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Symposium

A sustainable agriculture project at Chesapeake Farms: a six-year summary of weed management aspects, yield, and economic return

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A 6-yr project comparing four cash grain–farming systems relevant to the mid-Atlantic region of the United States was conducted from 1993 to 1999. A wide range of parameters was sampled including soil health, nutrient and agrichemical movement, economic viability, and insect and weed communities. The systems and their approaches to weed management were: continuous no-till corn without (System A1) or with (System A2) rye cover crop and preplanned herbicides based on expected weed infestations; System B was a 2-yr corn–soybean rotation with conventionally tilled corn and no-tillage soybean, with preplanned herbicides based on expected weed infestations; System C was a 2-yr rotation with no-till corn, conventionally tilled wheat, and no-till double-cropped soybean, using postemergence (POST) herbicides on the basis of field scouting; and System D was a 3-yr rotation of corn-soybean-winter wheat with rye and hairy vetch cover crops, using cultivation and reduced rates of POST herbicides based on field scouting. Spring weed assessment in 1999 was similar for species evenness (Shannon's E) and diversity (Shannon's H′) indices. Weed density was lowest in System C because wheat in this system received a spring herbicide application. In the final fall assessment, Shannon's H′ was greater in System D than System C. Common lambsquarters, eastern black nightshade, and jimsonweed were more abundant in System D than Systems A1, A2, and C. Fall 1999 assessment also indicated Canada thistle was more prevalent in Systems A1 and A2 than the other three systems. During the 6-yr period, densities of jimsonweed, eastern black nightshade, morningglory species, crabgrass, and fall panicum dramatically increased in a particular system for 1 to 2 yr, then declined to levels similar to other systems. Overall, weed communities were quite stable and effective weed management did not result in dramatic changes in the weed community, regardless of the approach to cropping systems or weed management.

Nomenclature: Canada thistle, *Cirsium arvense* (L.) Scop.; common lambsquarters, *Chenopodium album* L.; crabgrass species, *Digitaria* spp.; eastern black nightshade, *Solanum ptycanthum* Dun.; fall panicum, *Panicum dichotomiflorum* Michx.; jimsonweed, *Datura stramonium* L.; morningglory species, *Ipomoea* spp.; corn, *Zea mays* L.; hairy vetch, *Vicia villosa* Roth.; rye, *Secale cereale* L.; soybean, *Glycine max* (L.) Merr.; winter wheat, *Triticum aestivum* L.

Key words: Integrated weed management, relative abundance, Shannon's E, Shannon's H′, weed communities.

Relatively few research studies have been conducted to examine entire crop production systems for an extended period of time. Few of these studies have attempted to examine multiple components of the system. However, this type of research is critical to understanding the interrelated components of farming practices. Agriculture is a dynamic biological system, where changes in one portion of the system can alter the outcome of seemingly unrelated aspects. Thus, farming systems need to be studied in their totality as much as possible. Achieving quality scientific results in a farming-systems project with multiple objectives through collaborative resources requires dedication and mutually shared interests, objectives, and motivation that can be fragile, especially because project practices shift with time to retain relevance with local practices. It is also difficult to balance number of treatments, parameters examined, budget constraints, and statistical rigor in a multidisciplinary research project such as this. Others have expressed similar concerns with long-term, multidisciplinary research (Drinkwater 2002; Mueller et al. 2002). Yet there is a synergy associated with this type of multidisciplinary, long-term research. Agriculture is a complex endeavor with diverse stakeholders and interdependent societal and scientific concerns. Sustainability is a similarly complex concept. It is essential that scientists and stakeholders from the various relevant disciplines collaborate so that their efforts obtain a more thorough understanding of various farming systems.

The Sustainable Agriculture Project at Chesapeake Farms was a long-term comparison of cash grain–farming systems relevant to the mid-Atlantic region of the United States. All four cropping systems strived for sustainability but with different approaches ranging from heavy reliance on off-farm input and a prophylactic approach to pest management to decreased reliance on purchased inputs, with greater use of crop rotations, cover crops, and manures and of minimal herbicide input. The systems demonstrate varying reliance on crop rotations and in-season management and labor; made optimal use of fertilizers, crop protection chemicals, and other purchased inputs; and used best management practices to prevent sediments, nutrients, and pesticides from moving to surface and groundwater. Metrics were developed by a panel of diverse stakeholders to compare the systems against elements of sustainability, namely productivity, profitability, environmental compatibility, and societal concerns. Collaborators included environmental and agricultural nonprofit organizations, government agencies, academia, agri-business, and a group of concerned farmers. Each contributed specific talents, diverse thinking, and resources needed to ensure the project's success and give the project the depth of thought needed to help meet the groups' common challenges. A Farmer Advisory Board guided all decisions, assisted with outreach, and ensured compliance with local concerns.

Previous reports from this project have documented the effects of the different systems on pesticide concentrations in surface-water runoff and shallow groundwater (Forney et al. 2000) and on nutrient and sediment loads in surface-water runoff (McGrath and Sims 1999; McGrath et al. 2001). Witmer et al. (2003) has published the results of studies with ground-dwelling and foliar arthropods. This article presents aspects of the project that relate to weeds, including the impacts of the farming systems on weed populations and seedbanks, as well as productivity and profitability.

Materials and Methods

Site Background and Study Implementation

The research was established at Chesapeake Farms near Chestertown, MD. Soils ranged from gravelly upland soils to low-lying hydric soils. The predominant soil type in the study area is Mattapex Variant silt loam (fine-loamy, mixed, mesic Aquic Hapludult). The Ap horizon (approximately 28 cm) has about 2% organic matter and pH is maintained in the 6.0 to 7.0 range by liming.

Before 1991, conventionally tilled corn was grown each year for approximately 20 yr. Weed management relied largely on various combinations of triazines, chloroacetamides, and thiocarbamate herbicides and cultivation.

