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Author(s): Douglas D. Buhler, Robert G. Hartzler and Frank Forcella
Source: *Weed Science*, Vol. 45, No. 3 (May - Jun., 1997), pp. 329-336
Published by: Weed Science Society of America and Allen Press
Stable URL: http://www.jstor.org/stable/4046027
Accessed: 10-12-2016 03:02 UTC

Weed Science, 45:329–336. 1997

Symposium: Importance of weed biology to weed management
Weed Science Society of America, Norfolk, Virginia, 1996

Implications of weed seedbank dynamics to weed management

Douglas D. Buhler
Corresponding author. Research Agronomist, National Soil Tilth Laboratory, U.S. Department of Agriculture, Agricultural Research Service, 2150 Pammel Drive, Ames, IA 50011

Robert G. Hartzler
Department of Agronomy, Iowa State University, Ames, IA 50011

Frank Forcella
Research Agronomist, North Central Soil Conservation Laboratory, U.S. Department of Agriculture, Agricultural Research Service, Morris, MN 56267

The species composition and density of weed seed in the soil vary greatly and are closely linked to the cropping history of the land. Altering tillage practices changes weed seed depth in the soil, which plays a role in weed species shifts and affects efficacy of control practices. Crop rotation and weed control practices also affect the weed seedbank. Information on the influence of cropping practices on the weed seedbank should be a useful tool for integrated weed management. Decision aid models use information on the weed seedbank to estimate weed populations, crop yield loss, and recommend weed control tactics. Understanding the light requirements of weed seed may provide new approaches to weed management. Improving and applying our understanding of weed seedbank dynamics is essential to developing improved weed management systems. The principles of plant ecology must be integrated with the science of weed management to develop strategies that take advantage of basic plant responses in weed management systems for agronomic crops.

Key words: Population dynamics, tillage systems, weed ecology.

Regeneration of plants from seed requires that a portion of the seed are at the right place at the right time and are physiologically capable of germination. This physiological state often occurs within a limited period in the life of seeds and must coincide with appropriate environmental conditions (Cousens and Mortimer 1995). Soil is the medium for these processes for most annual weed species. In addition, seed in soil provides a "memory" (Cavers 1995) through persistent seed (those lasting more than 1 yr) that overlap annual inputs of new seeds.

Regeneration strategies of commonly occurring weed species vary. For example, seeds of some species germinate soon after they are shed (Bazzaz 1990). Seeds of these species typically have a short life in the soil and persistence is dependent on annual seed production and dispersal. In other species, seeds may remain in the soil for long periods with intermittent germination of a part of the population (Murdoch and Ellis 1992). Some of these seeds are very long-lived. While reports of extreme longevities of such seeds are impressive, these seeds usually represent a small proportion of the total seedbank (Wilson 1988). In agronomic situations, the majority of the seeds that germinate during the first few years represent the major threat for crop yield loss and control costs. While the persistent portion of the seedbank is important in long-term population dynamics, understanding the short-term dynamics of seedbanks will aid in predicting crop yield losses and control costs.

In agronomic crop production systems, the seedbank in the soil is the primary source of new infestations of annual weeds each year and represents the majority of weed pests (Cavers 1983). Weed seedbank characteristics influence both the weed populations that occur in a field and the success of weed management. Many processes are involved in the generation and regulation of the weed seedbank in the soil (Figure 1). Management practices have major impacts on these processes (Burnside et al. 1986; Schweizer and Zimdahl 1984; Wilson 1988) and represent opportunities for regulating seedbank characteristics in crop production systems. The purpose of this paper is to review processes that regulate seedbanks of annual weed species in agronomic crop production systems and to examine the effects of selected management practices on weed seedbanks. The review will focus on field research exploring the impacts of cultural practices on seedbanks and resultant weed populations and how this information can be better used to manage weed communities in agronomic crop production systems.

