Electronic Journal of Integrative Biosciences 7(2):1-24. 2 May 2009

Is No-Tillage Enough? A Field-Scale Watershed Assessment of Conservation Effects

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Keywords: No-tillage, crop rotations, hydrology, sustainability, CEAP

ABSTRACT

No-tillage and contour strip cropping are two conservation practices recommended by the Natural Resources Conservation Service (NRCS). Our objective was to quantify the effects of those practices after imposing them on deep loess soils in two field-scale watersheds in western Iowa. Hydrology, soil fertility, and crop yield response were evaluated for a 9-yr period after converting both watersheds from conventional tillage, continuous corn (*Zea mays* L.) to a no-tillage corn – soybean [*Glycine max* (L.) Merr.] rotation or no-tillage contour strip-cropping with a 6-year corn, soybean, and alfalfa (*Medicago sativa* L.) rotation. Despite having three of the most intense rainfall events recorded during the 45-year research record for this site, no-tillage plus contour strip-cropping reduced runoff 20% for rainfall amounts of 35 to 80 mm d^{-1} (1.4 to 3.2 in d^{-1}). No-tillage alone, however, resulted in increased runoff. After a 4-yr transition period, the diversified 6-yr rotation reduced N fertilizer requirements for corn by approximately 75% compared to the long-term average [178 kg N ha^{-1} (159 lb N ac^{-1})] for continuous corn. Improved genetics, coupled with the conservation practices and good agronomic management, increased corn yield by 2 Mg ha^{-1} (32 bu ac^{-1}) compared to the long-term average. Average soybean [3.6 Mg ha^{-1} (54 bu ac^{-1}) and 1st, 2nd, and 3rd year alfalfa yields [4.2, 7.5, and 7.5 Mg ha^{-1} (1.9, 3.3, and 3.3 tons ac^{-1}), respectively] were typical for this region. Economic comparisons emphasize the impact of market price and importance of agronomic management. We conclude that implementing conservation practices that include diversified crop rotations plus very reduced or no-tillage operations can be profitable for land owners/operators and more environmentally sustainable for taxpayers supporting conservation for clean water and healthy soils.

Abbreviations: ARS – Agricultural Research Service; CEAP – Conservation Effects Assessment Project; DLRS – Deep Loess Research Station; K – Potassium; NRCS – Natural Resources Conservation Service; P – phosphorus; SOM – soil organic matter; USDA – U.S. Department of Agriculture

INTRODUCTION

Conservation became an integral part of U.S. agriculture policy when the 1935 Soil Conservation and Domestic Allotment Act (Public Law 74-46) was passed in response to the 1930s Dust Bowl disaster (Elliott, 1936; Rasmussen, 1983). Societal benefits of promoting good stewardship on private lands were soon observed and agricultural conservation programs have continued to this day.

The 2002 Farm Bill significantly expanded conservation programs and called for greater federal funding (Mausbach and Dedrick, 2004), but with the proposed increase came many questions regarding the efficacy of current and past conservation programs. The Office of Management and Budget (OMB) wanted to know if American taxpayers were getting measurable environmental benefits for their investments. They charged the Natural Resources Conservation Service (NRCS) with verifying implementation of conservation practices and showing how effective those practices were for improving water quality, soil quality, water conservation and wildlife habitat on croplands, grazing lands and wetlands (USDA-NRCS, 2007).

To help answer those questions, we recognized that a farming system transition that was made in 1996 on two watersheds at the Deep Loess Research Station (DLRS) in western Iowa could provide quantitative data regarding the effects of no-tillage and no-tillage plus rotational contour strip cropping on hydrology, soil fertility and crop yield response for soils representative of Major Land Resource Area (MLRA) 107. The DLRS had been an Agricultural Research Service (ARS) research site since the 1960s and thus had well documented management and response records (Appendix Table A1).

The DLRS farming system transition was based on previous studies that documented tillage and crop rotation effects in the U.S. Corn and Soybean Belt. Several of those studies had indicated that diversified cropping systems and reduced tillage could decrease off-field losses of sediment, nutrients and chemicals (Burwell et al., 1975; Johnson, et al., 1979; Laflen and Tabatabai, 1984;

Andraski et al., 1985; Buhler et al., 1993; Kanwar and Baker, 1993). The primary mechanisms attributed to those anticipated effects were improved water infiltration, resistance to erosion and stabilization of surface soil through better aggregation and residue cover, and improved nutrient and water use throughout the growing season. However, information comparing yields and economics on a systems basis with those from the historical management practices was not readily available. Furthermore, although previous studies had suggested that reduced tillage and extended cropping systems would be more sustainable than the continuous corn grown on the site since the early 1960s, quantitative evidence was lacking.

During or shortly after the cropping system transition was completed, several publications provided evidence to support our hypothesis that reduced tillage and extended crop rotations were environmentally more sustainable and could produce competitive yields and economic returns. For example, in Minnesota, Randall et al. (1997) documented that perennial cropping systems that included alfalfa or CRP (Conservation Reserve Program) land that had a mix of alfalfa and perennial grasses had flow-weighted nitrate-nitrogen (NO_3-N) concentrations in tile drainage that were 37 and 35 times lower than from continuous corn (CC) or corn-soybean (CS) systems, respectively. They attributed these results to increased season-long evapotranspiration (ET) by the perennial crops that led to less drainage through tile lines and greater uptake and/or immobilization of N compared to that from annual row crops.

Karlen et al. (1999) had previously examined the long-term effects of a CC monoculture system at the DLRS in terms of agronomic production and sustainability. They found that Carlson's (1990) earlier reports that the weather-related factors of plant-available water and heat stress which affected corn yields in central Iowa also controlled corn grain yield at the DLRS. In addition, CC yields declined over time in relation to the degree of soil erosion and loss of soil organic carbon. The CC system also selectively favored foxtail (*Setaria spp.*) populations that gradually became very difficult to manage.

In a northeastern Iowa study (Kanwar et al., 2005), an extended corn-soybean-oat (*Avena sativa* L.)/berseem clover (*Trifolium alexandrium*) strip intercropping rotation had significantly greater corn yields than a simple CS rotation (9.03 vs. 8.58 Mg ha^{-1}; $P < 0.05$). Karlen et al. (2006) also found that for three locations in northern Iowa and one in southwestern Wisconsin, the short- and long-term crop rotations they studied showed that including at least three years of forage crops resulted in the highest soil quality ratings based on a number of physical, chemical and biological indicators. For all locations, CC consistently had the lowest soil quality ratings based on the measured indicators. They concluded that this signified that CC cropping systems could have several negative effects on all aspects of soil quality. They concluded that diverse and extended crop rotations would improve the sustainability of agriculture throughout the northern Corn and Soybean Belt. Weinhold et al. (2006) reached similar conclusions that extended crop rotations had positive impacts on soil quality indicators from their assessments of several cropping systems tailored for the Northern Great Plains.

