling populations in corn and soybean fields are described by the negative binomial distribution (Johnson et al. 1995; Wiles et al. 1992). Spatially, weed seed and seedling distributions vary from areas of very high population density to areas where no weeds are found (Cardina et al. 1995; Mortensen et al. 1995). For example, velvetleaf and common sunflower are two predominant annual weed species found in corn and soybean production fields in Nebraska and occurred in field surveys in approximately 30 site-year grid-sampling studies (Johnson 1994; Johnson et al. 1995; Wyse 1996). Eighty percent of sampled quadrats in one field had no common sunflower seedlings in 1992 and 1993, while no velvetleaf seedlings were observed in 44 and 64% of these quadrats in 1992 and 1993, respectively (Johnson et al. 1996). Mean velvetleaf seedling densities were 11 and 3 plants m^{-2}, while maximum observed densities were 128 and 61 plants m^{-2} in 1992 and 1993, respectively. Mean common sunflower seedling densities were 0.69 and 2.1 plants m^{-2}, and maximum densities were 63 and 134 plants m^{-2} in 1992 and 1993, respectively (Johnson et al. 1996). Average weed density estimates mask the real variation in occurrence of these species, variation that could contribute strongly to weed persistence and spatial heterogeneity.

Variation in weed seedling density across a grower's field influences the extent of response to weed control efforts. Growers have observed that herbicide performance is reduced in years following weed control failures (Hartzler and Roth 1993). Weed population densities can dramatically increase in years following poor control because of greater seed production and a resulting increase in the seedbank (Wilson and Lawson 1992). Poor weed control in 1989 no-tillage corn fields significantly decreased the response to weed control of 1990 annual grass populations (Hartzler and Roth 1993). This result could be attributed to a higher annual grass seedbank whose germination is high on the soil surface in no-till fields. In other field studies, Burrill and Appleby (1978) and Winkle et al. (1981) observed more surviving individual plants when high density weed populations were treated with preemergence herbicide at low doses.

A curvilinear relationship was found to exist between ini-

Table 1. Soybean planting, weed management application, weed seedling assessment, and frost and harvest dates for velvetleaf study at Lincoln, NE.

	Terrace		Slope		Lowland	
Operation	1995	1996	1995	1996	1995	1996
Soybean planting	June 7	May 22	June 7	May 6	June 7	May 7
Initial seedling count	July 17	June 19	June 27	June 20	June 27	June 20
Herbicide application	July 21	June 21	June 28	June 21	June 28	June 21
Interrow cultivation	Aug. 2	June 28	July 14	June 28	July 14	June 28
Surviving seedling count	Aug. 14	July 23	July 25	July 23	July 25	July 23
Killing frost	Sept. 21	—	Sept. 21	—	Sept. 21	—
Soybean harvest	Oct. 18	Oct. 12	Oct. 17	Oct. 17	Oct. 17	Oct. 16

tial weed density and the response to soil-applied herbicides. It was observed that at low densities, individual plant fresh or dry weight was less (Burrill and Appleby 1978; Hoffman and Lavy 1978; Winkle et al. 1981), mortality of individuals was greater (Khedir and Roeth 1981), and fewer survivors remained after treatment (Andersen 1981; Pannell 1990) compared to higher densities. For example, Italian ryegrass (*Lolium multiflorum* Lam.) shoot dry weight decreased by 76% at a density of 10 plants in 550 g of soil pot^{-1} compared to only 14% at 100 plants pot^{-1} in response to 0.5 mg kg^{-1} diuron (Burrill and Appleby 1978). Diuron rates above 0.8 mg kg^{-1} resulted in complete kill of all ryegrass densities. Physiological studies determined that less soil-applied herbicide was taken up by individual plants as density increased (Hoffman and Lavy 1981; Winkle et al. 1981). For example, white mustard (*Brassica hirta* Moench) at 25 plants pot^{-1} absorbed 47 ng atrazine per seedling compared to 106 ng atrazine seedling^{-1} at five plants pot^{-1} (Winkle et al. 1981).

Interactions of weed density with foliar-applied herbicides have not been reported in the literature directly but more as anecdotal evidence of a potential interaction. Effectiveness of foliar-applied herbicides is highly dependent on the timing of application and on the growth stage of the weed. Significant variation in plant size has been observed as a result of high density plant populations (Nagashima et al. 1995; Weiner and Thomas 1986). Such size differences could result from variation in factors contributing to growth rates such as seed age or emergence time (Ellison and Rabinowitz 1989; Willson et al. 1987), genetic variation, resource competition, or effects of herbivores, parasites, or pathogens (Cousens and Mortimer 1995; Weiner and Thomas 1986). Additional variation in site characteristics across a grower's field, such as soil texture, organic matter content, and nutrient status, influence both crop and weed growth rates and resulting reproductive fitness (Bell and Lechowicz 1991; Cousens and Mortimer 1995). Such variation in size could interact with foliar-applied herbicides such that overlapping leaf canopies could protect smaller individuals from obtaining a lethal dose.

Because weed populations vary within fields and postemergence herbicide and mechanical weed control have become increasingly important weed management practices, the objective of this study was to determine the influence of velvetleaf and common sunflower seedling density variation on seedling survivorship and reproductive fitness in response to varying management intensities.

Materials and Methods

Velvetleaf Study

Field experiments were conducted in 1995 and 1996 at the Rogers Memorial Farm, 20 km east of Lincoln, NE. The 64-ha farm is characterized by sloping terrain (Hanna et al. 1982) with soil conservation structures in place. Three experimental locations were selected: a man-made flat terrace (Terrace), a linear slope of 2 to 5% (Slope), and level lowland area (Lowland). These field locations sampled the extent of variation in field site attributes that occurred in growers' fields with this hillslope topography. The Terrace site was located 460 to 570 m west of and in a landscape position 10 to 12 m higher than the Lowland location. The Slope site was located 610 m north of the Lowland location at an intermediate landscape position. Soil types on the Terrace and Slope were Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudolls), while the soil type in the Lowland area was Kennebec silt loam (fine-silty, mixed, mesic Cumulic Hapludolls).

