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Approaches to crop production that successfully reduce weed seed production can benefit farming systems by reducing management inputs and costs. A 5-yr rotation study was conducted in order to determine the effects that interactions between crop rotation, tillage, and amount of herbicide and fertilizer (management inputs) have on annual grass and broad-leaved weed seed production and fecundity. There were 10 crop rotation and tillage system combinations and three levels of management inputs (high, medium, and low). Green and yellow foxtail were the major weed species, and together they yielded between 76 and 93% of collected weed seeds. From 1990 to 1994, average grass weed seed productions were 7.3 by 10^3, 3.7 by 10^3, 6.1 by 10^3, and 5.7 by 10^3 seeds m^{-2}, whereas average broad-leaved weed seed productions were 0.4 by 10^3, 0.4 by 10^3, 1.4 by 10^3, and 0.4 by 10^3 seeds m^{-2} in crop rotations using conventional tillage (moldboard plow), conservation tillage, no tillage, and ridge tillage, respectively. Crop rotations using conventional or ridge tillage consistently produced more grass and broad-leaved weed seeds, especially in low-input plots. There was little difference in weed seed production among input levels for crop rotations using conservation tillage. Comparing rotations that began and ended with a corn crop revealed that by increasing crop diversity within a rotation while simultaneously reducing the amount of tillage, significantly fewer grass and broad-leaved weed seeds were produced. Among the rotations, grass and broad-leaved weed fecundity were highly variable, but fecundity declined from 1990 to 1994 within each rotation, with a concomitant increase in grass and broad-leaved weed density over the same period. Crop rotation in combination with reduced tillage is an effective way of limiting grass and broad-leaved weed seed production, regardless of the level of management input applied.

Nomenclature: Corn, *Zea mays* L. 'Pioneer 3769'; soybean, *Glycine max* (L.) Merr. 'Pioneer 9171'; wheat, *Triticum aestivum* L. 'Butte 86,' 'Guard'; alfalfa, *Medicago sativa* L. 'Coyote 999'; intermediate wheatgrass, *Elytrigia intermedia* (Host) Nevski subsp. 'Oake'; orchardgrass, *Dactylis glomerata* L. 'Benchmark'; creeping foxtail, *Alopecurus arundinaceus* Poiret 'Retain'; switchgrass, *Panicum virgatum* L. 'Sunburst'; big bluestem, *Andropogon gerardii* Vitam var. *gerardii* 'Bonilla'; green foxtail, *Setaria viridis* (L.) Beauv.; yellow foxtail, *Setaria glauca* (L.) Beauv.

Key words: Crop rotation, tillage, management inputs, grass weeds, broad-leaved weeds, weed density, seed production, fecundity, SETLU, SETVI, AMBEL, CHEAL, POLPY.

Despite management efforts, many weeds escape control and produce seeds that replenish seedbanks and increase the potential for future weed infestations. Seed production from weed escapes accounts for the majority of those seeds incorporated into the seedbank each year (Forcella et al. 1996a; Norris 1996b). High seedbank populations can ultimately lead to high weed densities; it may require several years of intensive management to minimize the problem associated with these densities. Therefore, approaches to crop production that successfully minimize the number of weed seeds entering the seedbank will benefit farming systems by reducing subsequent management needs and input costs.

Typically, seasonal weed emergence from the seedbank can range from 0.1 to 30% (Forcella 1992). Consequently, crop production systems are dependent on management options that successfully reduce the effect that weeds have on crops. One such option, crop rotation, can reduce weed infestations while maintaining or increasing crop yields (Gantzer et al. 1991; Mitchell et al. 1991). In crop rotations, different attributes of crops (i.e., varying patterns of resource competition, allelopathic interference, soil disturbance, and mechanical damage) are combined to create an inhospitable environment that prevents proliferation of some weed species (Liebmann and Dyck 1993).

Tillage, another management option, is an important component of many crop production systems. Tillage can effectively control weeds, but this process increases labor and fuel requirements as well as soil erosion when compared with other systems (Mannering et al. 1987). However, reduced tillage systems rely heavily on herbicides for weed control (Buhler 1995), and, therefore, they may be less economically sustainable. Some tillage operations can cause weeds to emerge and thrive at a time when applying additional control measures will not be economically justifiable or effective. For example, Forcella and Lindstrom (1988) found that additions to the seedbank were supplied by weeds, the germination of which was stimulated by the ridging operation in ridge tillage systems, thereby causing 10-fold greater germination and 140-fold greater seed production than are created with conventional tillage.

Aside from tillage, fertilizers and herbicides continue to be important management inputs in annual crop production systems. Though fertilizers can enhance crop yields (Di Tomaso 1995; Wicks et al. 1995), they can also increase weed density and biomass (Carlson and Hill 1986), thereby resulting in higher weed seed production (Zanin and Sattin 1987). In his review, Di Tomaso (1995) provides evidence that at high soil-nutrient levels, weeds can accumulate more nutrients and, consequently, can be more competitive than corresponding crops. However, through manipulation of the fertilization strategy, the competitive ability of crops can be enhanced (Di Tomaso 1995). Herbicides reduce weed densities and indirectly reduce weed seeds that are produced and enter the seedbank. Although herbicides are effective in controlling weeds, increasing environmental awareness (including evolution of resistance) has created a desire to reduce the amount of herbicides applied to agricultural fields. However, reduced herbicide inputs may lead to increased weed escapes and weed seed production, which may in turn magnify crop management problems in future years.