In 1991 and 1992, in anticipation of study initiation, soybean was grown on the site in the interest of reducing the severe johnsongrass [*Sorghum halepense* (L.) Pers. SORHA] infestation, using postemergence (POST) quizalofop applications. Additional weed control included preemergence (PRE) applications of a combination of chlorimuron and linuron and POST applications of combinations of chlorimuron and thifensulfuron.

The four farming systems designed for the study were subjected to distinct rotation schemes, tillage practices, fertility programs, and approaches toward weed management. Production practices utilized are currently in use on farms in the Mid-Atlantic region of the United States.

In the spring of 1993, all plots received lime and fertilizer according to soil test results and were uniformly tilled.

The four cropping systems were arranged in a Latin square design with four replicates. Each plot was divided into two subplots to accommodate each crop in the rotation of the system (System D, having a 3-yr rotation, had a third subplot). Main plots were 27 by 18 m, with no space between subplots. Mowed grass alleys, 18 m wide separated each main plot.

Cropping Systems

Each cropping system was managed using commercial farming equipment, with all procedures being performed as close to the ideal time as possible for best management practices, considering prevailing weather conditions. Pesticide applications were made with commercially formulated products.

System A consisted of continuous no-till corn, without (A1) or with winter rye cover crop (A2). Corn was planted in 76-cm rows. Systems A1 and A2 used a prophylactic approach to pest and nutrient management, in which crop protection was accomplished largely through preplanned applications of pesticides labeled to control the anticipated pests. System A used approximately 3,600 g ha^{-1} of pesticides annually, including atrazine and cyanazine plus 2,4-D for control of existing vegetation at planting time (as well as paraquat for control of the rye cover crop in System A1). A combination of nicosulfuron and dicamba was applied POST for perennial weeds and escaping annuals. Within this approach, the triazines were applied in 1994 and 1995 at rates designed to provide season-long annual weed control, and weeds not effectively controlled with PRE herbicides were treated with a spot application of nicosulfuron plus dicamba, which was applied to approximately 30% of the field in 1994. However, by 1995, because of the long history of triazine use on the farm, triazine-resistant common lambsquarters required spot treatment on approximately 80% of the plot area. For subsequent years, a planned approach was used with a reduced rate of triazines PRE followed by broadcast POST application of nicosulfuron plus dicamba. Soil insecticides were used in-furrow at planting time (tefluthrin in 1994 and 1995, chlorethoxyfos in subsequent years), and es-fenvalerate was included in the nonselective herbicide application before planting.

System B used a 2-yr tilled corn and full-season no-till soybean rotation. Before planting corn, the soil was prepared with either a chisel plow or deep ripper, depending on soil moisture. Corn was planted in 76-cm rows and soybean was planted in 38-cm rows. Similar to System A, System B also relied on prophylactic pest and nutrient management and used approximately 3,400 g ha^{-1} of pesticides annually. For corn, these included atrazine, cyanazine, and metolachlor applied and incorporated into the top 5 cm of the soil before planting corn. Spot applications of nicosulfuron plus dicamba were made to control perennial weeds. During the soybean phase of the rotation, herbicides that prevented buildup of triazine-resistant weeds were used. The prophylactic approach to weed control for soybean included an application of a mixture of metribuzin, chlorimuron, and alachlor applied before planting. Glyphosate was included if additional control of existing vegetation was needed. A POST spot application of chlorimuron plus thifensulfuron plus quizalofop for perennial weeds and emerged annual species was used.

System C was a 2-yr corn, winter wheat, and soybean rotation with no-till corn, conventionally tilled wheat, and no-till double-crop soybean. Corn, soybean, and wheat were planted in rows spaced 76, 38, and 18 cm, respectively. System C used prescription pest and nutrient management, in which crop protection practices and fertility applications were on the basis of scouting and diagnostics within an integrated pest management (IPM) approach. System C used approximately 200 g ha^{-1} of pesticides annually. In corn, glyphosate with or without 2,4-D was applied at planting time to control existing vegetation. A combination of nicosulfuron plus dicamba was applied POST for annual weed control in 1994 and 1995; atrazine was added to this mixture in 1996. In wheat, a combination of thifensulfuron plus tribenuron was applied each year for control of winter-annual and perennial weeds. For soybean, glyphosate was applied at planting time if needed (1996 only), followed by a prepackaged mixture of chlorimuron, thifensulfuron plus quizalofop applied POST.

System D was a 3-yr corn, soybean, and winter wheat rotation with winter rye and hairy vetch cover crops. It relied, whenever possible, on cultural and biological pest and nutrient management, within an IPM approach. System D used approximately 22 g ha^{-1} of pesticides annually. Corn was seeded in 76-cm rows into a hairy vetch cover crop that was flail-mowed. A POST application of a nicosulfuron plus dicamba mixture was made to a band 38 cm wide as needed to control weeds in the corn row with mechanical cultivation used between the rows. In 1995 and 1996, when the initial corn planting was attacked by slugs (species unknown), resulting in an inadequate corn population, glyphosate was applied when corn was replanted, and in 1996 this eliminated the need for the POST herbicides. After corn harvest, rye was seeded without tillage with a spinner seeder. In the spring, glyphosate was applied to destroy the rye cover crop and any existing weeds before soybean planting. Soybean was seeded in rows spaced at 76 cm. A POST application of imazethapyr was made to a band 38 cm wide as needed to control weeds in the soybean row with mechanical cultivation used between the rows. Wheat was seeded without tillage in 18-cm rows in the fall after soybean harvest, and a combination of thifensulfuron and tribenuron was applied the spring after wheat seeding. During summer fallow after wheat harvest, sufficient tillage (disc and combination surface-tillage tools) was used to prepare a fine seedbed for vetch seeding.