Adoption of no-tillage and especially no-tillage plus extended crop rotations was expected to affect partitioning of water between runoff and infiltration because of increased crop water use associated with greater species diversity and an increased length of growing season (Dinnes, 2004; Zhang and Schilling, 2006 a,b). Similar conclusions were reached by Tomer et al. (2005, 2006) who reported that conservation tillage stabilized watershed hydrology and better maintained water holding characteristics in the surface of deep-loess soils, compared to conventional tillage.

A previous study on DLRS Watershed 3 showed the interconnectedness of land management and hydrologic response on the deep loess soils. Tomer et al. (2005) found that when another conservation practice (ridge tillage) was implemented, it was very effective for reducing runoff by increasing infiltration. However, this practice increased base flow and created a potential surface water quality problem when fertilizer N applications exceed crop requirements and thereby provide residual nitrate-nitrogen (NO_3-N) for leaching. We expected the extended rotation which included alfalfa would be more productive and sustainable because the legume would reduce subsequent N fertilizer requirements for corn. Including alfalfa in the rotation would stabilize soil structure, reduce runoff, increase infiltration, decrease soil erosion, and increase soil organic matter.

Our objective was to examine productivity and environmental effects of two conservation practices – no-tillage and no-tillage plus contour strip-cropping – imposed on deep loess soils representative of MLRA 107. Effects on hydrology, soil fertility status, crop yield, and economic return were quantified.

MATERIALS AND METHODS

Field-scale watershed research was initiated at the DLRS, near the town of Treynor, Iowa, in 1964. Four field-scale watersheds associated with the DLRS were representative of MLRA 107 in western Iowa and northwestern Missouri (Figure 1). The predominant soils included Typic Hapludolls, Typic Udorthents and Cumulic Hapludolls (USDA-SCS, 1989), all classified as fine-silty, mixed mesic with moderate to moderately rapid permeability. The landscape consists of steeply sloping hills with highly erodable soils and frequent gully formation in row-cropped fields. Upland soils often have low soil organic matter (SOM) content, while those in low-lying areas have higher levels because of greater soil water content and deposition. The Monona series is located on summit and shoulder positions, with Ida and Dow on sideslopes, and Napier and Kennebec located on toeslopes and in drainageways. All of the series are quite homogeneous, generally non-stratified, with uniform texture, high available soil water holding capacity, and good aeration as well as being non-restrictive to plant root development (USDA-SCS, 1989).

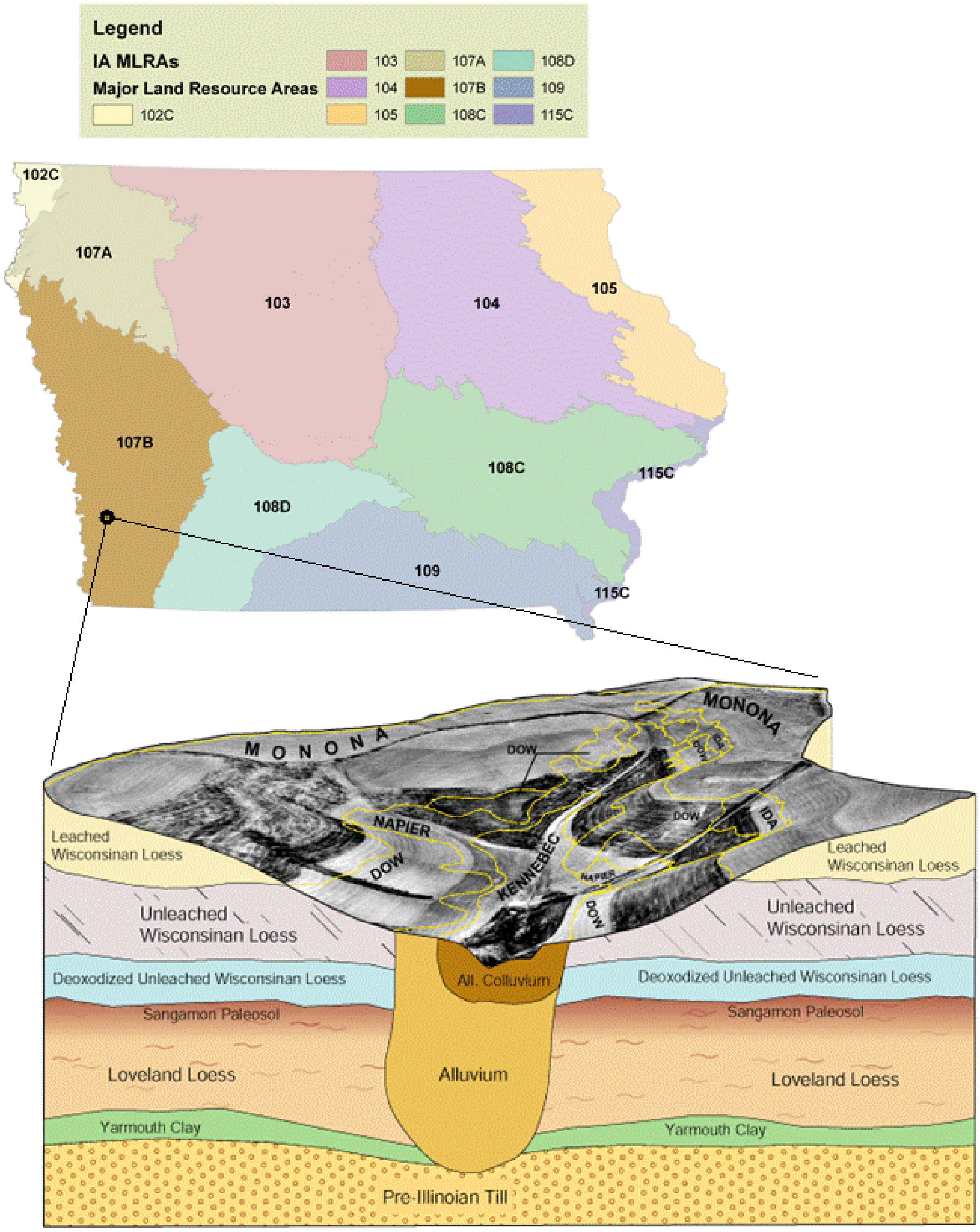
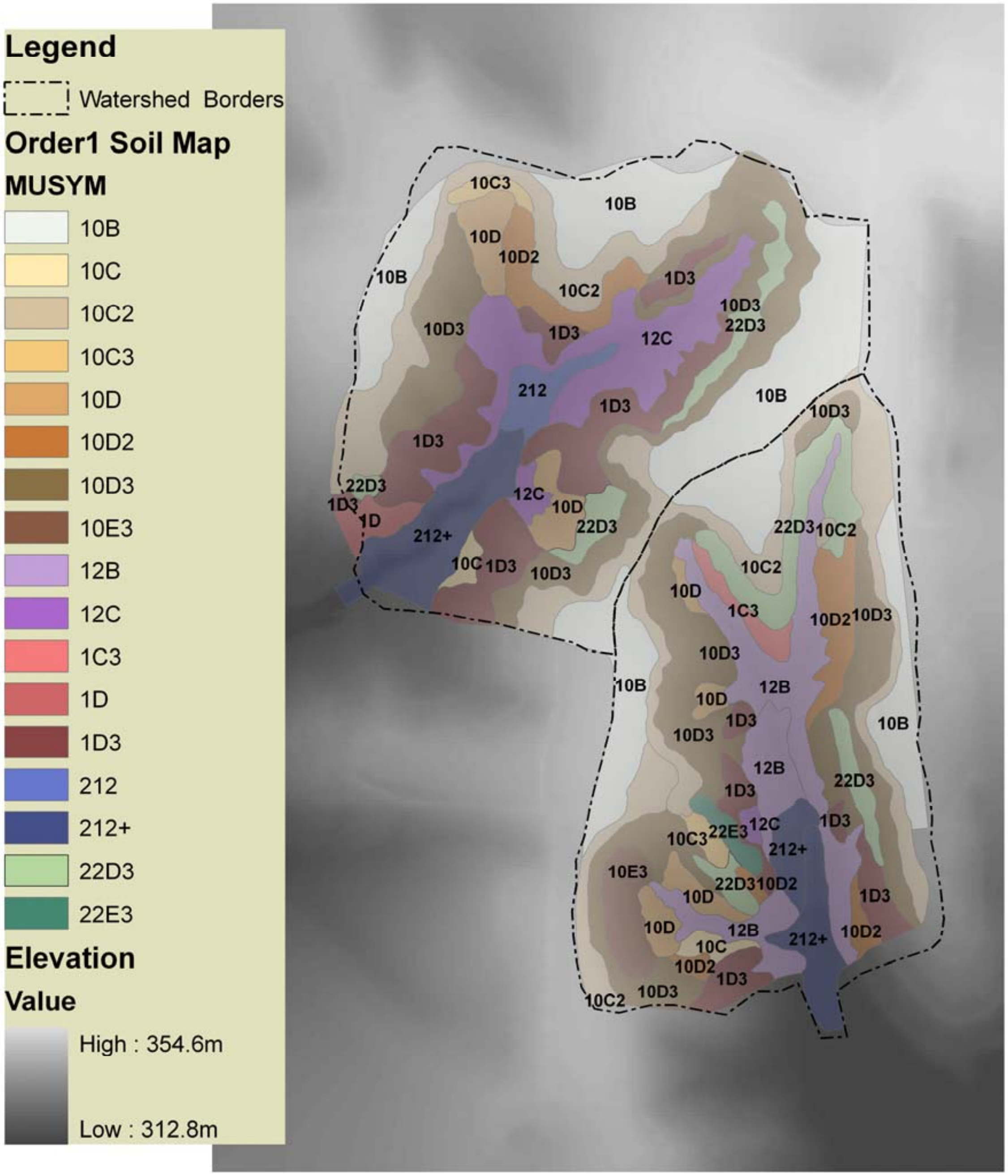