The experimental design was a split plot within each field location such that weed management treatments were main plots and velvetleaf seedbank densities were split plots. Soybean was no-till planted into standing ridges in 0.76-m-wide rows on June 7, 1995, and May 22, 1996, in the Terrace location and on June 7, 1995, and May 6, 1996, in the Slope and Lowland locations (Table 1). Each weed management plot was six soybean rows wide (4.5 m) and 11 m long. Velvetleaf seed was collected the previous fall from a population of plants in a neighboring field and stored at room temperature until spring. Velvetleaf seed densities of 0, 10, 20, 50, 100, and 500 were sown within 5 d of soybean planting into 0.80-m-long by 1.25-m-wide plots spanning the center two crop rows, randomized, and separated by 1 m within each weed management plot. Velvetleaf began to emerge within 14 d after planting in all locations. All other weeds were removed by hand.

Weed management treatments were selected to represent increasing intensities of postemergence herbicide and mechanical weed control. Three treatments were applied: none, bentazon alone (0.84 kg ha^{-1} in 1995, 0.56 kg ha^{-1} in Terrace location 1996, and 1.12 kg ha^{-1} in Slope and Lowland locations in 1996), or bentazon with interrow cultivation. Herbicide applications were made with a tractor-mounted sprayer using 8003 flat-fan nozzles delivering 225 L ha^{-1} at 260 kPa. Bentazon and 28% urea ammonium nitrate (2.8 L ha^{-1}) were applied when velvetleaf was in the four- to six-leaf stage, approximately 4 wk after soybean

TABLE 2. Crop planting, weed management application, weed seedling assessment, and harvest dates for common sunflower study at Mead, NE.

	Corn		Soybean	
Operation	1994	1995	1994	1995
Crop planting	May 10	May 22	May 18	June 3
Initial seedling count	June 6	June 14	June 14	June 28
Herbicide application	June 8	June 21	June 19	July 10
Interrow cultivation	July 10	June 28	July 10	July 14
Surviving seedling count	July 15	July 18	July 15	Aug. 4
Crop harvest	Oct. 15	Oct. 20	Oct. 15	Oct. 20

planting. Interrow cultivation was conducted within 2 wk after herbicide application. The experiment was replicated four times within each location.

Velvetleaf seedling density was determined 1 to 4 d prior to herbicide application and 2 wk after interrow cultivation (Table 1). Velvetleaf seed capsules were harvested as they matured for reproductive fitness estimates from mid-August until frost in 1995 and until soybean harvest in 1996 and total capsule number per plot was determined.

Sunflower Study

Field experiments were conducted in 1994 and 1995 at the Agricultural Research and Development Center near Mead, NE, located 60 km north of Lincoln, NE. Soil type was a Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudolls). Seedbed preparation involved two spring cultivations for corn and, for soybean, fall disking and two spring cultivations, in both years. Granular fertilizer was applied according to Nebraska soil recommendations, and a preemergence treatment of alachlor was applied at 2.84 kg ha^{-1} for grass suppression.

The 1994 study was the first year of a 4-yr project to study common sunflower patch development in response to weed management within a corn–soybean rotation. Thus, the experimental area was divided in two, so as to have corn and soybean planted in each year. The experimental design was a split plot within each crop, such that two weed management treatments were main plots and three common sunflower densities were the split plots. Corn was planted May 10, 1994, and May 22, 1995, and soybean was planted on May 18, 1994, and June 3, 1995 (Table 2). At the time of crop planting, common sunflower seed was sown into 0.61- by 2.13-m plots at densities of 250, 1,250, and 2,500 seed 1.3 m^{-2}. Common sunflower density plots were replicated four times within each weed management treatment plot. Common sunflower seedlings began to emerge within 10 d after planting, and all other broadleaf weeds were removed by hand.

Weed management treatments were bentazon at two rates (0.56 and 1.12 kg ha^{-1}), together with interrow cultivation. Herbicide applications were made with a tractor-mounted sprayer using 8003 flat-fan nozzles delivering 225 L ha^{-1} at 260 kPa. Bentazon and 28% urea ammonium nitrate (2.8 L ha^{-1}) were applied to four- to six-leaf stage common sunflower seedlings, approximately 4 wk after planting. Interrow cultivation was conducted approximately 2 wk after herbicide application.

Common sunflower seedling density was determined 2 to 4 d before herbicide application and 1 wk after interrow cultivation (Table 2). To estimate common sunflower seed production, a total of 60 common sunflower seedheads were harvested from plants adjacent to the experimental area, seedhead diameter was measured, and seed number per head was determined. A linear regression model related seed number to average seedhead diameter. Prior to crop harvest, total seedhead number and average seedhead diameter were measured in each plot, and the regression model was used to estimate seed production per plot.

Statistical Analysis

Density of surviving weed seedlings was regressed against initial seedling density to model seedling survivorship in response to weed management. A test for heterogeneity of slope estimates (intercept not different from zero) was used to determine if at least one slope was different among weed management treatments within a location. Pairwise differences in slopes within a location were tested using *F*-tests. An *F*-test compared the change in residual sums of squares of a combined model vs. the sum of the residual sums of squares of the two individual models at the $\alpha = 0.05$ level (Seefeldt et al. 1995).

The relationship between surviving seedling density and reproductive fitness (capsule or seed production) was described by the rectangular hyperbola model (Gonzalez-Andujar and Fernandez-Quintanilla 1991):

$$S = \frac{b \times D}{1 + (b \times D/a)} \qquad [1]$$

where S is an estimate of weed reproduction (capsule or seed number) per unit area, D is surviving seedling density (number per unit area), b is the slope as $D \rightarrow 0$, and a is the asymptote representing the maximum estimate of weed reproduction as $D \rightarrow \infty$. The simple linear regression model, $S = b \cdot D$, was fit if an asymptote was not reached. A test for lack of fit of Equation 1 was not possible because there was no replication of surviving seedling density as a treatment effect. Differences within locations and among weed control treatments were tested using *F*-tests as described above.