Weed seed production in crops has previously been ignored but is now gaining in importance because of our need to understand weed fecundity (Norris 1992, 1996a, 1996b). Weed seed production can be reduced by management factors, although a few weed escapes can produce enough seed to replenish weed seedbanks (Hartzler 1996). Because weeds are prolific seed producers (Stevens 1957), elimination of weed seed production for a few years can lead to the incorporation of fewer weed seeds into the seedbank (Burnside et al. 1986; Hartzler 1996; Schweizer and Zimdahl 1984). Therefore, weed-management techniques that reduce weed seed production are desirable and need to be investigated in order to provide new approaches to weed management. For example, information on the effects of management practices on weed seed production and weed fecundity is essential for the development of weed-management decision aids (Buhler et al. 1997).

Weed-management decision aids are population models that incorporate weed biology into the decision-making process in order to reduce herbicide use while maintaining weed control and increasing economic returns (Buhler et al. 1997). For example, WEEDSIM (Forcella et al. 1996b; Swinton and King 1994) requires weed fecundity estimates to predict future weed infestations so that current management recommendations maximize long-term economic returns. WEEDSIM is a decision aid that uses seed production levels, in conjunction with other weed-biology parameters (seedbanks, emergence times, and competitive abilities), to determine the weed-management strategy that maximizes profit for the farmer after taking into account such variables as expected crop yield, commodity price, management costs, weed-crop competition, and so forth (Forcella et al. 1996b; Swinton and King 1994). We can insert different plant parameter values into this software program and observe the sensitivity of the recommendations to varying fecundities. Unfortunately, little information exists on weed seed production and fecundity within crop rotations. Such information will provide answers as to whether crop rotations can reduce weed seed production and fecundity and can, therefore, be a viable option for seedbank management. This study was conducted in order to determine the effects of crop rotation, tillage, and management inputs of herbicide and fertilizer on grass and broad-leaved seed production and weed fecundity.

Materials and Methods

The study was established in 1990 as a long-term rotation experiment and was continued through 1994 at the Eastern South Dakota Soil and Water Research Farm near Brookings, SD, on a well-drained, gently sloping (1 to 5%) Vienna loam (Udic Haploboroll, fine-loamy, mixed) soil with a pH of 6.5 and 3.5% organic matter. The crop rotation/tillage system treatments (rotations) were as follows: continuous corn/moldboard plow (CCCCC-mp); corn–soybean/moldboard plow (CSCSC-mp); soybean–corn/moldboard plow (SCSCS-mp); corn–soybean–wheat–alfalfa/conservation tillage (CSWAC-ct); soybean–wheat–alfalfa–corn/conservation tillage (SWACS-ct); wheat–alfalfa–corn–soybean/conservation tillage (WACSW-ct); alfalfa–corn–soybean–wheat/conservation tillage (ACSWA-ct); continuous grass/no tillage (GGGGG-nt); corn–soybean/ridge tillage (CSCSC-rt); and soybean–corn/ridge tillage (SCSCS-rt). Three levels of fertilizer and herbicide (management inputs) were included, and they can be described as follows: (1) "low input," with no chemical fertilizers or pesticides, except for "low-input" soybean plots that were treated with herbicides at 25% of the recommended label rate (Table 1); (2) "medium input," with one-half the recommended rates of fertilizer and herbicide; and (3) "high input," which was fertilized for maximum Brookings County, SD, target yields, and treated with pre- and postemergence herbicides and with soil insecticide (for insect control) when necessary.

The experiment contained a split-plot design with three replications. Main plot treatments were the rotation/tillage systems, and management input was the subplot. Each subplot was 30 by 30 m. The same tillage treatments were applied to the same whole plot each year. Moldboard plow plots were plowed (20 cm deep) in autumn and disked twice in spring prior to planting of corn or were chisel-plowed (20 cm deep) in autumn and disked twice in spring prior to planting of soybeans. Conservation tillage plots were chisel-plowed (20 cm deep) in autumn and disked twice in spring (15 cm deep) prior to planting of corn, soybeans, and wheat. Ridge tillage plots were cultivated twice after planting corn and soybeans, and ridges were built with the second cultivation. Ridges were truncated each year during planting by clearing disks that preceded a commercially available no-till planter.

Crop Establishment and Maintenance

Corn

All corn subplots were seeded at the rate of 20 kg ha^{-1} (65,000 seeds ha^{-1}). Application of herbicides (for weed control) to high-input, medium-input, and low-input subplots is shown in Table 1. Based on soil tests, starter fertilizer was applied at planting in high-input and medium-input subplots, whereas nitrogen (N) was incorporated as a side dress with the second cultivation (Table 2). No herbicides or fertilizers were applied in the low-input subplots, and

Table 1. Preemergence (pre) and postemergence (post) herbicides applied to high, medium, and low input plots of wheat, alfalfa, corn, soybeans, and grass during the experimental period (1990–1994) at Brookings, SD.