Figure 1. Deep Loess Research Station Watersheds 1 and 2 locations within Iowa's landform regions, and typical landscape soil series and underlying stratigraphy of a deep-loess southwestern Iowa watershed (adapted from Karlen et al., 1999).

Two conservation practices – no-tillage and no-tillage plus contour strip cropping – were imposed on DLRS Watersheds 1 and 2 in 1996. Both watersheds had very similar physical characteristics and soils (Figure 2), with drainage areas above the weirs being 34.9 ha (86 ac) for Watershed 1 and 36.4 ha (90 ac) for Watershed 2 (Figure 2). The distribution of soil map units and erosion classifications were similar although there are minor differences in aspect. Elevation differences were minimal with yield plots in Watershed 1 ranging from 325 to 349 m (1066 to 1145 ft) and those in Watershed 2 ranging from 328 to 353 m (1076 to 1158 ft) above sea level. Landscape attributes including slope percentage and aspect, profile and plan curvature, sediment index, stream-power index, wetness index and drainage catchment area did vary between the two watersheds, with

Watershed 1 being slightly steeper, by an average of 1.1% (Karlen et al., 1999). Tomer et al. (2005), after examining the hydrologic records for the 25 years prior to 1996 when the two watersheds were managed identically with conventional tillage and continuous corn, concluded that terrain differences probably caused Watershed 2 to have 11% less runoff and 20% greater baseflow than Watershed 1. Using autoregressive models, they found that variation in baseflow and total stream discharge from these watersheds was similarly timed at multi-year, seasonal, monthly, and daily time scales, with these differences influencing only the regression-model intercepts.



Soil Map Unit Symbols (Soil MUSYM):
1 = Ida silt loam 10 = Monona silt loam 12 = Napier silt loam
22 = Dow silt loam 212 = Kennebec silt loam

Figure 2. Watershed 1 (lower right) and 2 (upper left) boundaries and soil map unit distribution at the Deep-Loess Research Station near Treynor, IA USA.

From 1963 through 1995, conventional tillage that ran parallel to landscape contours was used to prepare a seedbed for corn each year. During that period, conventional tillage first consisted of moldboard plowing, disking, and harrowing before planting and then controlling weeds with herbicides and cultivation. From 1978 on-ward, moldboard plowing was replaced by chisel plowing and cultivation for weed control was stopped as herbicides became more effective for total weed control. Phosphorus (P) and potassium (K) application rates were based on prevailing ISU Extension Service recommendations, with a limited number of soil test analyses being used to monitor soil pH, P, K, and SOM levels. Average P fertilizer rates were 32 and 28 kg P ha^{-1} yr^{-1} (29 and 25 lb ac^{-1} yr^{-1}) for Watersheds 1 and 2, while K rates averaged 22 kg ha^{-1} (20 lb ac^{-1} yr^{-1}) for both watersheds (Karlen et al., 1999). Nitrogen (N) rates averaged 178 kg ha^{-1} yr^{-1} (159 lb ac^{-1} yr^{-1}) for both watersheds (Karlen et al., 1999), except for a 6-yr period (1968 – 1974) when Watershed 1 received an average application rate of 448 kg N ha^{-1} yr^{-1} (400 lb ac^{-1} yr^{-1}) to determine leaching potential following excessively high N application rates (Schuman et al., 1975: Tomer and Burkart, 2003). Following crop harvest in autumn 1995, both watersheds were sampled along multiple transects to determine the baseline pH, P, and K content.