Weed Seedbank Dynamics

The species composition and density of weed seed in soil vary greatly and are closely linked to the cropping history of the land. Seed composition is influenced by farming practices, and varies from field to field (Buhler et al. 1984; Fenner 1985; Robinson 1949) and among areas within fields (Benoit et al. 1989, 1992; Mortensen et al. 1993). Reports of seedbank size in agricultural land range from near zero to as much as 1 million seed m^{-2} (Fenner 1985). Generally, seedbanks are composed of many species, with a few dominant species comprising 70 to 90% of the total seedbank (Wilson 1988). These species are the primary pests in agronomic systems because of resistance to control measures and adaptation to the cropping system. A second group of species, comprising 10 to 20% of the seedbank, are generally those adapted to the geographic area but not to current production practices. The final group accounts for a small percentage of the total seed and includes recalcitrant seeds from previous seedbanks, newly introduced species, and

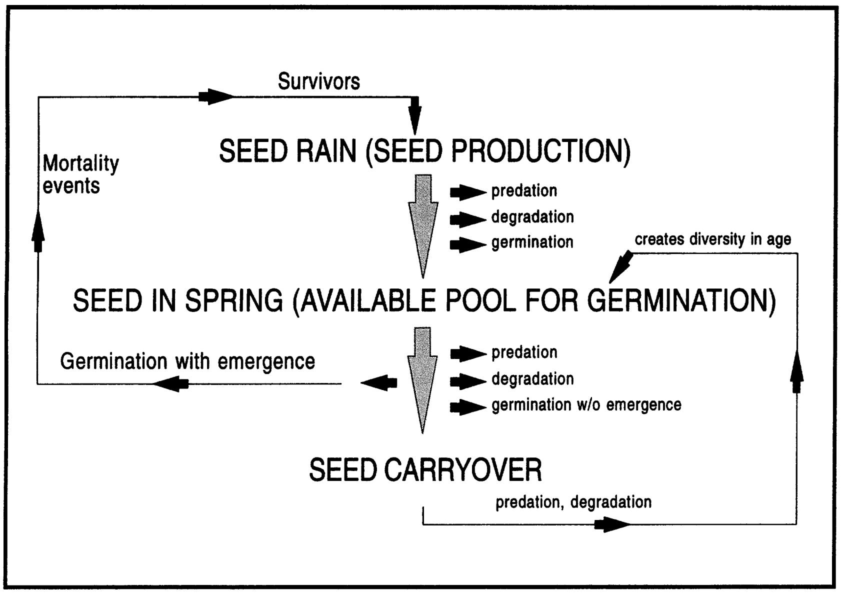

FIGURE 1. Weed seed cycle.

seeds of the previous crop (Wilson et al. 1985). This group undergoes constant change due to seed dispersal by humans, other animals, wind, and water.

Additions to the Seedbank

New seeds may enter the seedbank through many sources, but the largest source is plants producing seed within the field (Cavers 1983). A characteristic of many weed species is the potential for prolific seed production (Cousens and Mortimer 1995; Stevens 1957). However, weeds present in agricultural fields usually produce less seed due to competition from the crop, damage from herbicides, and other factors. Common cocklebur (*Xanthium strumarium* L.) growing without crop competition produced more than 7,000 seed plant^{-1}, whereas common cocklebur plants growing with soybean [*Glycine max* (L.) Merr.] produced 1,100 seed (Senseman and Oliver 1993). Velvetleaf (*Abutilon theophrasti* Medik.) seed production was reduced up to 82% by competition with soybean (Lindquist et al. 1995). Increased shading, which often occurs when weed emergence is delayed compared to the crop, also reduced seed production. For example, 76% shade starting when seedlings were 3 wk old reduced velvetleaf seed production as much as 94% (Bello et al. 1995). Herbicide applications that do not kill plants may also reduce seed production. Sublethal doses of herbicide reduced seed production of several weed species as much as 90% (Biniak and Aldrich 1986; Salzman et al. 1988). Although seed production in most weed species can be reduced by management factors, seed production will likely remain great enough to maintain or increase the seedbank with low to moderate weed infestations (Hartzler 1996; Schweizer and Zimdahl 1984).