Results and Discussion

Seedling Survivorship

High initial velvetleaf and common sunflower seedling density resulted in more survivors after application of a weed management treatment compared to low seedling density (Figures 1 and 2). For example, as initial velvetleaf seedling density increased from 0 to 100 plants m^{-2}, the average

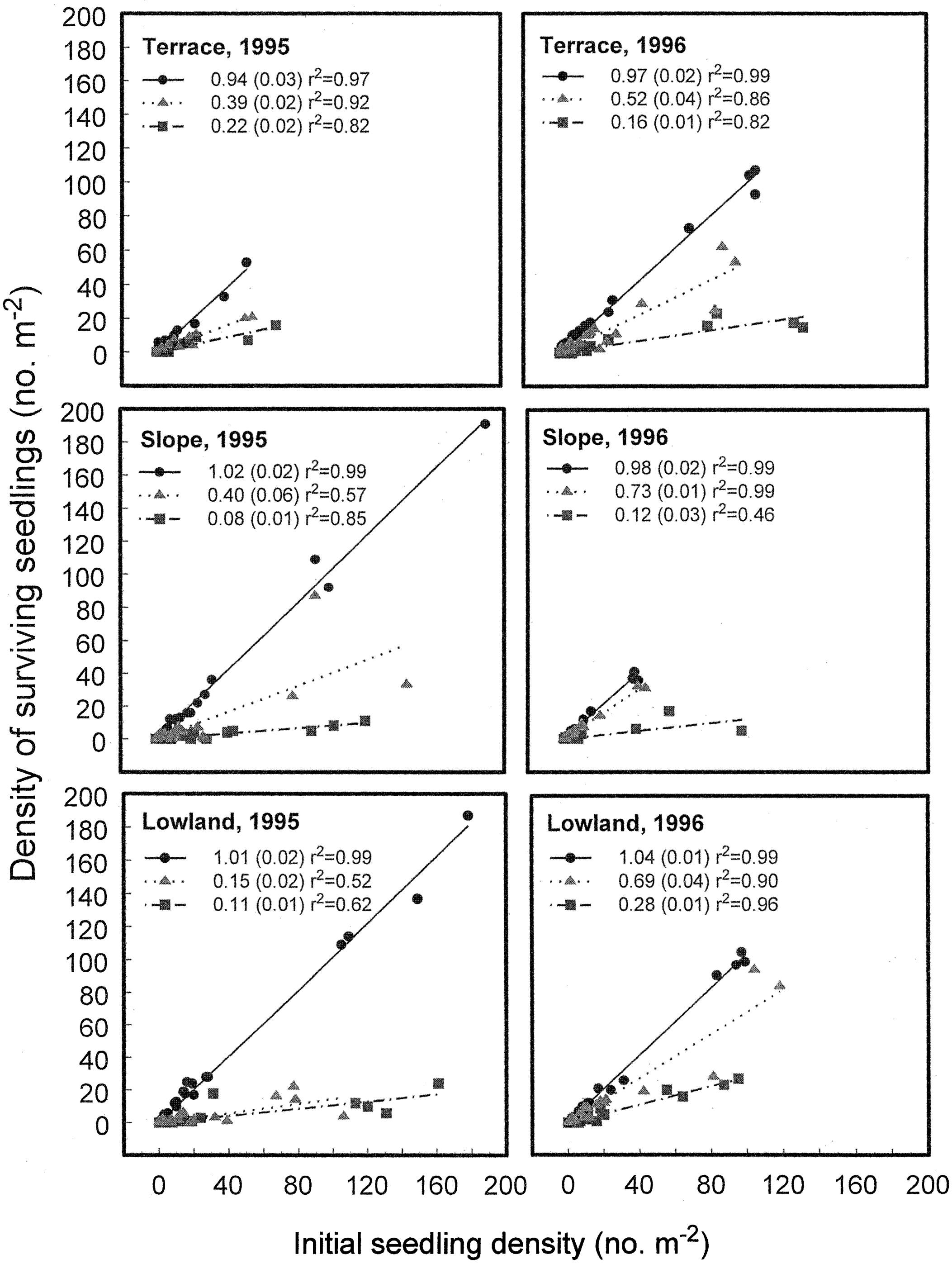

FIGURE 1. Effect of three weed management treatments (none ●, bentazon ▲, and bentazon plus interrow cultivation ■) on the relationship between initial seedling density and density of surviving velvetleaf seedlings across three field locations at Lincoln, NE, in 1995 and 1996. Linear slope estimate (±SE) and regression coefficients are reported for each management treatment, location, and year.

seedling density remaining after application of bentazon alone was 0 to 68 plants m^{-2} in the Lowland location in 1996 (Figure 1). In the common sunflower study, initial seedling densities ranged between 21 and 367 plants 1.3 m^{-2}, with 0 to 52 plants 1.3 m^{-2} remaining after application of half-rate bentazon and interrow cultivation in corn in 1994 (Figure 2).

The slope of the regression between initial seedling density and density of surviving seedlings represents the average proportion of seedlings surviving a given weed management treatment (survivorship). With no weed management applied, average velvetleaf survivorship was approximately one, except at the Lowland location in 1996, with deviations from unity as a result of continued emergence after the census was taken (e.g., Lowland location 1996, survivorship = 1.04) or naturally occurring seedling mortality.

Year, field location, and crop influenced the number of seedlings established. In general, recruitment of velvetleaf seedlings from the planted seedbank was higher in 1995 than in 1996, although it reversed for the Terrace location (Figure 1) and was attributed to a delay in planting in 1995. Recruitment was higher in the Lowland location, with an