Crop scouting was performed throughout the cycles of each system, using procedures recommended by University of Maryland (Anonymous 1999). The approach for pest management for Systems A and B was on the basis of the observations made through scouting to maintain awareness of pest problems and for planning the subsequent years' pest management programs. Pest control interventions for Systems C and D were on the basis of IPM parameters (economic thresholds and prevailing circumstances such as weather). In addition to the pesticides mentioned previously, spider mites were treated as needed in soybean with dimethoate.

Cropping Systems Economics

Records of all systems activities and their associated costs were maintained throughout the project. Purchased input costs were based on local retail costs, not reflecting any particular seasonal or volume discounts. Activities such as tillage, planting, and harvest, as well as a typical value for land rent, were valued according to University of Maryland published custom-rate charges (Johnson and West 1993). All costs were standardized to a unit area basis. Crop yields were determined using a calibrated weigh wagon to measure the output from each experimental unit, excluding border rows. Crop moisture was measured for each plot, and yield values converted to standard moisture. Crop returns were on the basis of the prevailing local market price for the grain on the day of harvest each year. For corn, a standardized drying charge was calculated for each system to account for differences in maturity at harvest associated with different planting dates and growing conditions for each system. Total costs, gross returns, and net returns were calculated for each system.

Weed Population Monitoring

Throughout the course of the study, weeds were surveyed in the fall and spring to determine how populations were responding to the differences in management. Weeds were counted by species in March before tillage or herbicide application to winter wheat, and in the fall before crop harvest. A fall assessment was preferred over a midseason assessment because of the use of soil-applied herbicides, cultivation, and cover crops. The fall assessment allowed an evaluation of the cumulative effect of all weed control operations. All weeds in 16 locations (0.5 m^2 at 16 locations) in each subplot were counted. Number of shoots, or sprigs, of perennial species was also counted. The 16 locations were in a four by four grid arrangement to allow for weed assessments to be collected in approximately the same location in the subplots for each assessment. March assessments were not taken in all systems in 1994 to 1996.

Weed seedbank assessment was made in the fall of 1999, after 6 yr of systems–rotations–practices. Sixteen soil cores (5 cm diameter by 10 cm deep) were taken from each plot, following the same pattern as used for weed species counts. Soil was thoroughly mixed, dried, and 2.5 kg was weighed and placed in trays in the greenhouse. Weed seedlings were identified after emergence and then removed. When seedling emergence stopped (4 to 5 wk), soil was mixed by hand and flats replaced in the greenhouse. After three series of mixing the soil, soil was frozen for 2 wks and the emergence–mixing cycle was repeated twice.

Data Analysis

This study was designed to examine the impact of the systems on weed population composition, productivity, and profitability, not the impact of the specific crops on weed composition. Data were analyzed at the system level; therefore values represent data averaged over crop sequence.

Data were analyzed as a Latin square. Weed density and number of species were transformed with a log x + 1 transformation. Relative abundance, a synthetic importance value that includes density and frequency components, was calculated to overcome problems of a potential nonuniform weed distribution (Derksen et al. 1994, 1995). Relative abundance values were calculated by plot for each weed species as follows:

TABLE 1. Total number of plants, number of species present, Shannon's H′ (diversity) and E (evenness) indices for all weed species present in spring and fall assessments in 1999, after 6 yr of cropping. Seedbank data is based on soil samples collected in the fall of 1999.[a]

Assessments	Parameters	Management systems[b]				
		A1	A2	B	C	D
Spring	Weed density (no. 8 m^{-2})	421 ab	454 ab	596 a	116 c	240 b
	Number of species (no. 8 m^{-2})	6 b	7 ab	9 a	6 b	7 b
	Shannon's H′	1.04	1.17	1.38	1.22	1.16
	Shannon's E	0.59	0.60	0.62	0.72	0.59
Fall	Weed density (no. 8 m^{-2})	96	44	87	81	64
	Number of species (no. 8 m^{-2})	5	5	5	4	7
	Shannon's H′	0.67 ab	0.84 ab	0.92 ab	0.47 b	1.35 a
	Shannon's E	0.39 b	0.53 ab	0.76 a	0.28 b	0.71 a
Seedbank	Weed density (no. 2,500 g^{-1})	175	144	242	157	173
	Number of species (no. 2,500 g^{-1})	15 a	12 b	15 a	15 a	17 a
	Shannon's H′	1.69 bc	1.52 c	1.92 ab	1.83 b	2.09 a
	Shannon's E	0.63 b	0.62 b	0.71 a	0.68 ab	0.74 a

[a] Values within a row followed by the same letter are not significantly different, LSD $\leq$ 0.05.
[b] System A1 is continuous no-tillage corn; System A2 is continuous no-tillage corn with no-tillage planted rye cover crop; System B is reduced tillage corn rotated with no-tillage soybeans; System C is no-tillage corn followed by reduced tillage winter wheat followed by no-tillage double-cropped soybeans within a 2-yr rotation; and System D is a 3-yr rotation of no-tillage corn planted in vetch cover crop followed by fall planted rye cover crop, second year is no-tillage soybean, followed by reduced tillage winter wheat with vetch planted after wheat harvest. Systems A1, A2, and B relied upon a prophylactic approach to pest management. System C relied upon prescription (POST) weed control, and System D emphasized cultural and biological pest management with cultivation and reduced rate of POST herbicides where needed. See text for detailed description of tillage and pest management strategies.

$$\text{relative abundance} = (\text{relative density} + \text{relative frequency})/2. \quad [1]$$

Relative density was calculated as the number of individuals (including perennial shoots and sprigs) for a given species within the 16 quadrats for each plot divided by the total number of individuals within the plot. Relative frequency was calculated as the proportion of quadrats in which the species was present per plot divided by the total frequency of all species. Number of shoots, or sprigs, of perennial species was considered separate plants.