Seed may also enter fields from external sources such as farm equipment, contaminated crop seed, animals, wind, or manure. The number of seeds introduced into the seedbank by these sources is usually smaller than those produced by weeds in the field; however, these sources can be important in establishing infestations of new species. Many weeds (e.g., Canada thistle [*Cirsium arvense* (L.) Scop.], horseweed [*Conyza canadensis* (L.) Cronq.], and dandelion (*Taraxacum officinale* Weber in Wiggers) have seeds adapted to wind dispersal. Dandelion and horseweed have become problems in no-tillage systems partially due to the wind transport of seeds (Buhler 1995).

Manure can also be a source of weed seed. While the majority of seeds are killed when passing through the digestive tracts of animals, a small percentage typically survive (Harmon and Keim 1934). A study of 20 New York dairy farms found that, on average, spreading manure introduced 350 weed seed m^{-2} (Mt. Pleasant and Schlather 1994). This seemingly high number of seeds is low compared with the number already present in most seedbanks. If manure is spread on fields from where the feed was harvested, seeds returned to the field will be of little consequence. However, manure can be a source of new weed problems if feed is moved among farms and contaminated with seed of species not currently found in the field.

Another mechanism of weed seed transport is farm machinery moving between fields. This has become increasingly important as machinery is moved greater distances due to increasing farm size. Movement of weed seed by combines and other harvest equipment is of particular concern (Currie and Peeper 1988). Careful management can reduce the risk of spreading weed seed into non-infested fields. Practices include working infested fields last or thoroughly cleaning machinery after working in infested fields.

Seed Losses

Although seed of many weed species have the potential for long-term survival in the seedbank, most seeds have a short life (Murdoch and Ellis 1992). Factors accounting for the loss of weed seed in the soil include germination, decay, predation, and physical movement. The relative importance of these mechanisms varies with species and environmental conditions.

In weed management, we are primarily interested in those seeds that germinate and emerge. These seeds result in new plants that may reduce crop yields and require control. Sporadic germination in time and space (Forcella et al. 1992, 1996b) is a characteristic allowing weeds to survive despite our efforts to eradicate them. Dormancy is a primary mechanism regulating these variable germination patterns. Several types of seed dormancy exist (Nikolaeva 1977), and most weed species possess one or more types. There have been several recent reviews of seed dormancy and related literature (Bradbeer 1988; Dyer 1995; Egley and Duke 1985; Lang et al. 1987; Taylorson 1987; Wilson 1988), so an extensive discussion will not be presented here. In a recent review on exploiting weed seed dormancy through agronomic practices (Dyer 1995), it was concluded that management practices can influence dormancy. Many environmental and edaphic factors that affect seed germination behavior are altered during tillage, planting, and harvesting. Even slight adjustments in planting date, cultivation timing, harvest method, or residue management may have significant effects on weed seed dormancy dynamics.

Dormancy in a population of seed is influenced by both genetics and environment (Murdoch and Ellis 1992). For example, seed coming from the same mother plant may have different degrees of dormancy depending upon environmental conditions at the time of seed development and seed position on the inflorescence (Dekker et al. 1996; Gutterman 1985, 1992). To complicate matters further, induction of seed into secondary dormancy may play a key role in determining emergence patterns (Forcella et al. 1996b; Taylorson 1987). Hydrated, nondormant giant foxtail (*Setaria faberi* Herrm.) seeds were induced into secondary dormancy by exposure to 35 C in the laboratory (Taylorson 1982). This may be relevant in the field because soil temperatures near the surface often reach 35 C in early spring (Gupta et al. 1983).