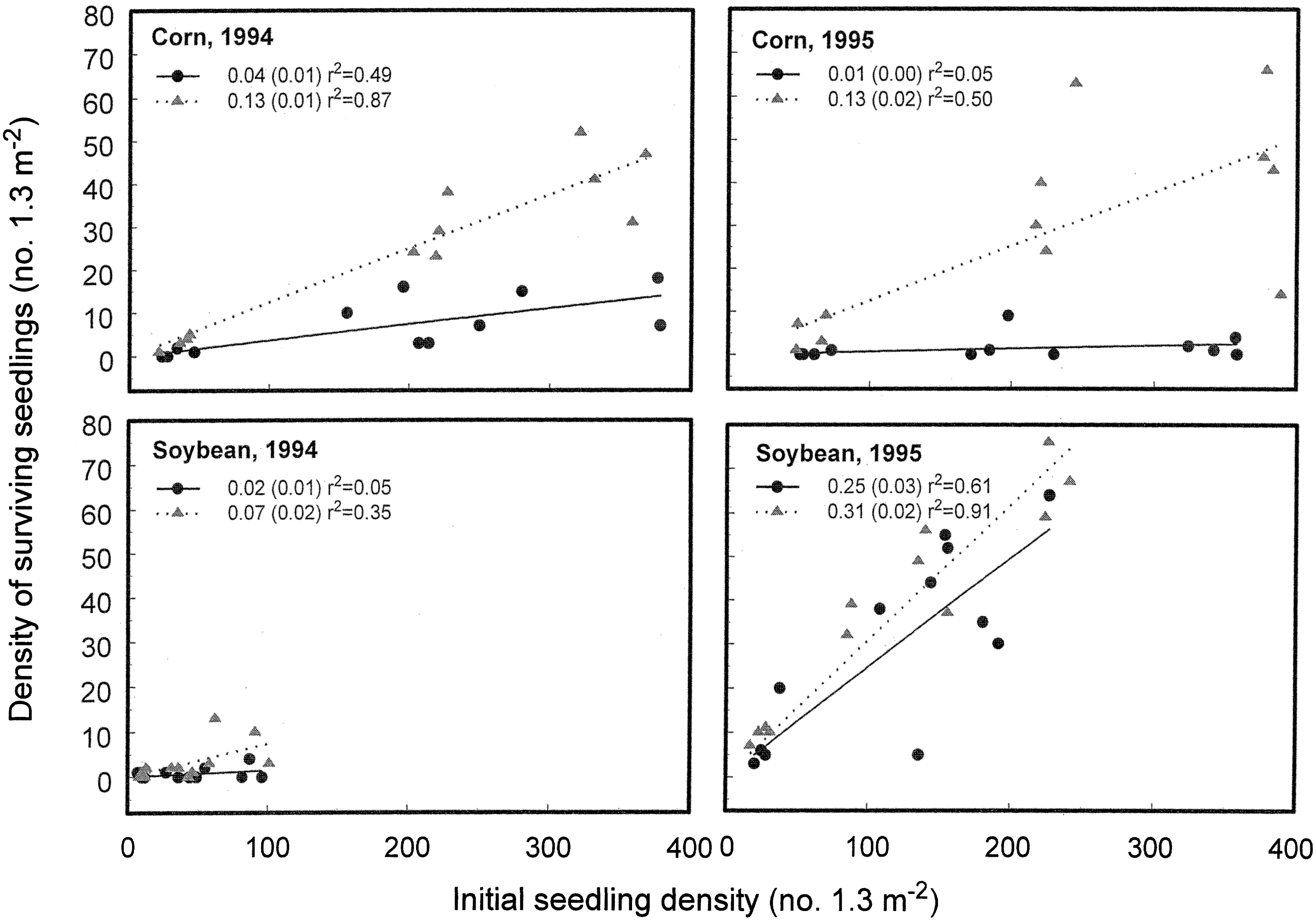

FIGURE 2. Effect of two weed management treatments (0.56 kg ha^{-1} bentazon ▲ and 1.12 kg ha^{-1} bentazon ●) with interrow cultivation on the relationship between initial seedling density and density of surviving common sunflower seedlings at Mead, NE, in 1994 and 1995. Linear slope estimate (±SE) and regression coefficients are reported for each management treatment, crop, and year.

average of 135 seedlings emerging from a seedbank density of 500 seed m^{-2} in 1995, followed by the Slope location (103 plants m^{-2}) and the Terrace location (45 plants m^{-2}). The three farm locations varied in extent of stressful conditions such that the Lowland was more protected with windbreaks and terrace berms on three sides. The Terrace location was at a higher elevation relative to the other locations and was exposed to prevailing winds. The Slope location was susceptible to erosion, such that soil moved across the surface perpendicular to the crop rows and across the weed plots, reducing successful recruitment. Maximum initial common sunflower seedling densities were 376 and 389 plants 1.3 m^{-2} in corn and 101 and 241 plants 1.3 m^{-2} in soybean for 1994 and 1995, respectively (Figure 2). Because soybean and common sunflower seed were sown 8 to 10 d later than corn, initial seedling densities were reduced and attributed to the temperature-sensitive secondary dormancy mechanism of common sunflower induced by warming soil temperatures (Teo-Sherrell 1996).

Positive linear relationships existed between initial velvetleaf and common sunflower seedling density and density of surviving seedlings for a given weed management treatment (Figures 1 and 2). We initially hypothesized that this relationship would be a curvilinear function where, at very high densities, overall population survivorship would be higher because the herbicide dose received by an individual seedling would decrease as interplant distances decreased (Hoffman and Lavy 1978; Pannell 1990; Winkle et al. 1981). Three reasons for not detecting a curvilinear response include: (1) differences in activity of soil- vs. foliar-applied herbicides, (2) seedling densities that were not high enough and interplant distances that were large enough such that each plant had a uniformly high probability of receiving a biologically effective dose, or (3) weed management treatments that were too intense for the range of densities studied.

Velvetleaf survivorship with application of bentazon alone ranged from 0.15 to 0.73, and by including interrow cultivation, survivorship was reduced to a range of 0.08 to 0.28 across locations and years (Figure 1). At the Lowland location in 1995, survivorship was the same between bentazon alone and bentazon with interrow cultivation ($F_{1,46}$ = 1.97, P = 0.17). Survivorship to bentazon alone across locations in 1995 was similar for the Terrace and Slope locations ($F_{1,46}$ = 0.001, P = 0.97) and for the Slope and Lowland locations ($F_{1,46}$ = 1.92, P = 0.17) but not between the Terrace and Lowland locations ($F_{1,46}$ = 40.09, P = 0.0001). Across locations in 1996, survivorship response to bentazon alone (1.12 kg ha^{-1}) was similar for the Slope and Lowland locations ($F_{1,40}$ = 0.22, P = 0.64). Survivorship estimates were generally higher in 1996 than in 1995 with the application of bentazon alone or bentazon with interrow cultivation (Figure 1). Velvetleaf seedlings were generally smaller and had reduced fitness relative to the crop in 1995 because of residual herbicide effects of imazaquin from the previous year's weed control before the study was established. The second year of the study was established where no residual herbicide had been applied, and consequently, fitness of the velvetleaf seedlings, and survivorship, was greater in 1996.