		High-input plots		Medium-input plots		Low-input plots	
Crop	Year	Herbicide	Application rate[a]	Herbicide	Application rate[a]	Herbicide	Application rate[a]
Corn	1990	Alachlor + Atrazine (pre)[b]	1X	Alachlor + Atrazine (pre)[b]	½X	—	—
		Alachlor + Cyanazine (pre)	1X	Alachlor + Cyanazine (pre)	½X		
	1991	Alachlor + Atrazine (pre)[b]	1X	Alachlor + Atrazine (pre)[b]	½X	—	—
		Alachlor + Cyanazine (pre)	1X	Alachlor + Cyanazine (pre)	½X		
		Bromoxynil (post)	1X	Bromoxynil (post)	½X		
	1992	Alachlor + Cyanazine (pre)	1X	Alachlor + Cyanazine (pre)	½X	—	—
		Bromoxynil (post)	1X				
	1993	Alachlor + Cyanazine (pre)	1X	Nicosulfuron (post)	½X	—	—
	1994	Alachlor + Cyanazine (pre)	1X	Cyanazine (post)	½X	—	—
Soybean	1990	Alachlor + Metribuzin (pre)	1X	Alachlor + Metribuzin (pre)	½X	—	—
	1991	Alachlor + Metribuzin (pre)	1X	Alachlor + Metribuzin (pre)	½X	Bentazon (post)	¼X
		Bentazon (post)	1X	Bentazon (post)	½X		
	1992	Alachlor (pre)	1X	Alachlor (pre)	½X	Bentazon (post)	¼X
		Bentazon + Acifluorfen (post)	1X	Bentazon + Acifluorfen (post)	½X		
	1993	Alachlor + Metribuzin (pre)	1X	Bentazon (post)	½X	Bentazon (post)	¼X
		Bentazon (post)	1X				
	1994	Flumetsulam + Metolachlor (pre)	1X	Thifensulfuron (post)	½X	Thifensulfuron (post)	¼X
		Thifensulfuron + Bentazon (post)	1X				
Wheat[c]	1990–1994	MCPA (post)	1X	MCPA (post)	½X	—	—
Alfalfa[d]	1990	MCPA (post)	1X	MCPA (post)	½X	—	—
Grass[e]	1990	2,4-D (post)	1X	2,4-D (post)	½X	2,4-D (post)	¼X

[a] 1X = recommended label rate; ½X = 50% of recommended label rate; ¼X = 25% of recommended label rate.
[b] Alachlor + atrazine applied in 1990 and 1991 to continuous corn only.
[c] MCPA applied to wheat plots from 1990 to 1994.
[d,e] Herbicide applied to alfalfa and grass plots in the year of establishment (1990) only.

TABLE 2. Fertilizer type and amount applied to each crop within the high and medium input subplots within each rotation at planting (P) or as a topdress (TD) from 1990 to 1994 at Brookings, SD.

		High-input plots		Medium-input plots	
Crop	Year	Fertilizer (% N-P-K)	Rate (kg ha^{-1})	Fertilizer (% N-P-K)	Rate (kg ha^{-1})
Corn	1990–1994	13-33-13 (P)	110	13-33-13 (P)	55
	1990	46-0-0 (TD)	222	46-0-0 (TD)	111
	1991	46-0-0 (TD)	140	46-0-0 (TD)	70
	1992	46-0-0 (TD)	82	46-0-0 (TD)	41
	1993	46-0-0 (TD)	122	46-0-0 (TD)	61
	1994	46-0-0 (TD)	96	46-0-0 (TD)	48
Soybeans	1990–1994	13-33-13 (P)	110	13-33-13 (P)	52
Wheat	1990	46-0-0 (P)	100	46-0-0 (P)	50
	1991–1992	46-0-0 (P)	116	46-0-0 (P)	58
	1993	46-0-0 (P)	102	46-0-0 (P)	51
	1994	46-0-0 (P)	90	46-0-0 (P)	45
Alfalfa	1990	0-45-0 (P)	72	0-45-0 (P)	36
	1991–1994	—[a]	—	—	—
Grass	1990–1994	—	—	—	—

[a] Dashes indicate no fertilizer applied to plots.

weeds were controlled with one pass of a rotary hoe and two cultivations.

Soybeans

All soybean subplots were seeded at the rate of 70 kg ha^{-1} (300,000 seeds ha^{-1}). Application of herbicides for weed control in the differing input subplots is shown in Table 1. Based on soil tests, fertilizers were applied at planting to high-input and medium-input subplots (Table 2). No fertilizers were applied to low-input subplots, and weeds were controlled with one rotary hoeing, two cultivations, and occasional postemergence herbicide applications at 25% of the recommended label rate (Table 1).

Wheat and Alfalfa

Apart from 1990, the year of establishment, wheat was always underseeded with alfalfa. In 1990, 1992, 1993, and 1994, 'Butte 86' wheat seed was seeded, whereas in 1991, 'Guard' wheat was seeded, both at about 100 kg ha^{-1}. In all years, 'Coyote 999' alfalfa was seeded at 12 kg ha^{-1}. The subplots were harrowed after seeding in order to cover the alfalfa seed. For weed control, herbicides were applied to high-input and medium-input wheat subplots each year and only in the year of establishment in alfalfa subplots (Table 1). Starter N fertilizer was applied to high-input and medium-input wheat subplots each year, whereas high-input and medium-input alfalfa subplots were fertilized once in 1990, the year of establishment (Table 2).