The percentage of seeds in the seedbank that germinate in a given year is influenced by the species and environment encountered by seeds. For common annual species in cultivated soil, approximately 1 to 50% of the seedbank will emerge in a given year (Cousens and Mortimer 1995; Forcella et al. 1992, 1996b; Roberts and Ricketts 1979; Wilson and Lawson 1992), with great variation both within and among species. The most commonly reported range of emergence under agronomic conditions is 3 to 6% of the weed seedbank. In field experiments conducted from 1991 through 1994 (Forcella et al. 1996b), information on weed emergence was collected for 22 site-years from Ohio to Colorado and Missouri to Minnesota. Average emergence percentages for some major species were as follows: giant foxtail, 31%; velvetleaf, 28%; common ragweed (*Ambrosia artemisiifolia* L.), 15%; pigweed species (*Amaranthus* spp.), 3%; and common lambsquarters (*Chenopodium album* L.), 3%. Coefficients of variation for the species mean values ranged from 62 to 135%. Reasons for the high variation among site-years within species are not fully understood. However, for some species, induction of secondary dormancy by microclimatic variables was thought to play a major role.

Seeds are an important food source for many insects, birds, and small mammals. In natural systems, more than 70% of seeds may be consumed by animals (Crawley 1992). Seed predation is usually less in agricultural systems due to intensive soil disturbance, seed burial by tillage, and lack of habitats for predators. However, studies have found significant weed seed loss from predation when seed remain on the soil surface (Brust and House 1988; Reader 1991). For example, as much as 69% of the weed seed was lost to predation in no-tillage soybean compared with 27% with conventional tillage (Brust and House 1988). A poorly defined proportion of the seeds decay in soil after being infected by fungi or other microorganisms (Kremer 1993). The available data suggest that microorganisms associated with seeds before and upon entry into soil may contribute to depletion of a portion of the seedbank.

TABLE 1. Effect velvetleaf seed production in 1990 on velvetleaf emergence in subsequent years (adapted from Hartzler 1996).

	1990 velvetleaf population (plants m^{-2})		
Year	0	0.2	0.4
	plants m^{-2}		
1991	6 (2)[a]	91 (32)	145 (41)
1992	7 (2)	128 (51)	203 (78)
1993	7 (11)	34 (11)	62 (20)
1994	2 (3)	23 (8)	37 (19)

[a] Values in parentheses are the standard error of the mean.

Other mechanisms for seed loss exist, such as water moving through a field and movement with tillage and harvesting equipment (Wilson 1988). However, these mechanisms appear to make minor contributions to weed population dynamics overall.

Management Impacts on the Weed Seedbank

Weed Management

Weed seed densities can be greatly reduced by eliminating seed production for a few years; conversely, soil with low seed density can increase at an extremely rapid rate if plants are allowed to produce seed. The number of seeds in the seedbank in continuous corn (*Zea mays* L.) in Colorado dropped by approximately 70% after 3 yr of atrazine [6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine] application plus interrow cultivation (Schweizer and Zimdahl 1984). Atrazine use ceased in some plots after the first 3 yr, and weeds were controlled with one or two cultivations. After 3 yr of cultivation only, the seedbank was approximately 25 times greater than where atrazine use and cultivation were continued. In a similar study in Nebraska (Burnside et al. 1986), broadleaf and grass seed density in the soil declined 95% after a 5-yr weed-free period. During the sixth year, herbicide use ceased and seed density increased to 90% of the original level at two of five locations.

Velvetleaf was planted in soybean at 0.2 and 0.4 plant m^{-2} and allowed to produce seed in a previously uninfested field (Hartzler 1996). Each plant that produced seed produced more than 1,000 new plants over the next 4 yr (Table 1). Velvetleaf emergence peaked in Year 2 and dropped by 80% between Years 2 and 4.

These studies provide examples of the affect of weed management on the weed seedbank and illustrate the rapid decline in the seedbank when seed introductions are reduced or prevented. However, in most weed species, a small number of seeds remain viable in soil for long periods. When weed management practices are not entirely effective, this seed reserve can germinate, mature, and within a short period produce enough seed to replenish the seedbank.

Crop Rotation

Crop rotation is effective for weed management (Liebman and Dyck 1993 and references therein) because selection pressure is diversified by changing patterns of disturbance. This diversification prevents the proliferation of weed species well suited to the practices associated with a single crop.