Field Operations

Beginning in 1996, both watersheds were converted to no-tillage with crop rows planted parallel to landscape contours. Figure 3 shows the distribution of corn and soybean in Watershed 1 and the contour strip-cropping in Watershed 2. Contour strips in Watershed 2 were imposed parallel to landscape contours using a crop strip width of 33.5 m (110 ft) to accommodate our farmer-cooperator's planting and harvesting equipment. The number of point-rows was minimized by including small grass/legume strips between crop strips as needed.

Over the nine year period (1996 to 2004) numerous field operations were conducted to implement the conservation practices (Appendix Figure A1). Seasonal timing varied appreciably depending upon weather and soil conditions, and many operations were done only on a limited basis in response to weed and insect infestations that exceeded economic thresholds or to make fertilizer and lime applications during transition from conventional- to no-tillage management. For example, pre-plant tillage, consisting of one or two passes with a disk-harrow was done in 1996. All areas of corn in both watersheds were cultivated during the first year of transition. To reduce weed pressure in 2001 to 2003, corn in both watersheds was rotary hoed soon after emergence.

Pesticide applications (Appendix Tables A2 to A4) varied widely in their timing, rates and chemistries because of the different crops and differences between the cooperators participating in the farmer-researcher partnership used for DLRS farming operations (Karlen et al., 2007). Pre-emergence herbicides were applied either a few days before, during, or after planting corn and soybean (Appendix Figure A1). Post-emergence herbicide applications for corn and soybean were targeted for balance between peak weed emergence and early growth stages in June and July depending on weather patterns. The only insecticide application during the nine-year period for corn occurred at planting during the first year to minimize western corn rootworm (*Diabrotica virgifera virgifera*) pressure following 33 years of continuous corn. Alfalfa production required insecticide applications for all strips in 1997 and 1999 and for A1 and A2 strips in 2001 and 2002 to manage potato leafhopper [*Empoasca fabae* (Harris)] infestations (Appendix Table 4). Herbicides to manage grass outbreaks, primarily yellow foxtail (*Setaria glauca)*, were applied to the A1 and A2 strips in midsummer of 2001 to 2003. In mid- to late-fall, herbicides were applied to kill A3 alfalfa strips in preparation for rotation to first year corn (C1).

Fertilizer and lime applications for Watersheds 1 and 2 (Table 1) varied in rate, form and date of application (Appendix Figure 1). Agricultural lime rates were based on ISU Extension Service recommendations for soil samples taken along transects in both watersheds during the autumn of 1995. All crop areas received a 4.48 Mg ha^{-1} (2.0 tons ac^{-1}) effective calcium carbonate equivalent (ECCE) application of agricultural lime in early 1996. The Monona soils received another 7.4 Mg ha^{-1} (3.3 tons ac^{-1}) ECCE of agricultural lime in late 1996 to correct the much lower, near-surface soil pH values than at other landscape positions. No other agricultural lime applications were made during the remainder of the study. Soil P and K analyses were optimum or higher in 1995, so P, K and zinc (Zn) levels were managed through occasional broadcast applications at rates determined by soil-test results (Sawyer et al., 2006).

Nitrogen fertilizer management differed between Watersheds 1 and 2 because of differences in the conservation practices being evaluated. For both, a small amount of N fertilizer was occasionally applied prior to planting with P, K and Zn (Tables 1 and 2), but the majority of N fertilizer for Watershed 1 was a fixed rate based on the long-term average yield (Karlen et al., 1999). Beginning in 1997, N applications on Watershed 2 were based on late-spring soil nitrate test (LSNT) results (Blackmer et al., 1997), so that contributions of available N from prior legume crops could be accurately accounted. A sampling depth of 60 cm was used because previous studies (Karlen et al., 1998) showed relatively uniform soil NO_3-N concentrations to a depth of 90 cm (36 in) for both watersheds. As recommended by Binford et al. (1992), a critical N concentration of 16 µg g^{-1} was used because of the 60-cm sampling depth instead of the 25 µg g^{-1} NO_3-N suggested for 30 cm (12 in) soil samples. Fertilizer N rates were determined using Equation 1:

$$[(16\ \mu g\ g^{-1}\ NO_3\text{-N}) - (NO_3\text{-N}\ \mu g\ g^{-1}\text{ to }60\text{ cm})] \times 8.96 = \text{kg N ha}^{-1} \qquad [1]$$

Late-spring soil nitrate samples were collected across each corn strip within Watershed 2 and not isolated to the yield plot locations that were based on topographic position. LSNT results were determined for each corn strip but since the values were very similar for 1997 – 1999, a single target N application rate was computed by averaging the values for all C1 and C2 strips. For 2000 to 2004, there was a substantial difference in the amount of N fertilizer needed for C1 and C2, so the N fertilizer application rate varied (Table 1).

In spring 1996, N fertilizer was applied prior to corn planting in Watershed 1 but subsequent N fertilizer applications were side dress applied during the first three weeks of June. Our N fertilizer source was anhydrous ammonia in both watersheds for 1996 to 1998, but from 1999 to 2004, urea ammonium nitrate (UAN) solution was used because it could be applied more accurately to achieve the target N fertilizer rate.