Shannon's diversity index (H′) and evenness (E) were calculated (Magurran 1988) on the basis of a composite of the 16 quadrats per plot. Shannon's H′ index was calculated as follows:

$$H' = \left(N \log N - \sum n \log n\right) N^{-1} \quad [2]$$

and measures species diversity on the basis of proportional abundance of species, with a higher value representing greater diversity; N is the total weed population per unit area and n is the weed population of each species present in the area. Shannon's E is the ratio of observed number of species divided by the maximum number of species and was calculated as follows:

$$E = H'(\ln N)^{-1} \quad [3]$$

H′ is Shannon's diversity index and N is the total weed population per unit area. A high degree of evenness occurs when species are in equal abundance and it is associated with high diversity (Magurran 1988).

Results and Discussion

On the basis of weed density by species and diversity index (Shannon's H′), weed populations were similar for all systems at the start of the study in 1993 (data not presented). Weed management was quite successful for all systems for the duration of the study. One exception was in 1998 in System C, when annual grass control was poor. This was because of antagonism of the mixture of POST grass and broadleaf herbicides under the prevailing droughty conditions.

Weed Density and Diversity in the Final Year

Only Shannon's H′ will be discussed because it incorporates concepts of evenness (Shannon's E) and species richness. A total of 17 weed species were observed in the spring assessment in 1999 (data not presented). Plant density in the 1999 spring assessment was highest in Systems A1, A2, and B and lowest in System C (Table 1). Number of species was highest in System B and lowest in Systems A1, C, and D. Lower number of species in Systems A1, C, and D may be in part because of the timing of herbicide application in winter wheat and crop competition from the winter wheat or vetch phase of the crop rotations. The herbicides used in winter wheat would have eliminated most (or all) of the seed production whereas crop competition would have reduced the number of seeds produced from winter annual species compared with systems without winter crops. The timing of the spring tillage operation or nonselective herbicide application for corn or soybean production would have allowed many of the winter annual species to produce seeds. There were no treatment differences between Systems A1 and A2, thus the addition of rye had no impact on the spring weed composition. Shannon's H′ was not significantly different among the treatments.

Twenty-six species were identified in the fall 1999 assessment (data not presented). There was no statistical difference for plant density or number of species among the treatments (Table 1). Shannon's H′ was greater for System D than System C. This may be attributed to a more diverse cropping system and less herbicide-intensive weed management. On the basis of weed density, there were similar levels of weed control attained in all systems, regardless of management input, level of integrated control methods, or reliance on herbicide use. Mulugeta and Stoltenberg (1997) also observed that reduced input systems can provide as effective weed control as high input production systems.

It is possible that the separation between treatments for species number and Shannon's H′ would have increased had the study continued beyond 6 yr. Mulugeta et al. (2001) reported few differences when no-tillage was compared with moldboard plowing or chisel plowing over a 4 yr period, but a greater number of species was observed when no-tillage was practiced for 15 yr compared with these other tillage systems.

The influence of tillage on weed communities is contrary to many studies that report greater weed density and Shannon's H′ when tillage is eliminated compared with systems with some level of tillage (Blackshaw et al. 1994, 2001; Buhler and Oplinger 1990; Mulugeta et al. 2001; Schreiber 1992; Triplett and Lytle 1972). These discrepancies between studies may be due to the fact that weed management is generally confounded within tillage systems (Buhler and Oplinger 1990).

Derksen et al. (1993) also reported results not consistent with the predicted weed communities based on tillage. These authors described the discrepancies as a result of community fluctuations rather than consistent changes in community composition.

The influence of crop rotations and tillage systems on weed communities is complex, and often, conflicting results are presented in the literature. Crop rotation has been reported to have a limited influence on emerged weed and seedbank communities in previous research (Anderson et al. 1998; Andersson and Milberg 1998; Barberi and Cascio 2001; Barberi et al. 1997; Mulugeta and Stoltenberg 1997). Others have shown crop rotation can prevent the increase of one species over others when rotations allowed for effective herbicide programs coupled with crop rotations (Ball 1992; Schreiber 1992; Schweizer and Zimdahl 1984). Other researchers have reported crop rotation to be more important than tillage in determining weed composition (Thomas and Frick 1993). It is often difficult to separate influence of crop rotation on the basis of crop life cycle or its competitive ability vs. the weed management options available when a specific crop is grown. Drinkwater (2002) also discussed similar difficulties in systems-oriented research. A question of why a phenomenon is observed is better suited for additional studies where only a few variables are considered. However, on the basis of available literature, tillage seems to play a more important role than crop rotation.

Weed-management treatments used in this study were not static. Rather an approach toward weed management was predetermined for each system, and then the most efficacious herbicide or tactic within the parameters of the system was selected. Other studies examining the impact of herbicide application on weed communities have not observed differences when effective herbicide treatments were selected (Barberi and Mazzoncini 2001; Barberi et al. 1997; Dale et al. 1992; Kapusta and Krausz 1993; Mulugeta and Boerboom 1999; Mulugeta and Stoltenberg 1997). However, when static weed control treatments were imposed, there is a potential for those species not effectively controlled to produce seed and become dominant (Blackshaw et al. 1994, 2001; Manley et al. 2001).

Systems' Impact on Specific Weed Species—Spring Assessment

Relative abundance of six weed species differed among the four systems when assessed in the spring of the sixth year (Table 2). Mouseear chickweed (*Cerastium vulgatum* L. CERVU), a perennial species, was more common under continuous no-till corn production than Systems C and D. Fall tillage to plant winter wheat or vetch, in combination with herbicides applied to winter wheat effectively eliminated this species during the 6-yr period in Systems C and D. Common groundsel (*Senecio vulgaris* L. SENVU) was most abundant in the continuous no-till Systems (A1 and A2). Tillage before corn planting or herbicides applied to winter wheat (or both) was timed before flowering of this species and reduced its abundance in the other systems. It has been hypothesized that wind-borne species (such as common groundsel) will become more abundant in no-tillage systems (Buhler 1995; Derksen 1996).