Few studies have characterized the effects of crop rotation on the weed seedbank. In ridge-tillage (Forcella and Lindstrom 1988), soils harbored at least twice as many weed seed under continuous corn than a corn/soybean rotation. Truncation of the ridges at the time of crop planting removed about 35% of the weed seed from the ridges of continuous corn, and 90% of the seed from ridges of the corn/soybean rotation. Ridging the soil just before canopy closure stimulated germination of weed seed. The resulting weed population produced up to 1,000 seed m^{-2} in continuous corn and about 100 seed m^{-2} in the corn/soybean rotation.

Schreiber (1992) found that growing corn in a soybean/corn or soybean/wheat (*Triticum aestivum* L.)/corn rotation greatly reduced giant foxtail seed in soil compared to corn grown continuously, regardless of herbicide use or tillage system. The effects of crop rotation and environmental conditions associated with year and location were larger than tillage effects on weed species composition and abundance in two separate studies in Canada (Derkson et al. 1993; Thomas and Frick 1993). Similarly, Ball (1992) reported that cropping sequence was the dominant factor influencing species composition in weed seedbanks.

The mechanisms by which crop rotation reduces the size of weed seedbanks are related to the use of crop sequences employing varying patterns of resource competition, allelopathic interference, soil disturbance, and variable weed management strategies. Proliferation of otherwise well-adapted weed species is reduced by these processes, which provide a more diverse environment.

Tillage Systems

Tillage systems affect weed emergence, management, and seed production; therefore, changing tillage systems changes the composition, vertical distribution, and density of weed seedbanks in agricultural soils (Buhler 1995). Tillage is the primary cause of vertical seed movement in agricultural soils (Cousens and Moss 1990; Roberts 1963; Staricka et al. 1990). The effects of chisel and moldboard plowing on the vertical distribution of weed seed in the soil were evaluated using ceramic spheres (Staricka et al. 1990). Spheres, with similar size and density of weed seed, were found to depths of 12 cm following chisel plowing and 32 cm following moldboard plowing. In the chisel plowed plots, 48% of the spheres were found within 4 cm of the soil surface compared with 4% in moldboard plow plots.

Moldboard plow plots had fewer weed seed in the upper 20 cm of soil than chisel plow or no-tillage after 5 yr (Yenish et al. 1992). Moldboard plowing resulted in the most uniform distribution of seed over soil depths. In the no-tillage system, more than 60% of all weed seeds were found in the upper 1 cm of soil, and few seeds were found below 10 cm. The concentration of weed seed in no-tillage decreased logarithmically with increasing depth. In the chisel plow system, more than 30% of the weed seeds were in the upper 1 cm of soil and seed concentration decreased linearly with depth. Pareja et al. (1985) found 85% of all weed seed in the upper 5 cm of soil in a reduced tillage system, but only 28% in the same zone in the moldboard plow system.

TABLE 2. Effect of planting depth on the establishment and growth of velvetleaf and giant foxtail after 28 days in the greenhouse (from Buhler 1995).

	Velvetleaf		Giant foxtail	
Planting depth	Seedling establishment	Seedling height	Seedling establishment	Seedling height
cm	% of maximum observed			
0	18	45	86	100
1	73	82	100	76
2	73	100	86	83
4	91	82	81	89
6	100	70	50	24
LSD (0.05)	26	26	17	18

Seed and tracer distribution data (Pareja et al. 1985; Staricka et al. 1990; Yenish et al. 1992) substantiate differences in emergence depths of giant and green foxtail [*Setaria viridis* (L.) Beauv.] in different tillage systems in the field (Buhler and Mester 1991). Mean seedling emergence depths were smallest in no-tillage, followed by chisel plow, and were largest in the moldboard plow system in two soil types during 3 yr. At least 40% of the giant and green foxtail emerged from the upper 1 cm of soil in no-tillage compared to about 25% in chisel plow and less than 15% in moldboard plow plots. As many as 25% of the foxtail plants that became established in the moldboard plow plots emerged from greater than 4 cm compared to about 10% in chisel plow and less than 5% in no-tillage.