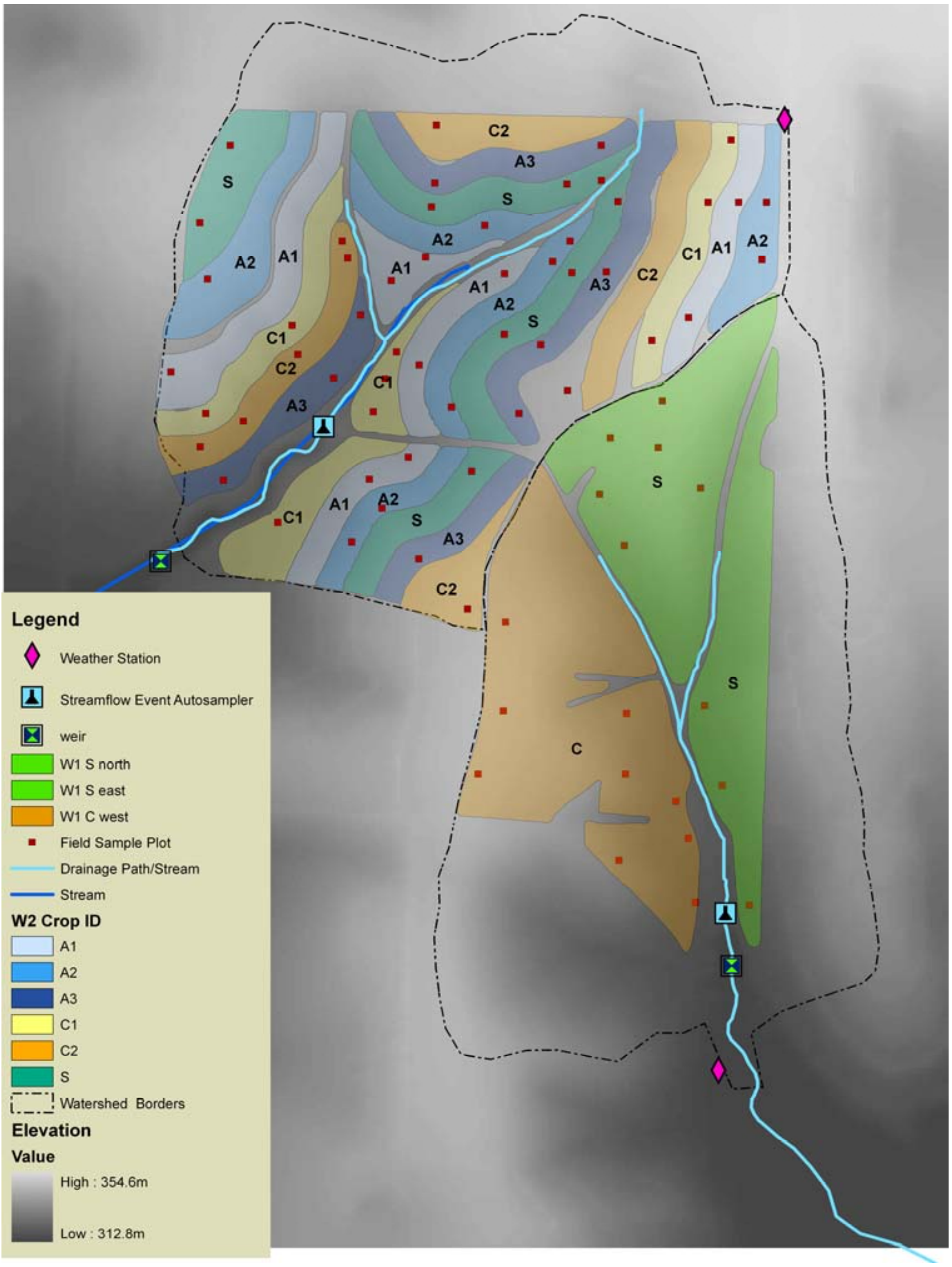


Figure 3. No-tillage corn and soybean locations in 1996 and 2002 (rotated for other years) within Watershed 1 (lower right) and the distribution of crops among contour strips (rotated annually in a 6-yr cycle) within Watershed 2 (upper left) at the Deep-Loess Research Station. The field sampling plots, weather station, and water sampling sites are also shown.

Table 1. Fertilizer and lime applied to Watersheds 1 and 2 between 1996 and 2004.

	Watershed 1			Watershed 2		
Year	Crop[†]	Material	Rate	Crop[†]	Material	Rate
1996	C, S	Ag-lime	4.5 Mg ha^{-1}	All	Ag-lime	4.5 Mg ha^{-1}
	C	NH3-N (SD)[‡]	206 kg N ha^{-1}	C1, C2, S	NPK (Bdcst)	2.7-5.4-10.4 kg ha^{-1}
	C, S	NPK (Bdcst)[‡§]	2.7-5.4-10.4 kg ha^{-1}	A1-3	NPK (Bdcst)	35.3-11.8-22.6 kg ha^{-1}
	C, S	Ag-lime (summit)	7.4 Mg ha^{-1}	C1, C2	NH3-N (SD)	228 kg N ha^{-1}
				All	Ag-lime (summit)	7.4 Mg ha^{-1}
1997	C	NPK (Bdcst)	9.4-18.9-36.1 kg ha^{-1}	C1, C2	NPK (Bdcst)	9.4-18.9-36.1 kg ha^{-1}
	C	NH3-N (SD)	142 kg N ha^{-1}	C1, C2	NH3-N (SD)	66 kg N ha^{-1}
1998	C	NPK+Zn (Bdcst)	0-14.1-26.9 + 9.0 kg ha^{-1}	C1, C2	NPK + Zn (Bdcst)	0-14.1-26.9 + 9.0 kg ha^{-1}
	C	NH3-N (SD)	143 kg N ha^{-1}	C1, C2	NH3-N (SD)	105 kg N ha^{-1}
1999	C	NPK+Zn (Bdcst)	8.7-4.9-18.9 + 5.8 kg ha^{-1}	C1, C2	NPK + Zn (Bdcst)	8.7-4.9-18.9 + 5.8 kg ha^{-1}
	C	UAN[¶] (SD)	113 kg N ha^{-1}	C1, C2	UAN (SD)	100 kg N ha^{-1}
2000	C	NPK (Bdcst)	15.7-22.0-23.0 kg ha^{-1}	C1, C2	NPK (Bdcst)	15.7-22.0-23.0 kg ha^{-1}
	C	UAN (SD)	124 kg N ha^{-1}	C1	UAN (SD)	68 kg N ha^{-1}
				C2	UAN (SD)	96 kg N ha^{-1}
2001	C	UAN (SD)	134 kg N ha^{-1}	C1, C2	NPK (Bdcst)	15.5-31.5-0 kg ha^{-1}
				C1	UAN (SD)	65 kg N ha^{-1}
				C2	UAN (SD)	94 kg N ha^{-1}
2002	C	UAN (SD)	134 kg N ha^{-1}	All	NPK (Bdcst)	15.5-31.5-0 kg ha^{-1}
				C1	UAN (SD)	62 kg N ha^{-1}
				C2	UAN (SD)	93 kg N ha^{-1}
2003	C	UAN (SD)	134 kg N ha^{-1}	C1	UAN (SD)	40 kg N ha^{-1}
				C2	UAN (SD)	81 kg N ha^{-1}
2004	C	UAN (SD)	134 kg N ha^{-1}	C1	UAN (SD)	62 kg N ha^{-1}

[†] C1-S-C2-A1-A2-A3: corn-soybean-corn-alfalfa-alfalfa-alfalfa six year annual crop rotation

[‡] Bdcst = Broadcast; SD = Sidedress

[§] Fertilizer nutrients in elemental form

[¶] UAN = urea-ammonium nitrate fertilizer solution

Table 2. Hydrologic budgets (average annual) for two watershed during two time periods. 1996 was omitted to allow one year of transition to respond to conservation practices first implemented that year.