Common chickweed [*Stellaria media* (L.) Vill. STEME] abundance was lowest in System C presumably because of effectiveness of the herbicides applied in winter wheat (Table 2). Herbicide applications before planting in Systems A1, A2, and B were not applied soon enough to prevent common chickweed seed production. Early flowering of common chickweed in the mid-Atlantic region requires early-spring control measures to prevent seed production. System D used a herbicide treatment for winter wheat, yet it was not applied annually because wheat only appeared in the rotation 1 yr out of 3. The lack of annual herbicide treatment allowed seedbank replenishment to occur.

Relative abundance of annual bluegrass (*Poa annua* L. POAAN) and mouse-ear cress [*Arabidopsis thaliana* (L.) Heynh. ARBTH] were greater in Systems B and C (Table 2). The presence of full-season soybean in the System B rotation allowed for a later planting date than corn, providing sufficient time for seed production. Also there was not an effective herbicide available to control annual bluegrass in winter wheat for System C. Sibara [*Arabis virginica* (L.) Rollins SIBVI] was most abundant with System B, yet it did not thrive well when winter wheat was included in the rotation or with continuous no-tillage corn (Systems A1 and A2).

Systems' Impact on Specific Weed Species—Fall Assessment

Five species differed in relative abundance among the four management systems in the fall of the final year of the study (Table 3). Canada thistle, a creeping perennial, was more abundant in continuous no-tillage corn, than in the tilled systems. Systems A1 and A2 used nicosulfuron plus dicamba that provided fair control of Canada thistle. System B plots were tilled only every other year, and glyphosate was used before soybean planting the other year of the cycle, together with chlorimuron applied POST to soybean. This was sufficient to prevent increase of Canada thistle abundance compared with continuous no-till corn.

Relative abundance of Canada thistle varied with treatments when assessed in the fall but not in the spring (Tables

TABLE 2. Relative abundance values for the most abundant species present in spring assessment of 1999, after 6 yr of cropping.[a]

Bayer code	Scientific name	Common name	Life cycle[c]	Management systems[b]				
				A1	A2	B	C	D
		Broadleaf species						
ARBTH	*Arabidopsis thaliana* (L.) Heynh.	Mouse-ear cress	WA	0 c	0.08 bc	0.37 a	0.22 ab	0.09 bc
CARHI	*Cardamine hirsuta* L.	Hairy bittercress	WA	0	0.11	0.04	0.05	0.05
LAMAM	*Lamium amplexicaule* L.	Henbit	WA	0.05	0.01	0.05	0.01	0.11
SENVU	*Senecio vulgaris* L.	Common groundsel	WA	0.52 a	0.60 a	0.22 b	0.06 c	0.33 b
SIBVI	*Sibara virginica* (L.) Rollins	Sibara	WA	0 b	0.01 b	0.13 a	0 b	0 b
STEME	*Stellaria media* (L.) Vill.	Common chickweed	WA	0.81 a	0.76 a	0.63 a	0.29 b	0.78 a
VIORA	*Viola rafinesquii* Greene	Field pansy	WA	0	0	0.04	0	0
ALLVI	*Allium vineale* L.	Wild garlic	P	0.03	0.12	0.13	0.07	0.08
CERVU	*Cerastium vulgatum* L.	Mouseear chickweed	P	0.15 a	0.11 ab	0.05 abc	0 c	0.01 bc
CIRAR	*Cirsium arvense* (L.) Scop.	Canada thistle	P	0.23	0.13	0.24	0.26	0.12
MYSMI	*Myosurus minimus* L.	Mousetail	P	0	0	0.01	0.05	0.02
TAROF	*Taraxacum officinale* Weber in Wiggers	Dandelion	P	0	0.01	0.01	0.05	0.03
		Grass species						
POAAN	*Poa annua* L.	Annual bluegrass	WA	0.08 bc	0.05 c	0.37 a	0.34 ab	0.07 bc

[a] Values within a row followed by the same letter are not significantly different, LSD ≤ 0.05.
[b] See footnote b in Table 1.
[c] Abbreviations: P, perennial; WA, winter annual.

TABLE 3. Relative abundance values for the most abundant species present in the fall assessment of 1999, after 6 yr of cropping.[a]

Bayer code	Scientific name	Common name	Life cycle[c]	Management systems[b]				
				A1	A2	B	C	D
		Broadleaf species						
ACCVI	*Acalypha virginica* L.	Virginia copperleaf	SA	0	0	0	0	0.04
	Amaranthus species	Pigweed spp.	SA	0.02	0.01	0	0	0.03
CHEAL	*Chenopodium album* L.	Common lambsquarters	SA	0 b	0.01 b	0.04 ab	0 b	0.16 a
DATST	*Datura stramonium* L.	Jimsonweed	SA	0.03 ab	0.02 b	0.04 ab	0.01 b	0.15 a
SOLPT	*Solanum ptycanthum* Dun.	Eastern black nightshade	SA	0 b	0.01 b	0.24 ab	0.01 b	0.30 a
XANST	*Xanthium strumarium* L.	Common cocklebur	SA	0	0	0.04	0	0.04
CIRAR	*Cirsium arvense* (L.) Scop.	Canada thistle	P	0.67 a	0.64 a	0.38 b	0.16 b	0.15 b
CYPES	*Cyperus esculentus* L.	Yellow nutsedge	P	0	0	0	0.20	0.01
PRTQU	*Parthenocissus quinquefolia* (L.) Planch.	Virginia creeper	P	0.09	0.01	0	0.01	0
PHTAM	*Phytolacca americana* L.	Common pokeweed	P	0.14	0.12	0.02	0.04	0.06
SOLCA	*Solanum carolinense* L.	Horsenettle	P	0.04	0.04	0.02	0.03	0
		Grass species						
	Digitaria species	Crabgrass spp.	SA	0.13	0.19	0.33	0.42	0.18
PANDI	*Panicum dichotomiflorum* Michx.	Fall panicum	SA	0	0.01	0	0	0.13
SETVI	*Setaria viridis* (L.) Beauv.	Green foxtail	SA	0.03	0	0	0	0.03
SORHA	*Sorghum halepense* (L.) Pers.	Johnsongrass	P	0 b	0 b	0.24 a	0.01 b	0.02 b

[a] Values within a column followed by the same letter are not significantly different, LSD ≤ 0.05.
[b] See footnote b in Table 1.
[c] Abbreviations: P, perennial; SA, summer annual.