Changes in seed depth in soil and corresponding differences in emergence depth may contribute to shifts among weed species under different tillage systems. In a greenhouse (Buhler 1995), velvetleaf establishment from seed germinating on the soil surface was only 18% of seed planted 6 cm deep (Table 2). Giant foxtail seed germinating on the soil surface had an establishment percentage similar to seed planted 1 to 4 cm deep, but giant foxtail establishment was reduced 50% when seed were planted 6 cm deep.

Buhler et al. (1996b) attempted to separate the effects of seedbank distribution and surface residue by establishing tilled and untilled plots with the same levels of corn residue. Velvetleaf densities were greatest in tilled plots without the residue, whereas redroot pigweed (*Amaranthus retroflexus* L.) densities were greatest when the residue was removed from untilled plots. The base level of residue reduced redroot pigweed densities up to 70% compared to plots with no residue in both tilled and untilled plots. Giant foxtail densities were several times greater in plots that were not tilled when averaged over residue levels. It was concluded that vertical seed distribution in the seedbank plays a more important role in weed population shifts among tillage systems than surface residue.

The effect of tillage practices on the population dynamics of summer annual weed species is complex and involves several factors. However, seed depth in the soil may be the most important factor. Weed species that can germinate and become established when seeds are at or near the soil surface have the greatest potential to proliferate under conservation tillage systems. Deep burial of seed of small-seeded species by moldboard plowing reduces germination and emergence. Conversely, seeds of large-seeded species remain near the soil surface in conservation tillage systems, inhibiting establishment and reducing seed burial that contribute to reinfestation following subsequent tillage operations (Lueschen and Andersen 1980; Warnes and Andersen 1984).

Weed Seedbanks and Weed Management

In theory, eliminating weed seedbanks should be relatively easy. Stop seed production and deplete the seedbank by managing soil to provide the optimum environment for germination. In practice, managing seedbanks is far more complex because of the difficulty in preventing seed production and introduction, the persistence of a small percentage of the seedbank, and the high seed production potential of many weed species.

Seedbank Philosophy

Some weed scientists argue that allowing even a single weed to produce seed is detrimental to long-term farm profits (Norris 1992). Most producers would agree that eliminating weed seed production is a worthy and possibly economically rational goal. However, concerns with attempting to eliminate weed seed production include (1) whether this goal can be attained by farmers over large areas of land given the dormancy and seed longevity characteristics of commonly occurring weed species, and (2) other problems, such as increased costs for labor, equipment, and herbicide; a greater time requirement per unit of land; weed resistance; increased soil erosion; and water contamination with herbicides. Loss of habitat for wildlife and other beneficial organisms may be created in the process. It could be argued that we have been attempting to eliminate seedbanks for many years, and have failed. It may be more realistic to accept weed seedbanks as an ever-present component of agricultural land and attempt to understand, interpret, and predict their behavior, then devise management systems that minimize the impacts of the resultant weeds rather than attempt to eliminate the seedbank.

Control Efficacy

Knowledge of seedbank characteristics should be useful in predicting weed management efficacy. The composition of the seedbank regulates the timing and density of weed populations, both important components affecting control efficacy. In a field with a large initial seedbank, metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] controlled 75% of the giant foxtail in plots where heavy infestations (530 plants m^{-2}) had produced seed the previous year (Hartzler and Roth 1993). In the same field, metolachlor provided 95% control in plots maintained weed-free the previous year. In a field with a small initial seedbank, low grass populations (eight plant m^{-2}) producing seed the previous year did not influence control. These results suggest that large changes in the seedbank affect weed control efficacy, but small changes do not have an effect. This is substantiated by research where increasing weed densities reduced weed control with herbicides and mechanical practices (Buhler et al. 1992; Winkle et al. 1981).