Watershed	Time period	Precipitation (P)	Stream discharge (Q)	Q/P	Runoff (R)	R/P	Baseflow (B)	B/Q
		mm	mm		mm		mm	
W1	1975-1995	819	187	0.228	69	0.084	118	0.631
	1997-2001	877	318	0.363	134	0.152	184	0.579
W2	1975-1995	819	208	0.254	62	0.076	146	0.702
	1997-2001	877	262	0.298	69	0.079	193	0.737

Field Sampling Sites

After developing the cropping system transition plan in 1996, a new set of sites for sampling crop yield and soil properties was established within each of the watersheds. Nine sites [3 landscape positions/soil map units (Monona, Ida, and Kennebec) that were replicated 3 times] were located in both the corn half and the soybean half of Watershed 1 (Figure 3). Within Watershed 2, the goal was to establish nine sampling sites (3 soils x 3 reps) within each of the contour strips assigned to the 6-year rotation. A digital elevation map was used to identify potential sites for summit, sideslope, and toeslope (Monona, Ida, and Kennebec, respectively) positions (Figure 3). Each site was to be approximately 30 m by 50 m (98 ft by 164 ft) in size, so that sampling could continue for several years. The location of each site was visually verified and corner positions were recorded using a Trimble[1] global positioning system (GPS). Subsequently, the center for each sampling site was identified so that crop yield samples could be collected by navigating to that point and then staying within the original plot boundaries. Unfortunately, during verification one Kennebec site was omitted so only 53 of 54 potential sites were established in Watershed 2.

Soil Fertility Evaluations

Soil samples were collected along several transects in the fall of 1995 to establish a soil fertility baseline prior to the cropping system change and to determine initial fertilizer and lime requirements. Starting in 1998, soil samples were collected biennially from each field-sampling site (Figure 3) after grain harvest. Samples were analyzed for pH and Mehlich III (Mehlich, 1984) extractable P and K. Soil extracts were analyzed using a simultaneous inductively coupled plasma-atomic emission spectrometer (ICP-AES) (Themo Jarrell Ash ICAP 61E, Franklin, MA).

Crop Yield Measurements

Alfalfa biomass samples were collected at each field sampling site in Watershed 2 two to four times each year prior to harvesting the entire strip for hay. After navigating to the center of each sampling site, six 0.65 m^2 (7 ft^2) areas were hand-clipped approximately 70 mm (3 in) above ground level within the sampling area, combined, and dried at 60° C (140° F).

Corn grain yields were measured by hand-harvesting 12.1 m^2 (0.003 ac) at each sampling site (Figure 3) where corn was being grown. After shelling, grain moisture was determined and weights were adjusted to a moisture content of 150 g kg^{-1} (15%) before calculating grain yield. For soybean, a plot combine was used each year from 1996 though 1999 to harvest small [~120 m^2 (0.03 ac)] areas near the center of each sampling site. From 2000 to 2004, GPS equipped yield monitors were attached to our farmer-cooperators' combines to measure soybean and corn yield data for both watersheds. Soybean yields were adjusted to a water content of 130 g kg^{-1} (13%). Unfortunately, the data collected by our cooperators were not reliable due to a multitude of problems including poor GPS coverage throughout the hilly terrain. For corn, there were back-up hand samples, but for soybean, plot yields for those years are simply not available.

Hydrology

Precipitation and stream discharge were monitored as described by Tomer et al. (2005). Briefly, stream discharge was measured using broad crested weirs with continuous monitoring of stream stage. Runoff and baseflow contributions to discharge were estimated based on hydrograph separation techniques using semi-logarithmic plots of total discharge. Precipitation was measured using tipping bucket rain gauges. Average daily precipitation common across both watersheds was used to represent precipitation inputs for this study. We compared runoff and baseflow from 1975 through 1995 with that observed from 1996 through 2001 to determine the effects of the two conservation systems on watershed hydrology. However, in comparing baseflow, we omitted 1996 to provide a transition period, given the slow movement of groundwater in these watersheds. Discharge records during 2002 to 2004 were not considered because drought minimized runoff, and leakage problems at the Watershed 2 weir required much of that watershed's baseflow record to be estimated after 2002. For runoff, our comparison was based on graphs of cumulative runoff (average mm yr^{-1}), sorted by increasing amounts of precipitation received (mm day^{-1}), excluding all precipitation events that did not result in runoff. Snowmelt events were also excluded. For baseflow, we compared how the relative difference in annual discharge between watersheds shifted after the conservation systems were implemented.

Economic Assessments

Costs and returns for the two crop rotations were computed for 2000 through 2004 using Iowa State University Extension's (ISUE) annually updated Ag Decision Maker accounting spreadsheet (ISUE FM-1712). Data from the first four years (1996 through 1999) were not used because management challenges (*e.g.* weed pressure and soil acidity) associated with changing from continuous corn to a diversified rotation resulted in some abnormally low yields and because rotation effects on N rate did not become evident until 2000. Also, some generalizations were required for both watersheds since economic analyses can vary widely from one farm to the next, even when the fields are side-by-side. To remove the variations inherent with crop marketing, federal commodity price supports were not included in our analyses. Default values within FM-1712 were used for inputs where actual costs were not recorded (*e.g.* fertilizer and pesticide prices) and for specific field operations where FM-1712 listed costs for custom operations and labor. Cropland costs for moderately productive land were used for all crops since both rotations were grown on similar soils and landscapes.

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[1] Mention of trademark proprietary product, or vendor is for information only and does not constitute a guarantee or warranty of the product by the USDA or imply its approval to the exclusion of other products or vendors that may also be suitable.

Three different economic scenarios were examined. Corn yields from hand-harvested plots were used for all scenarios. For soybean, USDA-NASS Pottawattamie County average yields for 2000 through 2004 were used because measured data were not available. However, before using the averages, measured yields for 1996 through 1999 (Table 4) were compared with the NASS averages for those years and found to be approximately 0.7 Mg ha^{-1} (10.5 bu ac^{-1}) lower which means that our economic estimates for soybean may be low for all three scenarios. For alfalfa, scenarios 1 and 2 used hand-harvested yield estimates, but for scenario three, average yields for Pottawattamie County were used because the measured yields averaged 1.6 Mg ha^{-1} (0.7 tons ac^{-1}) below the Pottawattamie County average and were lower than expected for the soils, weather patterns, and management practices being used. For scenario 1, corn, soybean, and alfalfa prices for 2007 ($126.02, $227.85, and $90.41 Mg^{-1}, respectively) were used to examine rotation differences based on recent economic trends. For scenarios 2 and 3, we used the average crop prices for each year listed by the NASS (Table 5).

Statistical Analyses

Statistical techniques developed for small-scale replicated field studies are not useful for evaluating conservation practices at the watershed scale because variation in topography, soil map unit distribution, runoff, drainage and subtle differences in farming operations among landowners prevent replication. Therefore, we present means and standard errors for the various landscape positions and years that were evaluated.