Continuous Grass

The designation of high-, medium-, and low-input levels for the continuous grass treatments was somewhat arbitrary. It was based on the expected cost of seed and on the anticipated levels of management that would be required for long-term maintenance. The high-input subplot was seeded with a mixture of three cool-season grasses in equal portions: intermediate wheatgrass, orchardgrass, and creeping foxtail. The medium-input subplot was seeded with equal portions of warm-season grasses: switchgrass and big bluestem. The low-input subplot was seeded with equal portions of cool- and warm-season grasses. Weeds were controlled with one herbicide application in the year of establishment (Table 1), and no fertilizers were applied. An early-season burn of all grass subplots was performed in 1994 in order to prevent the buildup of perennial weeds.

Weed Seed Production and Fecundity

During the course of this study, 1991 was the driest and warmest year, whereas 1993 was the wettest year. As a consequence of the wet and cool conditions in 1993, there was an abundance of weed growth, especially in low-input plots, that necessitated roguing of plants to facilitate timely management operations and harvesting of crops. Roguing was accomplished prior to seed set and establishment of seed traps. Most perennials (e.g., Canada thistle [*Cirsium arvense* (L.) Scop.]) and large problematic broad-leaved annuals that were not uniformly distributed within the experimental area [e.g., annual sunflower (*Helianthus annuus* L.)] were removed.

Weed seed production was measured by placing six seed traps along a diagonal line in the central portion of each plot, as outlined previously (Forcella et al. 1996c). In 1990, a rectangular 3.8-by-76–cm flat wooden board was used. Its top side was coated with a nontoxic, resinlike adhesive, which stayed tacky even after long periods of rain. In 1991, the trap was a circular petri dish with a 9-cm diameter and 0.5-cm side walls, coated with adhesive on the inside bottom. In 1992, 1993, and 1994, a circular plastic cup, with a 10-cm–diameter opening at the top and a 10-cm height, was used. Holes were cut in the bottom for drainage, above which a brass mesh screen was inserted to retain seeds. A wooden stake was attached for support in the soil, and the top rim of the cup was about 10 to 15 cm above the soil surface. Although some error may be attributed to changes in seed-trap design across the years (Forcella et al. 1996c), this potential error cannot account for the large differences and trends in seed production observed among years (see below).

Traps were placed in the subplots in early August, before the beginning of seed shedding (Forcella et al. 1996c). Traps

Table 3. Grass and broadleaf weed species present in the experimental area from 1990 to 1994 for weed seeds that were collected at Brookings, SD.

Year	Grass weed species[a]	Broadleaf weed species[b]
1990	ECHCG, SETLU, SETVI	AMARE, AMBEL, CHEAL, POLPY
1991	SETLU, SETVI	AMARE, AMBEL, CHEAL, HELAN, IPOHE, POLPY
1992	SETLU, SETVI,	AMARE, AMBEL, CHEAL, HELAN, IPOHE, POLCO, POLPY, XANST
1993	SETLU, SETVI	AMARE, AMBEL, CHEAL, HELAN, IPOHE, POLCO, POLPY, XANST
1994	ECHCG, SETLU, SETVI,	AMARE, AMBEL, CHEAL, HELAN, IPOHE, POLCO, POLPY, XANST

[a] ECHCG, barnyardgrass (*Echinochloa crus-galli* L.); SETLU, yellow foxtail (*Setaria glauca* L.); SETVI, green foxtail (*Setaria viridis* L.).
[b] AMARE, redroot pigweed (*Amaranthus retroflexus* L.); AMBEL, common ragweed (*Ambrosia artemisiifolia* L.); CHEAL, common lambsquarters (*Chenopodium album* L.); HELAN, common sunflower (*Helianthus annuus* L.); IPOHE, entireleaf morning glory (*Ipomea hederacea* L.); POLCO, wild buckwheat (*Polygonum convolvolus* L.); POLPY, pennsylvania smartweed (*Polygonum pennsylvanicum* L.); XANST, common cocklebur (*Xanthium strumarium* L.).

remained in place until crop harvest, at which time they were moved from interrows to adjacent crop rows in order to trap seeds dispersed by the harvester and to avoid damage by the harvester's tires. We determined that this necessary movement of the traps did not alter the differential seed entrapment capabilities. After crop harvest, all seeds were identified by species (Table 3), separated into "viable" and "nonviable" categories, and counted. Nonviable seeds were those that crushed when probed with fine-tipped forceps, whereas viable seeds remained firm under pressure. Viable weed seed production per plant, or estimated fecundity, was calculated by dividing the total seasonal seed production (seeds m^{-2}) by the population density (plants m^{-2}) of grass and broad-leaved weeds that appeared in the subplots. Weed densities were determined in July of 1990, 1991, 1993, and 1994 within six 25-by-40–cm quadrats in each subplot. Each quadrat was centered on a separate crop row, thereby forming a diagonal transect across the subplot.