Survivorship of common sunflower across crops and years ranged from 0.07 to 0.28 in response to a half-rate bentazon with interrow cultivation, while response to full-rate bentazon with interrow cultivation ranged from 0.01 to 0.28 (Figure 2). Across years in corn, common sunflower survivorship was not different in response to half-rate bentazon ($F_{1,22}$ = 0.003, P = 0.96) but was statistically different for full-rate bentazon ($F_{1,22}$ = 19.68, P = 0.0002) and was different between the two management intensities. Only in soybean in 1995 did half- and full-rate applications of bentazon together with interrow cultivation result in equal densities of surviving common sunflower seedlings ($F_{1,22}$ = 3.37, P = 0.08). This may be a result of delayed crop and weed planting, late herbicide application, and late seedling assessment (Table 2), where a second flush of seedlings appeared after herbicide application and interrow cultivation.

The extent of variation in survivorship estimates was indicated by the regression coefficient (r^2), which includes both lack of fit and experimental error (Figures 1 and 2). Even though herbicide applications were applied at the four- to six-leaf stage of velvetleaf, variation in other plant characteristics are known to increase with density (Nagashima et al. 1995; Weiner and Thomas 1986). For example, variation in herbicide tolerance, time of emergence, extent of leaf canopy overlap, and quality of individual safe sites all would be influenced by density. These factors contribute to the scatter of data points around the observed response between initial density and density of surviving seedlings.

The number of experimental plots with no surviving velvetleaf or common sunflower seedlings increased as weed management intensity increased, and these tended to be the low density plots (data not shown). To illustrate, with bentazon and interrow cultivation in the Lowland location in 1996, 5 out of a total of 20 plots had no velvetleaf seedlings remaining. Of these 5, 4 plots had seedbank densities < 50 seed m^{-2}. In the 1994 common sunflower study, 7 out of 12 plots had no seedlings remaining in soybean compared to 2 out of 12 in corn in response to full-rate bentazon with interrow cultivation. To show the influence of initial densities, the number of plots without surviving common sunflower seedlings in corn in 1995 decreased from 3 to 1 out of 4 as seedbank density increased from 250 to 2,500 seed 1.3 m^{-2}. This indicated that the probability of having no survivors remaining after weed control was inversely related to the initial seedling density.

The limitation of only evaluating seedling densities is that there is no accounting for fitness of individual plants (Rasmussen 1993). Therefore, weed reproduction of surviving seedlings as a measure of fitness was determined to further assess the influence of initial seedling density on weed management outcomes.

Reproductive Fitness

Velvetleaf capsule production in the absence of weed control was modeled by Equation 1 across all locations and years (Figure 3). The Lowland location was the most productive, and maximum production was 816 and 1,204 capsules m^{-2} in 1995 and 1996, respectively. It has been reported that velvetleaf seed production per unit area declines at very high densities as intraspecific competition increases (Pacala and Silander 1985; Thrall et al. 1989). This was not observed in this study. Velvetleaf capsule production was reduced as intensity of weed control increased (Figure 3). Equation 1 fit both bentazon alone and bentazon with interrow cultivation at the Lowland location in 1995, and the models were not different ($F_{2,44}$ = 0.83, P = 0.44). For the Terrace and Slope locations in 1995, capsule production had a linear relationship with surviving seedling density in response to bentazon alone, and no seedlings survived to reproductive maturity in the bentazon and interrow cultivation treatment. A killing frost on September 21, 1995, prevented many flowers from forming capsules, and many capsules remained immature. In 1996, Equation 1 fit capsule production across management intensities at the Lowland location and was different ($F_{2,44}$ = 3.72, P = 0.03). Within the Terrace or Slope location, similar linear models described capsule production across surviving seedling densities for both bentazon alone and bentazon with interrow cultivation. These results indicated that surviving plants produced similar numbers of capsules. The number of experimental plots with no capsule production increased from 0 to 11 and 14 plots out of 20 as management intensity increased from none to low to high in the Lowland location in 1995 (data not shown). The probability of no capsule production after weed control was inversely related to initial seedling density.

Overall, common sunflower seed production was 10 times higher in 1994 than in 1995 for both crops, probably as a result of earlier crop and weed planting (Figure 4). Seed production increased linearly with surviving seedling density. In corn across both years, seed production by survivors was similar for full-rate bentazon ($F_{1,21}$ = 0.66, P = 0.43) and across management treatments in 1995 ($F_{1,22}$ = 2.55, P = 0.12) but not in 1994 ($F_{1,21}$ = 7.17, P = 0.01). Seed production by survivors in response to half-rate bentazon was highly variable in 1994, resulting in differences between management intensities. In soybean in 1994, few to no common sunflower seedlings survived the application of full-rate bentazon, resulting in almost no seed production. In contrast in 1995, seedlings surviving half- and full-rate bentazon applications produced similar amounts of seed ($F_{1,22}$ = 4.22, P = 0.05). The number of experimental plots that produced no common sunflower seed decreased as initial seedling density increased (data not shown). Also, as intensity of control increased, more plots had no seed production, such that in corn in 1994, 1 and 2 plots out of 12 had no seed production at the half and full rates of bentazon treatments, respectively. In soybean in 1994, 6 and 10 out of 12 plots had no seed production in response to half and full rates of bentazon treatments, respectively. The probability of seed production increased with initial seedling density, even at a high intensity of weed management.