RESULTS AND DISCUSSION

Weather Patterns

Growing season (March through October) temperatures during this nine-year period varied considerably compared to the 1964 to 1995 DLRS average (16.4° C). Averages for four years (1996, 1997, 1999, and 2002) were 1.5, 0.9, 0.6, and 0.6° C lower; those for three years (1998, 2001, and 2003) were similar (± 0.3° C), while for 2000 and 2004 the average temperature was 1.2 and 0.6° C warmer. Precipitation for these same months was below average (731 mm) for five years (1997, 2000, 2001, 2002, and 2003 (-98, -126, -168, -19, and -31 mm, respectively), average for 2004, slightly above average (+34 mm) in 1996, and substantially above the long-term average in 1998 and 1999 (+262 and +278 mm, respectively). The amount of precipitation in 1998 and 1999 was also the greatest on record for the DLRS and had consequences for total runoff from the conservation systems implemented in the two watersheds.

Hydrologic Responses

Annual hydrologic budgets (Table 2) show that increases in average annual precipitation, discharge, runoff, and baseflow occurred in both watersheds after conservation treatments were implemented. Most surprising was the magnitude of the increase in discharge and runoff from W1, with runoff increasing from 8.4 to 15.2% of precipitation and total discharge increasing from 22.8 to 36.3% of precipitation after the no-tillage C-S rotation was implemented. In contrast, the runoff fraction in W2 remained less than 8% after the multi-year rotation was implemented, and fraction of precipitation in total discharge increased only from 25.4 to 29.8 % (4.4% difference). Because increases in runoff and baseflow were both larger in W1 than W2, these shifts in hydrology do not reflect trade offs between runoff and baseflow, but rather differences in evapotranspiration, which led to less average annual discharge in W2, i.e., 262 mm vs 318 mm in W1 (Table 2).

The three largest precipitation events in the 40-year history of the DLRS occurred after implementation of conservation systems [i.e., 100 mm on 14 June 1998, 127 mm on 13 June 2000, and 133 mm on 7 August 1999]. These large events affected the average annual hydrologic budgets discussed above. To segregate the impact of these large events, we compared rainfall-runoff relationships under the conservation and pre-conservation agricultural systems by plotting cumulative runoff against runoff-producing rainfall, sorted by increasing rainfall amount (Figure 4). This analysis clearly showed runoff increased in W1 after conversion to a no-tillage C-S rotation, but decreased in W2 after the contour-strip six-year rotation was implemented. The differences occurred across a range of daily rainfall amounts. Decreased runoff in W2 occurred for runoff-producing events exceeding 35 mm rainfall, whereas increased runoff from W1 was evident for rainfall events exceeding 45 mm. These differences are evident for maximum storm magnitudes up to about 75 mm day^{-1}, with cumulative runoff increasing by 18% in W1 and decreasing by 22% in W2. Increased runoff in W1 may have occurred due to surface crusting, as previously reported following implementation of no-tillage practices (Jones et al., 1994).

Runoff from the three largest storms could not be referenced to historical response under conventional tillage, but there was a marked difference between the two watersheds for these three events. Rainfall from the three storms summed to 360 mm, of which 247 mm became runoff in W1, but only 121 mm became runoff in W2 (Figure 4 illustrates the difference, although runoff values are plotted as annual averages not event totals). Therefore, the combination of no-tillage, contour strips, and a perennial crop have a greater benefit for reducing runoff from very large rainfall events than no-tillage alone.

Soil Fertility Responses

Baseline soil sampling in autumn 1995, before the two conservation practices were imposed, revealed that Watersheds 1 and 2 had relatively similar soil pH levels for summit, sideslope, and toeslope positions (Cambardella et al 2004). Most notable was the relatively low pH for the summit position after more than 30 years of continuous corn. Agricultural lime was applied to both watersheds before and after the 1996 cropping season (Table 1) to correct this condition. The lime applications generally increased soil pH from 1995 to 1998 for both watersheds