2 and 3). Obviously, the systems that reduced shoot density in the summer did not have enough impact during a 6-yr period to significantly reduce the number of creeping rootstocks.

Johnsongrass, another perennial species, was eliminated from the continuous no-till corn, Systems A1 and A2, during a 6-yr period (Table 3). The use of nicosulfuron, which is very effective for johnsongrass control, contributed to this species decline. Johnsongrass density was higher in System B than in the more diversified C and D cropping systems. POST herbicides for johnsongrass control (nicosulfuron or quizalofop or both) were applied broadcast in Systems A1, A2, and C, whereas spot applications were made in System B. This may have resulted in the differences among these systems.

Summer annual species, common lambsquarters, eastern black nightshade, and jimsonweed, were more abundant in System D than in Systems A1, A2, and C (Table 3). Many factors contributed to this phenomenon, particularly herbicide efficacy and wide row spacings for soybean in System D. These three weed species are not very sensitive to the soybean herbicide used in System D (imazethapyr applied POST). These three species were controlled before planting double-cropped soybean in System C, either because of mechanical harvesting or glyphosate application. Common lambsquarters at this location were triazine-resistant. The herbicide program for Systems A1 and A2 was adapted to specifically deal with this problem, and its abundance decreased in Systems A1 and A2 after 6 yr. POST herbicides used in Systems A1, A2, B, and C, along with atrazine use in corn, prevented these species from becoming more abundant.

Summer annual grasses were similar for all the systems in 1999 with a low relative abundance across all systems after 6 yr of cropping practices (Table 3). Previous research has often shown an increase in summer annual grasses when tillage is reduced or eliminated or cropping systems simplified to continuous corn (or both) (Buhler 1995; Buhler and Mester 1991; Cardina et al. 1991; Forcella and Lindstrom 1988; Menalled et al. 2001; Schreiber 1992; Zanin et al. 1997).

The addition of a rye cover crop in System A2 did not affect winter annual weeds (Table 2) or contribute to overall summer annual weed control compared with no rye (Table 3). Weed management in both continuous corn systems (A1 and A2) was quite intensive. Furthermore, the rye cover crop was not fertilized in the spring with nitrogen, which resulted in less tillering and shorter plants than in a fertilized rye crop. The potential benefit of rye for weed control was not maximized in this study because no additional nitrogen was applied. The reason to include the rye cover crop was primarily for its benefit of capturing any excess nitrogen remaining after the corn crop, with the intent of contributing to water quality goals in the Chesapeake Bay watershed.

Seedbank Assessment in the Final Year

The seedbank assessment showed that the number of plants emerging was similar for all systems (Table 1). System A2 had the fewest number of weed species. Shannon's H′ for the seedbank was highest for Systems B and D and lowest for Systems A1 and A2. The diversity of crops or increased amount of tillage associated with Systems B, C, and D (or both) would explain the increased Shannon's H′ for the seedbank assessment.

A total of 43 species were recorded in the seedbank assessment (data not presented). The seedbank after 6 yr contained six weed species that differed among the four management systems (Table 4). Common chickweed, mouse-ear cress, and annual bluegrass in the seedbank followed the patterns observed with spring assessments (Table 2). Similarly, eastern black nightshade abundance in the seedbank paralleled observations with the fall assessment (Table 3). The number of carpetweed (*Mollugo verticillata* L. MOLVE) plants developing from the soil seedbank was greater for System A1 than for A2. Rye may have influenced the lower density of this species, although the specific mechanism was not determined. Similar to the community of mature weeds, the seedbanks were influenced by the effectiveness of weed control (Barberi et al. 1998) and tillage (Barberi and Lo Cascio 2001; Mulugeta and Stoltenberg 1997).

The two most common species in the seedbank were carpetweed and purslane speedwell (*Veronica peregrina* L. VERPG), but neither was common in the fall or spring assessments. The relative dominance of a few weed species in the soil seedbank compared with a greater number of emerged species has been reported previously (Cardina et al. 1991; Mulugeta and Boerboom 1999; Mulugeta and Stoltenberg 1997). Carpetweed and purslane speedwell seeds may have constituted a large percentage of the seedbank before conducting this study (baseline data not available) such that the high numbers of emerged seedlings are not reflective of the treatments during a 6-yr period.

Effects With Time

Densities of jimsonweed, eastern black nightshade, morningglory species, crabgrass, and fall panicum dramatically increased in a particular system for a 1- to 2-yr period then declined to levels similar to other systems (Figure 1). For example, crabgrass species densities during the 6-yr period were fairly low except in System C (Figure 1). In 1998, crabgrass densities were extremely high in System C because of an antagonism of the mixture of POST grass and broadleaf herbicides under the prevailing droughty conditions. However, this increase in crabgrass densities did not influence densities the subsequent year (Table 3). Hartzler and Roth (1993) have reported that level of weed control was dependent on level of control the previous season when a poor to moderately efficacious weed management program was used.