Research Implications

Results of this work indicate that the number of individuals surviving a weed management treatment is directly related to the number of individuals initially present. Furthermore, increases in weed management intensity decrease

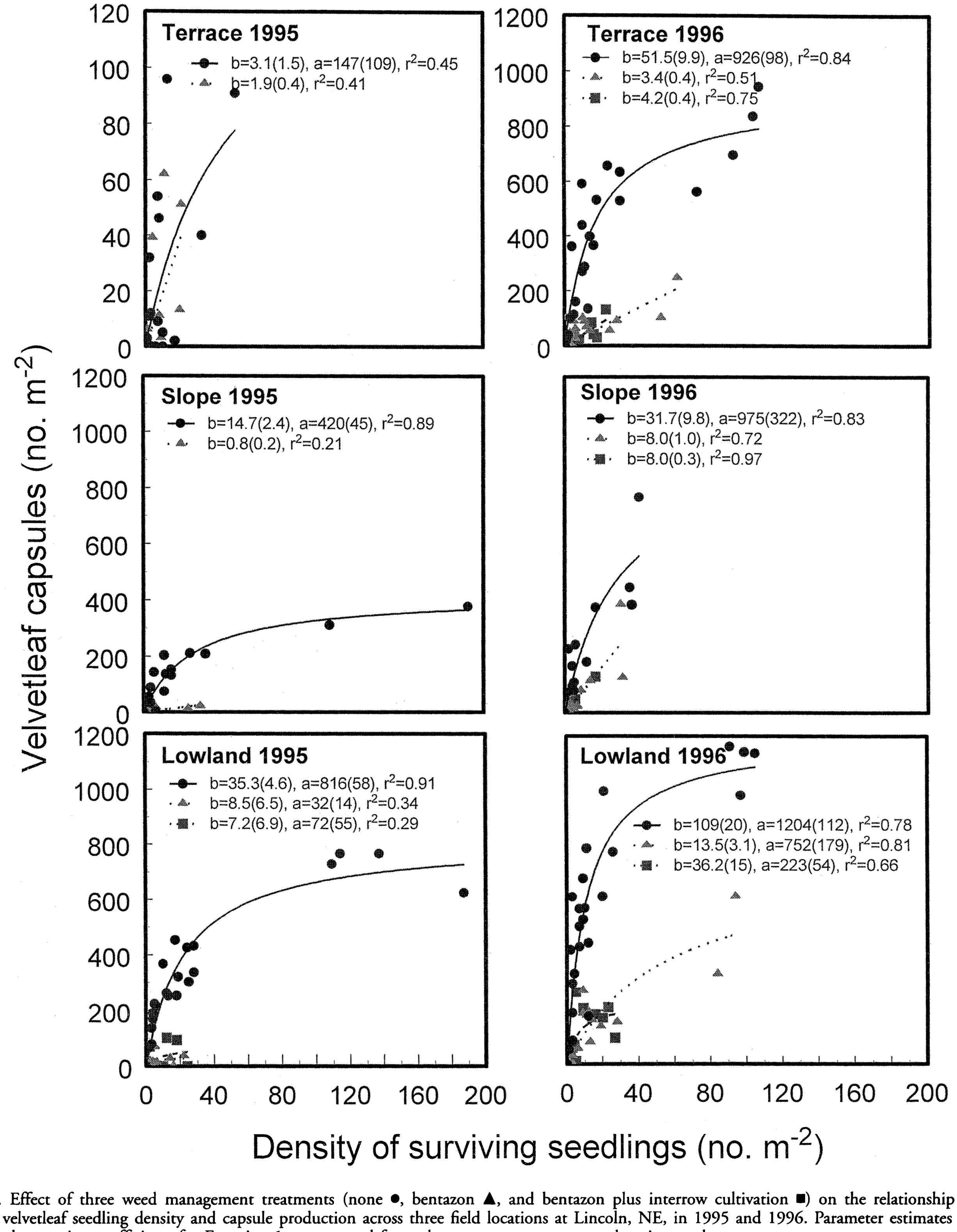

FIGURE 3. Effect of three weed management treatments (none ●, bentazon ▲, and bentazon plus interrow cultivation ■) on the relationship between surviving velvetleaf seedling density and capsule production across three field locations at Lincoln, NE, in 1995 and 1996. Parameter estimates (*b* and *a* ± SEs) and regression coefficients for Equation 1 are reported for each management treatment, location, and year.

the magnitude of, but do not overcome, the response. Proportionally, a linear survivorship response was observed and not a curvilinear function, as initially hypothesized for foliar-applied herbicides and as has been observed for soil-applied herbicides. Such a curvilinear response may yet be observed given even higher initial seedling densities and less intense weed management treatments.

Recognition of the importance of initial infestation level on weed management outcomes will assist researchers and growers in designing, evaluating, and implementing integrated weed management practices consistent with a given weed infestation. In recent years, many studies have been conducted to address reductions of herbicide inputs. By not accounting for the influence of initial seedling densities, of-