Daily rainfall and temperature data were collected at the nearby South Dakota Meteorological Station at Brookings, SD, from April 1 to October 31 of each year, and these data were used to determine monthly rainfall and to calculate cumulative growing degree days, using a base temperature of 10 C (Table 4).

Statistical Procedures

Analysis of variance was conducted on grass and broad-leaved weed seed production from 1990 to 1994, and plant fecundity estimates were conducted for 1990, 1991, 1993, and 1994, using the General Linear Model Procedure (SAS 1990). Main effects and interactions were examined, and means were compared using Fisher's Protected LSD Test ($P \leq 0.05$). Because there were significant interactions between year and rotations, data were not pooled.

Results and Discussion

Weed Seed Production

There were significant interactions between year and rotations as well as between rotations and management inputs for grass and broad-leaved weed seed production (Table 5). In 1990, the first year of the study, all rotations except ACSWC-ct and GGGGG-nt had low weed seed production that was due, in part, to low grass and broad-leaved weed densities (data not presented). From 1991 to 1994, there was a steady increase in grass and broad-leaved weed density. This increase in weed density was not uniform among different rotations, and annual grasses, particularly green and yellow foxtail, were more abundant than were broad-leaved weeds, yielding 76 to 93% of weed seeds collected in seed traps (Table 6). In contrast, the GGGGG-nt rotation had high grass and broad-leaved weed densities and seed production in 1990, with declines thereafter (Table 5).

Many grass weed seeds were produced in the CCCCC-mp, CSCSC-mp, SCSCS-mp, CSCSC-rt, and SCSCS-rt rotations, with peak weed seed production occurring in 1992 (Table 5). Fewer grass weed seeds were produced in the CSWAC-ct, SWACS-ct, WACSW-ct, and ACSWA-ct rotations, and no consistent trends were apparent (Table 5). In the GGGGG-nt rotation, there was high grass weed seed production in 1990, followed by a steady decline to 1992; insignificant amounts of weed seeds were produced in 1993 and 1994 (Table 5). In all rotations, broad-leaved weed seed production was much lower than that of grasses

Table 4. Monthly rainfall and cumulative growing degree days (GDD; base temperature 10 C) from April 1 to October 31 for 1990 to 1994 at Brookings, SD.

	1990		1991		1992		1993		1994	
Month	Rain (cm)	GDD	Rain (cm)	GDD	Rain (cm)	GDD	Rain (cm)	GDD	Rain (cm)	GDD
April	2.3	57	9.1	41	3.2	19	5.5	5	4.3	25
May	12.6	140	9.3	237	4.0	177	12.2	105	4.0	202
June	15.4	415	10.0	587	2.7	394	23.0	305	21.1	474
July	9.3	726	6.2	931	19.5	604	12.4	617	6.5	763
August	7.1	1,037	5.3	1,270	10.2	830	6.5	931	8.9	1,025
September	1.2	1,250	5.8	1,435	13.6	959	6.2	1,010	6.4	1,210
October	6.2	1,273	1.8	1,462	5.2	1,007	0.7	1,034	4.2	1,250
Total	54.1	NA[a]	47.5	NA	58.4	NA	66.5	NA	55.4	NA

[a] NA, not applicable.

TABLE 5. Grass and broadleaf weed seed production within the 10 crop rotation–tillage systems as influenced by management inputs from 1990 to 1994 at Brookings, SD.

Rotation–tillage system[a]	Management inputs	Grass weed seed production[b] (seed production m^{-2})					Broadleaf weed seed production[c] (seed production m^{-2})				
		1990	1991	1992	1993	1994	1990	1991	1992	1993	1994
CCCCC-mp	High	205	143	260	14	171	24	26	28	7	57
	Medium	435	6,758	8,225	984	1,596	54	0	1,095	1,463	2,064
	Low	2,525	8,568	36,168	9,402	6,026	161	3,854	1,413	569	2,365
CSCSC-mp	High	332	156	1,202	190	57	244	0	421	0	7
	Medium	940	2,917	5,422	2,222	1,090	570	13	253	119	7
	Low	1,358	12,656	40,422	5,570	17,851	349	234	267	253	0
SCSCS-mp	High	2,576	52	295	74	42	35	0	35	0	7
	Medium	922	1,250	9,754	1,066	29,327	63	13	42	74	14
	Low	5,511	16,185	49,142	9,494	33,445	140	794	879	285	64
CSWAC-ct	High	1,664	729	4,114	9,599	256	450	26	458	2,531	306
	Medium	452	143	3,657	5,960	997	362	13	63	169	35
	Low	786	8,620	6,533	4,177	7,137	569	403	795	253	64
SWACS-ct	High	898	742	56	35	86	216	1,341	35	7	0
	Medium	3,954	4,636	225	288	42,078	635	1,706	91	393	406
	Low	2,335	4,883	147	2,820	15,184	400	1,680	35	351	54
WACSW-ct	High	3,752	26	2,314	127	—	446	13	126	7	—
	Medium	4,150	65	7,293	541	—	894	13	2,397	28	—
	Low	4,716	0	1,997	4,082	—	847	13	499	21	—
ACSWA-ct	High	14,464	143	2,269	1,174	228	675	0	7	119	0
	Medium	20,223	638	2,925	1,941	221	255	0	91	0	7
	Low	6,777	1,732	15,999	1,238	164	477	91	91	0	0
GGGGG-nt	High	15,624	8,438	204	0	0	831	11,368	4,268	0	7
	Medium	34,360	1,159	0	0	157	1,843	260	7	0	0
	Low	31,280	273	169	0	14	2,167	0	155	0	7
CSCSC-rt	High	524	1,758	2,454	1,582	612	108	65	7	21	107
	Medium	1,497	4,063	14,592	6,238	4,766	370	26	2,518	154	11
	Low	1,873	8,750	15,162	5,267	10,065	198	195	436	126	14
SCSCS-rt	High	365	169	176	21	477	13	13	63	0	7
	Medium	1,537	1,849	9,944	2,595	11,718	122	0	232	1,948	1,318
	Low	4,043	14,857	26,762	6,667	9,503	306	78	204	1,526	2,821