Canada thistle shoot density assessed in the fall was relatively stable for Systems C and D during the 6-yr period (Figure 2). It is assumed this was because of the diversity of tillage, rather than crop rotation (Andersson and Milberg 1998; Barberi and Lo Cascio 2001; Mulugeta and Stoltenberg 1997). Shoot densities fluctuated in System B during this time period. In fact, a high density in 1997 of 63 shoots 8 m^{-2} declined to 12 shoots 8 m^{-2} in 1999. Weed control practices during these 3 yr were similar; however, the degree of Canada thistle control, likely varied on the basis of differences in growth stages, herbicide effectiveness, and application variables. Similar to annual species, poor control 1 yr did not have detectable implications after 6 yr. Canada thistle shoot density had a steady increase in System A1, with the most striking increases observed in the last 2 yr of this

Table 4. Number of plants of the most abundant species present in the seedbank when sampled in the fall of 1999, after 6 yr of cropping.[a]

Bayer code	Scientific name	Common name	Life cycle[c]	Management systems[b] A1	A2	B	C	D
		Broadleaf species		No. plants 2,500 g^{-1} of soil				
CHEAL	*Chenopodium album* L.	Common lambsquarters	SA	3	3	1	2	1
MOLVE	*Mollugo verticillata* L.	Carpetweed	SA	38 a	0 c	1 bc	9 ab	8 ab
SOLPT	*Solanum ptycanthum* Dun.	Eastern black nightshade	SA	3 bc	1 c	7 ab	5 ab	20 a
ARBTH	*Arabidopsis thaliana* (L.) Heynh.	Mouse-ear cress	WA	4 ab	2 b	16 a	3 ab	1 b
CARHI	*Cardamine hirsute* L.	Hairy bittercress	WA	1	1	1	1	1
ERICA	*Conyza canadensis* L. Cronq.	Horseweed	WA	1	1	1	1	1
LAMAM	*Lamium amplexicaule* L.	Henbit	WA	1	1	1	1	3
SENVU	*Senecio vulgaris* L.	Common groundsel	WA	1	0	1	1	2
SIBVI	*Sibara virginica* (L.) Rollins	Sibara	WA	4	3	8	2	3
STEME	*Stellaria media* (L.) Vill.	Common chickweed	WA	4 ab	7 a	9 a	3 b	9 a
VERPG	*Veronica peregrina* L.	Purslane speedwell	WA	72	67	48	53	51
MYSMI	*Myosurus minimus* L.	Mousetail	P	1 ab	1 b	5 a	2 ab	1 b
OXAST	*Oxalis stricta* L.	Yellow woodsorrel	P	0	0	1	1	2
		Grass species						
	Digitaria spp.	Crabgrass species	SA	12	18	64	39	19
POAAN	*Poa annua* L.	Annual bluegrass	WA	3 b	2 b	27 a	9 b	4 b

[a] Values within a column followed by the same letter are not significantly different, LSD $\leq$ 0.05.
[b] See footnote b in Table 1.
[c] Abbreviations: P, perennial; SA, summer annual; WA, winter annual.

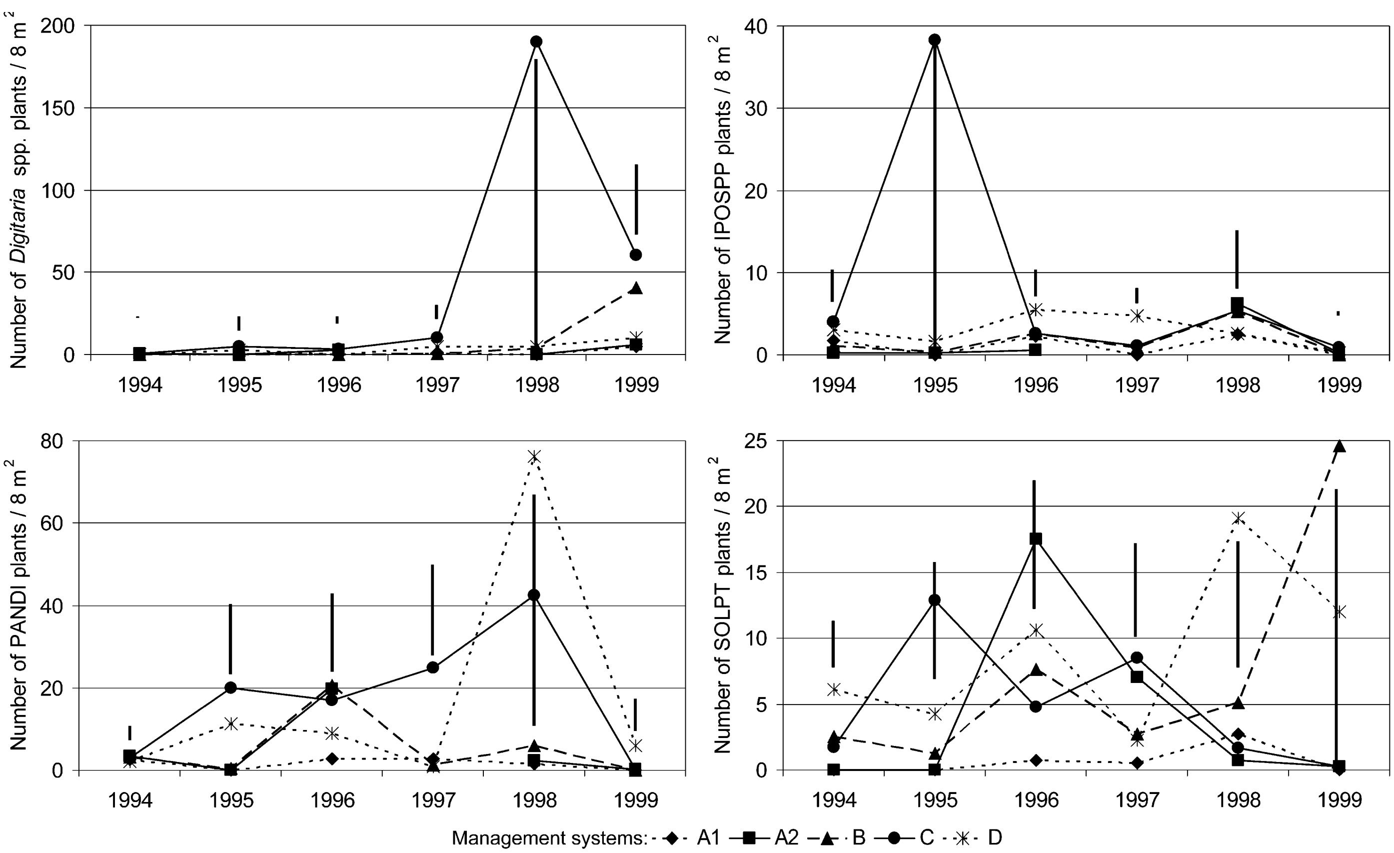

FIGURE 1. Fall density of crabgrass species, fall panicum, morningglory species, and eastern black nightshade during the 6-yr period at Chesapeake Farms, MD. Standard error bars are presented. Symbols represent the management systems of: A1; A2; B; C; and D.