Periodicity of germination and emergence of different weed species is also an important aspect of weed management. Knowledge of when different weed species are likely to emerge is important in planning effective weed control programs (Ogg and Dawson 1984). Wilson et al. (1992) found a 20-d difference in the time of initial emergence for nine summer annual weed species grown at the same location. The time of weed seedling emergence influences which species will be the most serious weeds with a given crop production practice or most susceptible to certain control measures. Stoller and Wax (1973) concluded that weed species that complete most of their emergence early are killed during soil preparation before planting corn or soybean. Ogg and Dawson (1984) observed distinct patterns of emergence for eight weed species and concluded that if a weed species has a restricted emergence pattern, the crop could be planted later and tillage used to destroy weed seedlings before planting. They also pointed out that knowledge of emergence patterns could be used for timing of cultivation and postemergence application of herbicides. Delaying soybean planting reduced weed populations and improved weed control with rotary hoeing and cultivation (Buhler and Gunsolus 1996). Reductions in weed density due to delayed planting varied by species, with a 25% reduction for pigweed species and nearly 80% for common lambsquarters.

Decision Aids

A potential use of seedbank information in weed management is the use of bioeconomic models that incorporate seedbank dynamics and prediction of weed emergence into the decision making process (King et al. 1986; Swinton and King 1994). A goal of these models is to incorporate weed population dynamics into weed management while accommodating multiple weed species and a wide range of control tactics.

Field evaluation of bioeconomic models has shown their potential to reduce herbicide use while maintaining weed control and increasing economic returns. In irrigated corn in Colorado (Lybecker et al. 1991), grain yields and gross incomes were similar for flexible, model-generated, and fixed weed management strategies. However, herbicide use was reduced and gross margins increased by using the model. They concluded that a bioeconomic model employed to make weed management decisions in corn could maintain weed control, increase gross margins, and decrease herbicide use.

A bioeconomic decision aid for management of annual weeds in corn and soybean (Swinton and King 1994) was tested in western Minnesota (Forcella et al. 1996a). After applying model-recommended treatments to the same plots for 4 yr, there were no increases in weed densities or decreases in corn or soybean yields. Model recommendations reduced weed control costs and resulted in an average annual herbicide application of 1.1 kg ai ha^{-1} compared to 3.5 kg ha^{-1} with a standard treatment. In a field evaluation of the same model in eastern Minnesota (Buhler et al. 1996a), model-generated treatments controlled weeds as well as a standard herbicide treatment (Table 3). Herbicide use decreased 27% using seedbank data and 68% using POST seedling data compared with a standard herbicide treatment.

TABLE 3. Herbicide load, weed control, corn yield, and net return to weed control using a bioeconomic weed management model (adapted from Buhler et al. 1996a).

Treatment[a]	Herbicide applied	Weed control[b]	Corn yield	Net return
	kg ha^{-1}	%	kg ha^{-1}	\$ ha^{-1}
1991				
Seedbank model	3.9	96	11,300	638
Seedling model	0.43	92	11,100	603
Standard herbicide	5.1	98	11,600	661
1992				
Seedbank model	4.0	93	7,840	297
Seedling model	2.2	92	9,380	410
Standard herbicide	5.1	93	9,910	440
1993				
Seedbank model	3.3	94	10,950	684
Seedling model	2.2	91	10,600	621
Standard herbicide	5.1	97	12,130	730

[a] Seedbank and seedling model treatments were generated by a bioeconomic model (Swinton and King 1994) using soil seed and seedling densities, respectively.

[b] Pooled over species.

Net economic return to weed control was not increased by using model-generated control recommendations. Although tactics differed, the bioeconomic model generally resulted in weed control and corn yields similar to a standard herbicide treatment.

Economic Thresholds

Economic thresholds for weed control have been criticized for not accounting for seed production by subthreshold populations of weeds on future weed management costs. Economic optimum thresholds (Cousens 1987) incorporate the impact of seed production on future weed populations. Bauer and Mortensen (1992) calculated the economic optimum thresholds for velvetleaf and common sunflower (*Helianthus annuus* L.) in soybean to be 7.5-fold and 3.6-fold lower than the single-year economic threshold, respectively. The larger ratio for velvetleaf reflected higher seed production and a greater seed longevity compared with that of common sunflower.