[a] CCCCC-mp, continuous corn—moldboard plow; CSCSC-mp, corn-soybean—moldboard plow; SCSCS-mp, soybean-corn—moldboard plow; CSWAC-ct, corn-soybean-wheat-alfalfa—conservation till; SWACS-ct, soybean-wheat-alfalfa-corn—conservation till; WACSW-ct, wheat-alfalfa-corn-soybean—conservation till; ACSWA-ct, alfalfa-corn-soybean-wheat—conservation till; GGGGG-nt, continuous grass—no till; CSCSC-rt, corn-soybean—ridge till; SCSCS-rt, soybean-corn—ridge till.

[b] For grass weed seed production, LSD (0.05) for each year was as follows: 1990, 1,521; 1991, 988; 1992, 2,097; 1993, 414; 1994, 1,316.

[c] For broadleaf weed seed production, LSD (0.05) for each year was as follows: 1990, 154; 1991, 539; 1992, 403; 1993, 202; 1994, 253.

and did not follow any particular trend, except in the GGGGG-nt rotation, in which broad-leaved weed seed production was high from 1990 to 1992 (similar to grass weed seed production) and declined thereafter (Table 5). Continuous grass production systems can be managed for pasture or hay, and because they are not cultivated and harvested frequently, they present an environment that prevents the establishment and seed production of annual weeds (Liebman and Dyck 1993). However, incorporating them into a rotation for the sole purpose of minimizing weed problems requires a significant period of time—at least 3 yr, as in our case.

TABLE 6. Grass, broadleaf, and other weed seeds as percentage of total amount of seeds collected and various species as percentage of total amount of seeds collected from 1990 to 1994 in the experimental area at Brookings, SD.

	Year				
	1990	1991	1992	1993	1994
Type of seed (%)					
Grass	92	84	93	76	94
Broadleaf	5	13	6	13	5
Other[a]	3	3	1	11	1
Species of seed (%)					
Foxtail	91	84	93	76	92
Common ragweed	2	3	<1	5	3
Pennsylvania smartweed	2	<1	<1	<1	1
Common lambsquarters	<1	9	4	7	<1

[a] Other weed seeds include mostly perennial weed species or annuals that were not uniformly distributed within the experimental area.

In most cases, the application of high management inputs resulted in significant reductions in grass and broad-leaved weed seed production within the CCCCC-mp, CSCSC-mp, SCSCS-mp, CSCSC-rt, and SCSCS-rt rotations (Table 5). Additionally, in these rotations, the application of high management inputs was necessary in order to maintain grass and broad-leaved weed seed production at their lowest levels from 1990 and 1994, compared with application of medium and low management inputs (Table 5). In contrast, the application of high management inputs within the CSWAC-ct, SWACS-ct, WACSW-ct, and ACSWA-ct rotations did not always result in lower grass and broad-leaved weed seed production, in comparison with application of medium and low management inputs (Table 5).

Reduced tillage, in combination with crop rotation, interacted with management inputs and provided for a unique trend in grass and broad-leaved weed seed production. For instance, within the CCCCC-mp, CSCSC-mp, and SCSCS-mp rotations, grass and broad-leaved weed seed production increased as management inputs were decreased (Table 5). In comparison, similar increases (but of lower magnitude) in grass and broad-leaved weed seed production were observed with the CSCSC-rt and SCSCS-rt rotations when management inputs were reduced. Further reductions in tillage, concomitant with increases in the diversity of crops within a rotation (as with the CSWAC-ct, SWACS-ct, WACSW-ct, and ACSWA-ct rotations), resulted in insignificant increases in grass and broad-leaved weed seed production when management inputs were reduced (Table 5).

There was a substantial decrease in grass weed seed production in 1993, particularly with crop rotations under moldboard plow and ridge tillage systems. This decline appears to have been largely the result of the cooler and wetter conditions that prevailed during that year (Table 4), conditions that may have delayed seed maturity long enough to reduce the number of viable seeds produced at the time of combine harvesting and seed collection.