study. System A2 showed a similar trend, but it was not as dramatic as System A1. Other studies have demonstrated that no-tillage systems favor Canada thistle populations compared with tilled systems (Coffman and Frank 1991; Donald 1990; Miller 1990; Triplett and Lytle 1972).

Yields and Net Returns

Year by system interactions for yield and net returns precluded the opportunity to make statistical comparisons among systems and crops across years. However, the within-year differences reveal the economic benefit of System B in this study. Six years' costs and returns data appear to favor System B with the 2-yr rotation of tilled corn and no-tillage soybean (Table 5) over the other systems. The relatively high corn yields in System B (Table 5) coupled with soybean net returns being higher for full-season soybean compared with corn (6-yr average for corn and soybean of \$180 ha^{-1} and \$371 ha^{-1} in System B, respectively) resulted in a more economically favorable system.

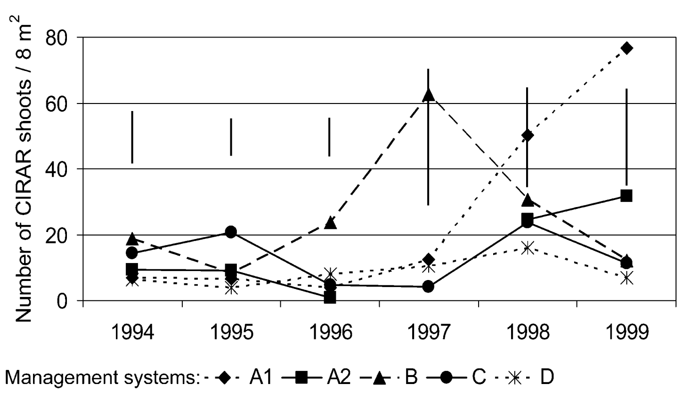

FIGURE 2. Canada thistle shoot densities in the fall during the 6-yr period at Chesapeake Farms, MD. Standard error bars are presented.

System D, with reduced inputs and a diverse rotation, performed second best, but net return was lower than System B (Table 5). System D soybean yielded as well as those of System B, but resulted in greater average costs because of charges for the rye cover crop and additional tillage. System D corn had the lowest yield averaged over the 6 yr. These lower yields were attributed partly to shorter growing season in 2 yr because of replanting required when slugs (species unknown) and other pests destroyed the initial stands.

System C no-till corn was the most profitable corn, delivering net returns of \$264 ha^{-1} on average yields of 8,938 kg ha^{-1} and costs of \$561 ha^{-1} (Table 5). Double-cropped soybean (System C) resulted in an economic loss in 3 of 6 yr (data not shown). Net return of winter wheat resulted in an economic loss in 4 of 6 yr, regardless of the management system (Systems C and D) (data not presented). With continuous corn in Systems A1 and A2, without and with cover crop, respectively, 6-yr average yields were comparable at 8,500 and 8,563 kg ha^{-1} (Table 5). In System A2, the additional costs of the rye cover crop and extra herbicide needed to kill the rye resulted in reducing profitability by \$64 ha^{-1} compared with System A1.

Effective weed management systems are possible regardless of the management approach. Because of the nature of

TABLE 5. Crop yield and net return for the four management systems during the 6-yr period of the study.

Management system[a]	Crop	1994	1995	1996	1997	1998	1999	6-yr average
		Yield						
		kg ha^{-1}						
A1	Corn	8,625	8,563	9,125	8,250	8,375	7,938	8,500
A2	Corn	8,500	9,313	9,250	6,938	9,500	7,875	8,563
B	Corn	9,375	11,000	10,188	8,625	9,875	8,500	9,563
C	Corn	8,375	9,438	10,750	7,625	8,500	8,750	8,938
D	Corn	9,438	8,813	8,500	7,563	8,625	6,375	8,250
SE[b]		660	962	1,058	811	824	1,459	1,199
B	Soybean	4,333	4,667	3,133	3,800	3,600	3,600	3,867
D	Soybean	4,067	4,133	2,933	3,733	4,067	4,067	3,800
C	Double-cropped soybean	2,267	2,733	1,733	1,200	1,400	1,400	1,800
C	Wheat	4,800	4,267	1,467	5,667	4,000	3,667	4,467
D	Wheat	3,667	5,467	2,200	7,067	3,333	4,867	4,400
		Net return						
		$[c] ha^{-1}						
A1		52	242	252	101	−183	40	84
A2		−54	264	205	−106	−158	−27	20
B		257	630	415	331	101	−84	274
C		40	321	111	111	−106	−44	119
D		151	440	138	225	30	−109	146
SE[b]		166	180	294	180	205	143	253

[a] See footnote b in Table 1.
[b] Abbreviations: SE, standard error of the mean.
[c] Net return is based on United States currency.

the treatments, this study was not able to determine subtle changes in weed communities. Overall, weed communities were quite stable and effective weed management did not result in dramatic changes in the weed community.

Research such as this is necessary to evaluate the influence of cropping systems on various parameters. This research is vital to understanding the cumulative impact of various production practices on sustainability. Although not all results can adequately be explained on the basis of cropping systems research, it serves as an impetus for further, more defined studies.

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