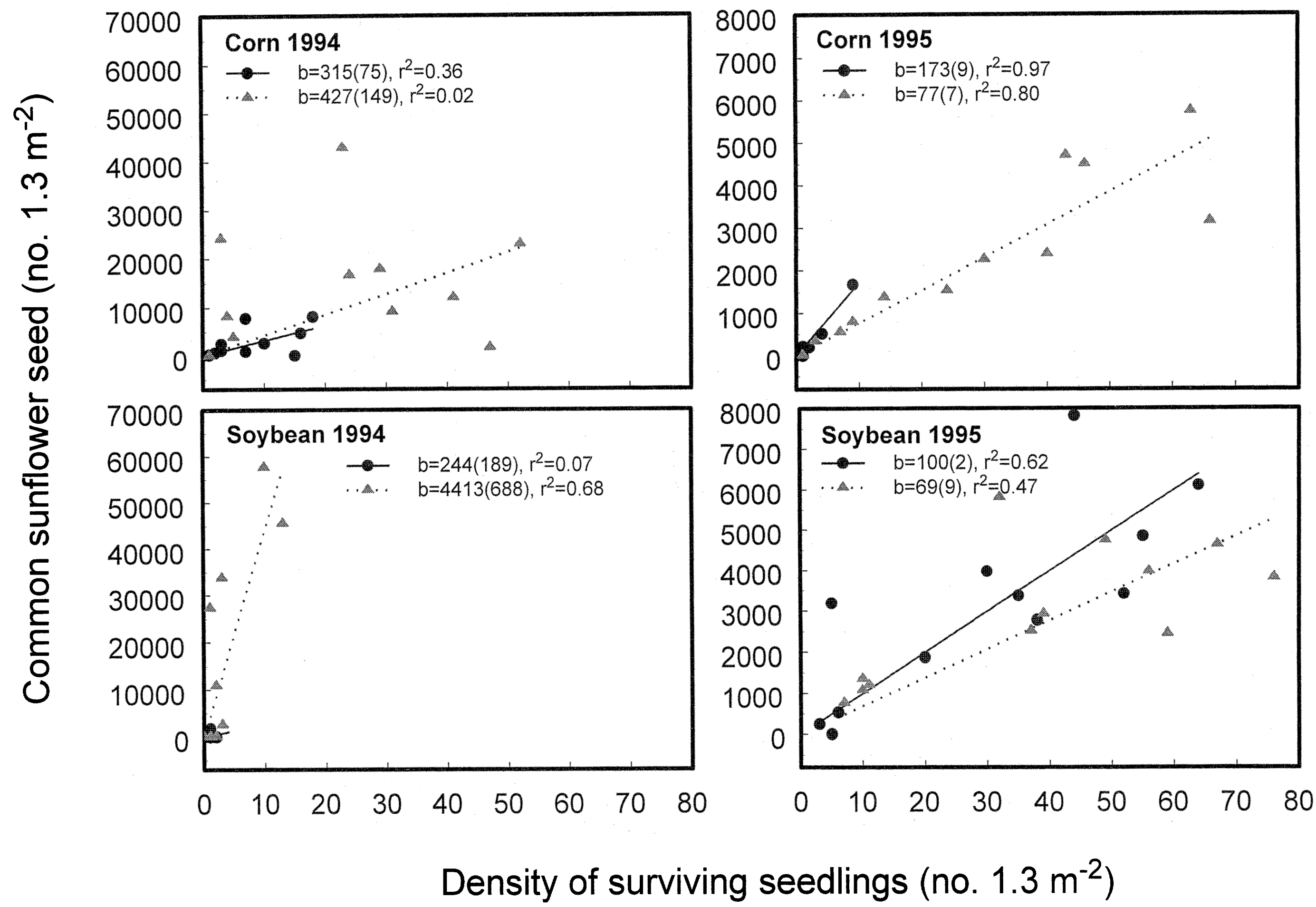

FIGURE 4. Effect of two weed management treatments (0.56 kg ha^{-1} bentazon ▲ and 1.12 kg ha^{-1} bentazon ●) with interrow cultivation on the relationship between surviving common sunflower seedling density and seed production in corn and soybean at Mead, NE, in 1994 and 1995. Linear slope estimate (b ± SE) and regression coefficients for Equation 1 are reported for each management treatment, crop, and year.

ten only the most intense management treatment was found to be effective (Defelice et al. 1989; O'Sullivan and Bouw 1993).

Infestation levels tend to be higher in weed research test plots on government or university farms compared to growers' fields (Dieleman and Mortensen 1998a). Reasons for higher infestations include overseeding of weed seed to gain spatial uniformity in efficacy trials or result from the historic buildup of weed populations after several years of experimental research. Average weed densities on growers' fields tend to be lower, have greater variation in spatial distribution, and occasionally, have high density clusters. In research farm experiments evaluating reduced herbicide use in a corn production system, average velvetleaf seedling densities were 85 and 74 plants m^{-2} in chisel-plow and no-tillage, respectively, over 2 yr (Buhler et al. 1995). Population density in the weedy check of 64 on-farm weed management evaluation studies was < 21 plants m^{-2} in 59% of the locations (Hartzler et al. 1993). From 30 field surveys in eastern Nebraska over 4 yr, average velvetleaf densities ranged from 0 to 10.8 plants m^{-2}, while single maximum observed velvetleaf densities ranged from 9 to 133 plants m^{-2} (Johnson 1994; Wyse 1996). Herbicide efficacy trial designs have included more untreated control plots to compensate for local density variation, but the influence of density variation on management outcomes has not been addressed.

Significant variation in density also exists across individual weed patches in growers' fields (Cardina et al. 1995; Dieleman and Mortensen 1998b; Donald 1994; Johnson et al. 1996). Structurally, patches have high density centers that appear stable but fluctuate numerically and patch edges that appear to shrink and swell spatially from year to year (Gerhards et al. 1997; Johnson et al. 1996). Distinct velvetleaf patches in a grower's field were surveyed in June 1995 and had seedling densities up to 63 plants m^{-2} in the center, which decreased to zero at the edges (Dieleman and Mortensen 1998b). Uniformly applying a weed control practice to such patches, characterized by a broad range of seedbank and seedling densities, should result in a greater number of survivors in high density patch centers. Those plants that survive also produce seed that is distributed within and around the center of the patch, a likely mechanism contributing to weed patch persistence. Conversely, the probability of seedlings surviving the same uniformly applied practice at the patch edges is low because of lower initial seedling densities.

In closing, weed management outcomes are dependent on initial seedling density with respect to absolute numbers of seedling survivors within the density range studied. It is likely that this response strongly contributes to the persistence of weed patchiness. If these findings are broadly applicable, and results of previous studies suggest they are, systems that match intensity of weed control to infestation level may provide the necessary control of high density patch centers. Intensity of weed control can be increased by using interrow cultivation, cover crops, increased crop seeding rates, or incrementally higher herbicide doses focused on areas of higher seedling densities.

Acknowledgments

Published as University of Nebraska Agricultural Research Division Journal Ser. 12209. Research was supported by a North Central IPM competitive grant titled "The relevance of field-specific weed populations to performance of integrated weed management systems." We thank Dawn Wyse-Pester, who conducted the common sunflower study at Mead, NE, as part of her M.S. research. We also thank Bob Hartzler, Linda Young, Marty Williams, Mike Burton, John Lindquist, and two anonymous reviewers for helpful comments on this manuscript.

Literature Cited

Andersen, R. N. 1981. Increasing herbicide tolerance of soybeans (*Glycine max*) by increasing seeding rates. Weed Sci. 29:336–338.

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

Bell, G. and M. J. Lechowicz. 1991. The ecology and genetics of fitness in forest plants. I. Environmental heterogeneity measured by explant trials. J. Ecol. 79:663–685.

Buhler, D. D., J. D. Doll, R. T. Proost, and M. R. Visocky. 1995. Integrating mechanical weeding with reduced herbicide use in conservation tillage corn production systems. Agron. J. 87:507–512.

Burrill, L. C. and A. P. Appleby. 1978. Influence of Italian ryegrass density on efficacy of diuron herbicide. Agron. J. 70:505–506.

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

Cousens, R. and M. Mortimer. 1995. Dynamics of Weed Populations. New York: Cambridge University Press. 332 p.