The importance of management inputs is further illustrated when comparing rotations that use corn as the first and last crop within the rotation (CCCCC-mp, CSCSC-mp, CSCSC-rt, and CSWAC-ct). In these rotations, the application of high and medium management inputs helped maintain grass and broad-leaved weed seed production at their lowest levels (Figure 1). However, the application of low management inputs resulted in a significant increase in grass weed seed production in the intensively tilled rotations (CCCCC-mp and CSCSC-mp) (Figure 1). Similarly, broad-leaved weed seed production increased significantly as inputs were reduced, particularly in the case of the CCCCC-mp rotation (Figure 1). Consequently, this suggests that reducing tillage while increasing the diversity of crops within a rotation can result in significant reductions in grass and broad-leaved weed seed production, especially when low management inputs are to be used.

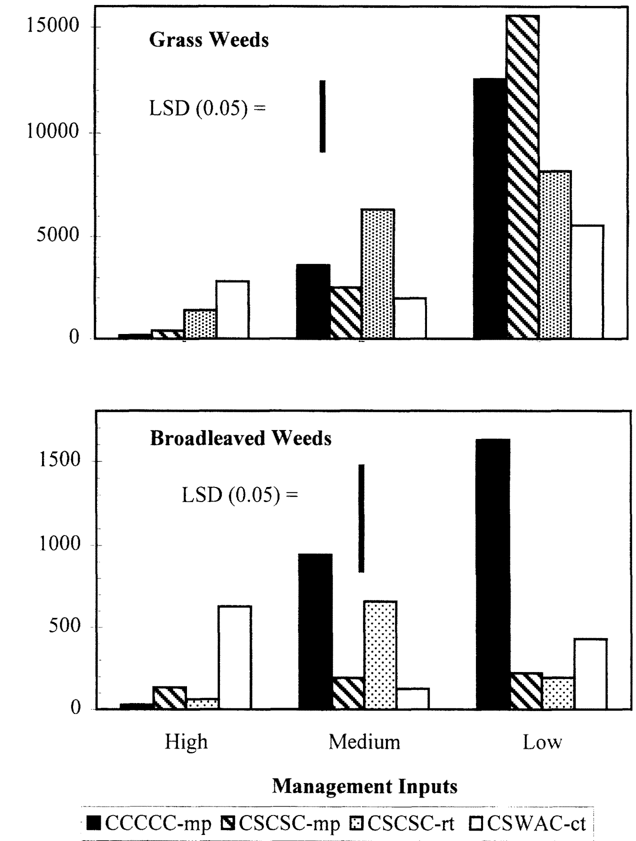

FIGURE 1. Influence of management inputs on grass and broad-leaved weed seed production in CCCCC-mp, CSCSC-mp, CSWAC-ct, and CSCSC-rt rotations at Brookings, SD. Least significant differences (LSDs) were based on Fisher's Protected LSD test ($P \leq 0.05$).

Weed Fecundity

A significant interaction between rotation and year of experiment was evident for grass and broad-leaved weed fecundity (Table 7). Weed seed production is related to weed density, whereby seed production initially increases with increasing weed density, after which a plateau is reached, and, subsequently, a decline in seed production occurs (Cardina et al. 1995; Fausey et al. 1997). Consequently, as weed density increases, there is a decrease in fecundity (Zanin and Sattin 1987). In general, our study supports these findings by showing a decline in weed fecundity from 1990 to 1994, particularly after 1992 (Table 7), despite increases in weed density (data not shown) and weed seed production (Table 5). Although weed seed production possibly reached a plateau in 1992 and started to decline in 1993 (Table 5), it is also likely that the cooler and wetter conditions that occurred in 1993 (Table 4) lowered seed production.

Weed fecundity estimates obtained from this study were highly variable among the rotations, although fecundity of individual plants decreased between 1990 and 1994 in a majority of the rotations (Table 7). Reliable and accurate information on weed seed production by individual plants is necessary for the development of long-term weed-management strategies that are ecologically based (Norris 1996b). For instance, relationships have been developed between inflorescence size and seed production in barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (Norris 1992) and in giant (*Setaria faberi* Herrm.), green, and yellow foxtail (Barbour and Forcella 1993), relationships that offer new approaches to estimating weed seed production. However, because of the variation in fecundity estimates in our study, further research is necessary in order to provide more accurate estimates of seed production by weeds subjected to competition from crop plants so that more accurate long-term predictions related to the population dynamics of weeds can be made.

TABLE 7. Estimated fecundities of grass and broadleaf weeds within the 10 crop rotation–tillage systems from 1990 to 1994 at Brookings, SD.

Rotation–tillage system[a]	Grass weed fecundity[b] (seed production plant^{-1})					Broadleaf weed fecundity[c] (seed production plant^{-1})				
	1990	1991	1992[d]	1993	1994	1990	1991	1992[d]	1993	1994
CCCCC-mp	239	1,716	—	6	8	42	410	—	144	20
CSCSC-mp	284	148	—	68	68	351	50	—	36	5
SCSCS-mp	1,111	92	—	13	9	79	22	—	4	9
CSWAC-ct	347	325	—	2	6	212	64	—	57	22
SWACS-ct	1,650	269	—	12	9	396	138	—	7	10
WACSW-ct	111	1	—	9	—	77	6	—	14	—
ACSWA-ct	612	47	—	0	0	42	27	—	2	0
GGGGG-nt	408	77	—	0	0	348	96	—	0	2
CSCSC-rt	781	2,623	—	9	4	171	95	—	18	46
SCSCS-rt	594	373	—	6	10	89	30	—	29	250

[a] CCCCC-mp, continuous corn—moldboard plow; CSCSC-mp, corn-soybean—moldboard plow; SCSCS-mp, soybean-corn—moldboard plow; CSWAC-ct, corn-soybean-wheat-alfalfa—conservation till; SWACS-ct, soybean-wheat-alfalfa-corn—conservation till; WACSW-ct, wheat-alfalfa-corn-soybean—conservation till; ACSWA-ct, alfalfa-corn-soybean-wheat–conservation till; GGGGG-nt, continuous grass—no till; CSCSC-rt, corn-soybean—ridge till; SCSCS-rt, soybean-corn—ridge till.