Field evaluation of a threshold-based decision support model showed that weed density the following year may be increased by seed production from sub-threshold weed populations (Buhler et al. 1996a). In one of 3 yr, increased weed densities following model-generated treatments reduced weed control and crop yields compared with a standard treatment the following year. Conversely, Forcella et al. (1996a) found that weed populations did not increase over 3 yr with model-based treatments compared to standard herbicide practices.

Management of Light

Exposure to light breaks seed dormancy in many plant species, including weed species. Because light can penetrate only a few millimeters in soil (Egley 1986), dormancy may be induced in light-requiring seeds by shallow burial (Pons 1991; Wesson and Wareing 1969). A major source of light for buried weed seed is the light flash received during tillage. Increased weed seed germination after tillage in the light vs. darkness was first documented in 1969 (Wesson and Wareing 1969). Tilling the soil during darkness reduced weed populations in recent field research (Buhler and Kohler 1994; Hartmann and Nezadal 1990; Scopel et al. 1994), suggesting that eliminating or modifying light exposure of soil during field operations may have practical application for management of light-sensitive weed species. However, since all weed species do not possess light-sensitive germination, tillage in the absence of light will rapidly select for light-insensitive species.

TABLE 4. Examples of research needs for developing weed seedbank information to support weed management systems.

Management goal	Specific research on weed seedbank dynamics
Management decision aids	Relationship of the seedbank to final weed populations Emergence dynamics of individual weed species Economic optimum thresholds Effects of management practices on weed seed production Effects of weed density on control efficacy
Prediction of emergence	Dormancy mechanisms Environmental drivers of germination and dormancy
New management methods	Effects of crop rotations Effects of living and dead mulches Seed predation and decay Seedling mortality Light requirements and impacts of management practices on light-sensitive species Tillage and cultural practices (i.e., planting date, crop density, row spacing, etc.)

Summary and Research Needs

Seedbank dynamics regulate communities of many of our most important weed species. A better understanding of seedbank dynamics is critical for the development of more efficient weed management systems. In the short term, weed biology research will not eliminate the inputs currently used to manage weeds. However, the knowledge gained will provide the foundation for development of new strategies and more efficient techniques (Table 4), resulting in more reliable weed management systems that are cost-effective and pose less threat to the environment.

As weed scientists develop new methods for weed management, it must be recognized that producers focus on cropping systems, not just weeds or the weed seedbank. Research must address all aspects of the farming operation to minimize losses due to weeds in the context of the entire operation. For example, rotation systems must include consideration for markets and uses for alternative crops. Economic analyses must be an integral component of research on alternative systems to answer questions about the costs and benefits of using weed seedbank information.

Weeds continue to thrive in the face of increased efforts to eliminate them. Weed seedbanks play a major role in this persistence. Research needs to be conducted to develop new weed management options and to provide information on the effects of management decisions (Table 4). Can we predict the timing and extent of weed emergence based on environmental variables? Can seed dormancy be circumvented to reduce variability in emergence and to reduce the persistence of seedbanks? How will threshold-based management systems affect weed populations and weed control? How can cultural practices be sequenced to reduce weed densities and subsequent yield losses? Can soils be managed to increase seed predation and decay? Each of these questions represents a major research effort. Weed science needs to develop means to support more research in these critical areas if we are to develop the understanding of the weed seedbank necessary for integrated weed management systems.

All forms of disturbance result in survival and selection of the best adapted plant species. Any cropping or weed control system that exerts a continuous, strong selection pressure will cause a buildup of the best adapted weed species and biotypes. Development of improved cropping systems will require an approach that concentrates on the processes and patterns linking scientific disciplines to agricultural systems. Agricultural systems are composed of interacting production, environmental, biological, economic, and social components. These interactions require the study of not only the parts, but also the whole system. Development of fully integrated and scientifically understood systems of weed management is a solution to ever-evolving weed problems and provides the basis for weed seedbank research.

Acknowledgment

Contribution from U.S. Department of Agriculture Research Service, National Soil Tilth Laboratory, Ames, Iowa.

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Received April 29, 1996, and approved October 1, 1996.