Defelice, M. S., W. B. Brown, R. J. Aldrich, B. D. Sims, D. T. Judy, and D. R. Guethle. 1989. Weed control in soybeans (*Glycine max*) with reduced rates of postemergence herbicides. Weed Sci. 37:365–374.

Dieleman, J. A. and D. A. Mortensen. 1998a. Influence of weed biology and ecology on development of reduced dose strategies for integrated weed management systems. Pages 333–362 *in* J. L. Hatfield, D. D. Buhler, and B. A. Stewart, eds. Integrated Weed and Soil Management. Chelsea, MI: Ann Arbor Press.

Dieleman, J. A. and D. A. Mortensen. 1998b. Velvetleaf (*Abutilon theophrasti*) patch attributes: whole-patch spatial patterns and within-patch dynamics. Proc. Weed Sci. Soc. Am. 38:9.11.

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

Ellison, A. M. and D. Rabinowitz. 1989. Effects of plant morphology and emergence time on size hierarchy formation in experimental populations of two varieties of cultivated peas (*Pisum sativum*). Am. J. Bot. 76:427–436.

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

Gonzalez-Andujar, J. L. and C. Fernandez-Quintanilla. 1991. Modelling the population dynamics of *Avena sterilis* under dry-land cereal cropping systems. J. Appl. Ecol. 28:16–27.

Hanna, A. Y., P. W. Harlan, and D. T. Lewis. 1982. Soil available water as influenced by landscape position and aspect. Agron. J. 74:999–1004.

Hartzler, R. G. and G. W. Roth. 1993. Effect of prior year's weed control on herbicide effectiveness in corn (*Zea mays*). Weed Technol. 7:611–614.

Hartzler, R. G., B. D. van Kooten, D. E. Stoltenberg, E. M. Hall, and R. S. Fawcett. 1993. On-farm evaluation of mechanical and chemical weed management practices in corn (*Zea mays*). Weed Technol. 7: 1001–1004.

Hoffman, D. W. and T. L. Lavy. 1978. Plant competition for atrazine. Weed Sci. 26:94–99.

Johnson, G. A. 1994. Model Parameterization, Parametric Sequential Sampling, and Geostatistical Analysis of Weed Seedling Populations. Ph.D. dissertation. University of Nebraska, Lincoln, NE. 193 p.

Johnson, G. A., D. A. Mortensen, and C. A. Gotway. 1996. Spatial and temporal analysis of weed seedling populations using geostatistics. Weed Sci. 44:704–710.

Johnson, G. A., D. A. Mortensen, L. J. Young, and A. R. Martin. 1995. The stability of weed seedling population models and parameters in eastern Nebraska corn (*Zea mays*) and soybean (*Glycine max*) fields. Weed Sci. 43:604–611.

Khedir, K. D. and F. W. Roeth. 1981. Velvetleaf (*Abutilon theophrasti*) seed populations in six continuous-corn (*Zea mays*) fields. Weed Sci. 29: 485–490.

Martin, A. R., D. A. Mortensen, and N. Burchell. 1994. Visual and photographic assessment of herbicide efficacy trials for use in bioeconomic modeling. Proc. Weed Sci. Soc. Am. 34:117.

Mortensen, D. A., L. G. Higley, J. A. Dieleman, J. L. Lindquist, and D. L. Holshouser. 1998. Ecological principles underlying integrated weed management systems. Proc. Weed Sci. Soc. Am. 38:13.8.

Mortensen, D. A., G. A. Johnson, D. Y. Wyse, and A. R. Martin. 1995. Managing spatially variable weed populations. Pages 397–415 *in* Site-Specific Management for Agricultural Systems. Madison, WI: ASA-CSSA-SSSA.

Mortensen, D. A., G. A. Johnson, and L. J. Young. 1993. Weed distribution in agricultural fields. Pages 113–124 *in* Soil Specific Crop Management. Madison, WI: ASA-CSSA-SSSA.

Nagashima, H., I. Terashima, and S. Katoh. 1995. Effects of plant density on frequency distributions of plant height in *Chenopodium album* stands: analysis based on continuous monitoring of height-growth of individual plants. Ann. Bot. 75:173–180.

O'Sullivan, J. and W. J. Bouw. 1993. Reduced rates of postemergence herbicides for weed control in sweet corn (*Zea mays*). Weed Technol. 7: 995–1000.

Pacala, S. W. and J. A. Silander, Jr. 1985. Neighborhood models of plant population dynamics. I. Single species models of annuals. Am. Nat. 125:385–411.

Pannell, D. J. 1990. Model of wheat yield response to application of diclofop-methyl to control rigid ryegrass (*Lolium rigidum*). Crop Prot. 9:422–428.

Rasmussen, I. A. 1993. Seed production of *Chenopodium album* in spring barley sprayed with different herbicides in normal to very low doses. Pages 639–646 *in* Proceedings of the 8th EWRS Symposium "Quantitative approaches to weed and herbicide research and their practical application." Wageningen, Netherlands: EWRS.

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

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

Teo-Sherrell, C.P.A. 1996. The Fates of Weed Seeds. Ph.D. dissertation. University of Nebraska, Lincoln, NE. 173 p.

Thrall, P. H., S. W. Pacala, and J. A. Silander, Jr. 1989. Oscillatory dynamics in populations of an annual weed species *Abutilon theophrasti*. J. Ecol. 77:1135–1149.

Weiner, J. and S. C. Thomas. 1986. Size variability and competition in plant monocultures. Oikos 47:211–222.

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

Willson, M. F., P. A. Thomas, W. G. Hoppes, P. L. Katusic-Malmborg, D. A. Goldman, and J. L. Bothwell. 1987. Sibling competition in plants: an experimental study. Am. Nat. 129:304–311.

Wilson, B. J. and H. M. Lawson. 1992. Seedbank persistence and seedling emergence of seven weed species in autumn-sown crops following a single year's seeding. Ann. Appl. Biol. 120:105–116.

Winkle, M. E., J.R.C. Leavitt, and O. C. Burnside. 1981. Effects of weed density on herbicide absorption and bioactivity. Weed Sci. 29:405–409.

Wyse, D. Y. 1996. Characterizing the Stability of Weed Seedling Populations. M.S. thesis. University of Nebraska, Lincoln, NE. 122 p.

Received April 1, 1998, and approved October 13, 1998.