[b] For grass weed fecundity, LSD (0.05) for each year was as follows: 1990, 540; 1991, 771; 1993, 12; 1994, 25.

[c] For broadleaf weed fecundity, LSD (0.05) for each year was as follows: 1990, 103; 1991, 150; 1993, 60; 1994, 97.

[d] Weed density data were not collected in 1992.

Fecundity estimates have important management implications. For example, the weed-management decision aid WEEDSIM (Swinton and King 1994) uses fecundity estimates to generate current-season management recommendations that maximize economic returns over the course of two or more growing seasons. However, these recommendations may change appreciably depending upon the magnitude of the fecundity estimate. This can be illustrated by using either the "Soil-Applied" or "Postemergence" versions of WEEDSIM. For example, assume that soybean is sown in mid-May, that its weed-free yield is about 2 Mg ha^{-1}, and that the seedbank of the sole competing weed, green foxtail, is 500 seeds m^{-2}. If green foxtail fecundity was < 115 seeds plant^{-1}, then timely rotary hoeing plus interrow cultivation would be WEEDSIM's only recommendation. However, if fecundity was > 115 seeds plant^{-1}, then WEEDSIM recommends trifluralin at 1 kg ai ha^{-1}, followed by interrow cultivation.

The Postemergence version of WEEDSIM reacts similarly to changes in fecundity. Assume here that a soybean crop will compete with a green foxtail population of 50 seedlings m^{-2}. If total foxtail fecundity is ≤ 75 seeds plant^{-1}, then WEEDSIM recommends only interrow cultivation, but if fecundity is > 75 seeds plant^{-1}, then the recommendation is that sethoxydim be applied at 0.3 kg ai ha^{-1}, followed by interrow cultivation. In both the Soil-Applied and Postemergence versions of WEEDSIM, the intensity of recommended control increases as fecundity increases. This occurs because higher fecundities of escaped weeds are projected to create greater and more expensive control problems in subsequent crops. Accordingly, WEEDSIM recommends higher levels of control in the current crop in order to eliminate major problems in succeeding years. The appreciable changes in recommended control options based on fecundity demonstrate the importance of this dynamic variable in weed-management decisions.

The use of crop rotations can result in lower densities of emerged weeds and in lower weed seed densities than are present in monocultures (Liebman and Dyck 1993). The reduction in weed density within crop rotations appears to be based on the use of crop sequences that create varying patterns that provide an environment that is not conducive to the survival of some weed species. For instance, in CSWAC-ct, SWACS-ct, WACSW-ct, and ACSWA-ct rotations, grass and broad-leaved weed seed production was lowest when alfalfa was the crop in rotation, except for during 1990, the year of establishment of the study, and during 1993, a relatively wet and cool year. In conservation tillage rotations, at least 30% of the plant residue from the previous crop is retained on the soil surface until after the succeeding crop is planted (Buhler 1995), and during our study, the crop preceding alfalfa in all cases was wheat. Wheat straw has been identified as having allelopathic compounds that inhibit seed germination and seedling growth for some weed species (Schreiber 1992; Steinsiek et al. 1982). Alfalfa residue has also been shown to possess allelochemicals that are capable of suppressing the seedling growth of some weed species (Chung and Miller 1995; Miller 1996; Weston 1996). The wheat and alfalfa crops may have worked individually or in tandem to reduce grass weed seed production significantly within the corn crop that followed alfalfa in the conservation tillage rotations, compared with corn crops under moldboard plow and ridge tillage systems (Table 5). Furthermore, the harvest schedules of both alfalfa and spring wheat preceded seed maturation of many species of weeds observed in this study. Thus, alfalfa cutting and baling and spring wheat combining, both of which took place in early August, may have disrupted seed development and reduced seed production of summer annual weeds.

The use of crop rotations has other benefits that can create diversity within the agroecosystem (i.e., changes in planting time, amount of tillage and cultivation, and rotation of herbicides that improve weed control). Other crop-management practices that were components within the conservation tillage rotations, such as cutting of alfalfa for hay or early-season harvesting of wheat, can prevent weeds from going to seed, thereby reducing the number that enter the soil seedbank. Increasing the diversity of crops in rotations and reduced tillage appears to have long-term benefits in terms of the production of fewer weed seeds, which results in a situation in which fewer weed seeds are incorporated into the seedbank. Limiting the amount of weed seed that replenishes seedbanks can potentially lower the amount of inputs required for weed management during ensuing seasons. Consequently, production systems that create conditions that limit the amount of management inputs that are applied to crops will benefit producers economically (Forcella et al. 1996b).

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