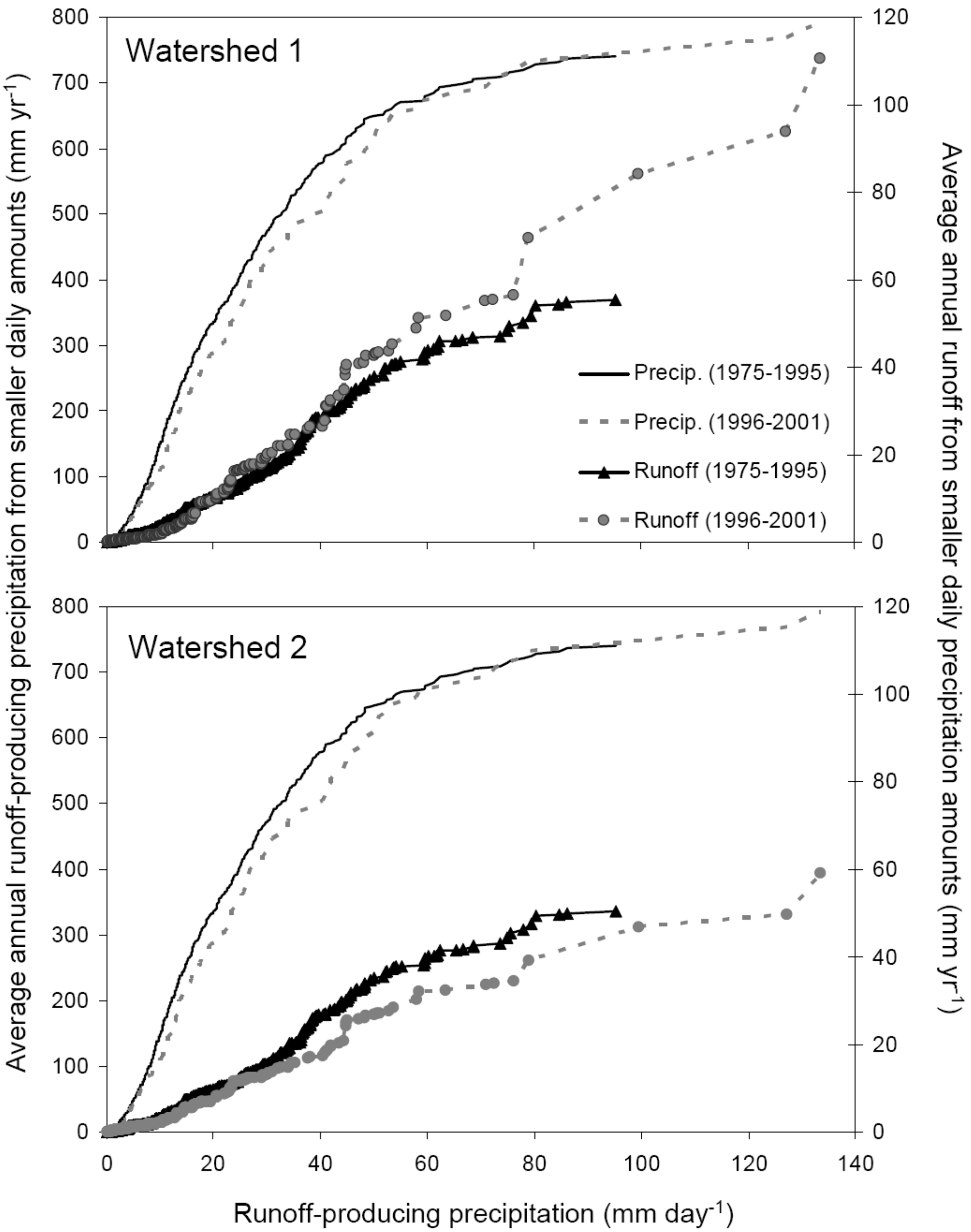

Figure 4. Average annual precipitation and runoff that accrued with increasing daily rainfall amounts, for two watersheds during two time periods. Only rainfall that produced runoff was included in calculations. Both watersheds were under conventional tillage /continuous corn during 1975-1995. Runoff increased after Watershed 1 was converted to a no-tillage corn-soybean rotation in 1996 (top graph), but decreased in Watershed 2 after a six-year rotation was implemented (bottom graph). The three largest events, which occurred in the late 1990s, resulted in little runoff under the six year rotation compared to the corn-soybean watershed.

Table 3. Soil-test data for the Deep Loess Research Station Watersheds 1 and 2 from 1995† through 2004.

		Watershed 1				Watershed 2			
Year	Topographic Position	*n*	pH (±S.E.)	P (±S.E.)	K (±S.E.)	*n*	pH (±S.E.)	P (±S.E.)	K (±S.E.)
				---------- µg g^{-1} ----------				---------- µg g^{-1} ----------	
1995	Summit‡	4	4.8 (0.2)	28 (10)	202 (12)	4	5.0 (0.2)	28 (7)	298 (56)
	Sideslope§	3	5.5 (0.8)	57 (14)	193 (2)	4	6.2 (0.7)	26 (12)	207 (12)
	Toeslope¶	4	6.8 (0.3)	26 (10)	209 (24)	4	6.2 (0.6)	31 (8)	273 (53)
1998	Summit	6	5.9 (0.1)	56 (4)	276 (17)	18	5.9 (0.1)	31 (2)	229 (15)
	Sideslope	6	7.4 (0.1)	25 (4)	166 (12)	18	7.3 (0.1)	13 (2)	160 (5)
	Toeslope	6	6.8 (0.2)	48 (4)	235 (13)	17	6.9 (0.1)	33 (2)	224 (13)
2000	Summit	6	5.8 (0.1)	43 (7)	199 (16)	18	5.8 (0.04)	17 (2)	162 (12)
	Sideslope	6	7.1 (0.1)	24 (9)	112 (12)	18	6.9 (0.04)	6 (1)	135 (9)
	Toeslope	6	6.4 (0.3)	30 (7)	165 (16)	17	6.3 (0.1)	19 (2)	184 (9)
2002	Summit	6	6.3 (0.1)	36 (5)	251 (12)	18	6.4 (0.1)	35 (3)	205 (10)
	Sideslope	6	7.4 (0.1)	13 (2)	184 (22)	18	7.5 (0.1)	12 (2)	175 (6)
	Toeslope	6	6.8 (0.3)	33 (4)	237 (23)	17	6.8 (0.2)	41 (3)	222 (10)
2004	Summit	6	5.3 (0.2)	30 (2)	259 (27)	18	5.3 (0.1)	33 (3)	173 (6)
	Sideslope	6	6.8 (0.04)	10 (2)	203 (18)	18	6.5 (0.1)	11 (2)	159 (4)
	Toeslope	6	5.9 (0.4)	29 (5)	292 (43)	17	5.7 (0.2)	36 (3)	189 (7)

† Data from Cambardella et al (2004)
‡ Summit position is predominantly Monona silt loam
§ Sideslope position is predominantly Ida and Dow silt loam
¶ Toeslope position is predominantly Napier and Kennebec silt loam

Table 4. Average crop yield (Mg ha^{-1}) as affected by topographic position (soil type) and conservation practice (Watershed) between 1996 and 2004.

Years	Topographic Position		Watershed 1		Watershed 2				
		n	Corn after soybean	*n*	Corn after alfalfa			*n*	Corn after soybean
1996 - 2004	Summit [†]	27	9.64 (0.32)	27	9.23 (0.47)			27	9.62 (0.37)
	Sideslope[‡]	27	8.40 (0.32)	27	7.84 (0.40)			27	8.00 (0.36)
	Toeslope[§]	27	10.39 (0.44)	26	10.35 (0.39)			25	10.19 (0.35)
		n	Soybean after corn	*n*	Soybean after corn				
1996 - 1999[¶]	Summit	12	4.01 (0.08)	12	3.99 (0.11)				
	Sideslope	12	2.93 (0.12)	12	2.79 (0.32)				
	Toeslope	12	4.03 (0.16)	12	4.18 (0.08)				
				n	1st year alfalfa	*n*	2nd year alfalfa	*n*	3rd year alfalfa
1997-2004[#]	Summit			24	4.50 (0.35)	24	8.10 (0.35)	24	8.52 (0.20)
	Sideslope			24	3.51 (0.27)	24	5.96 (0.40)	24	5.95 (0.26)
	Toeslope			22	4.45 (0.28)	22	8.52 (0.48)	23	7.99 (0.31)

[†] Summit position is predominantly Monona silt loam

[‡] Sideslope position is predominantly Ida and Dow silt loam

[§] Toeslope position is predominantly Napier and Kennebec silt loam

[¶] Soybean data for 2000 – 2004, collected by farmer-cooperator with yield monitor was lost due to problems with local GPS signals

[#] Alfalfa yield for 1996 was not included because of soil acidity-induced stand establishment problems during the first year of transition

Table 5. Crop prices used for economic scenarios two and three.

Year	Corn	Soybean	Alfalfa
		--------------- US$ Mg^{-1} -----------	
2000	68.92	165.01	92.06
2001	74.82	159.86	100.33
2002	87.42	203.60	93.71
2003	93.33	282.98	90.41
2004	78.37	211.68	94..26

and at each topographic position (Table 3), although the Monona soil continued to be at sub-agronomic levels (Sawyer et al., 2006) and appeared to be declining when the final samples were collected in 2004.

Soil-test P concentrations were in the high or very high categories according to state agronomic recommendations (Sawyer et al., 2006) when the no-tillage and contour strip-cropping practices were initiated. This presumably reflected the long-term history of P application and build-up under continuous corn (Karlen et al., 1999). At the request of our farmer cooperator, a nominal rate of P was applied for all crops in both watersheds in 1996 (Table 1). Within Watershed 1, P was applied only to corn production areas for 1997 to 2000. Watershed 2 had P applied to corn production strips for 1997 to 2002 and to soybean and alfalfa strips in 2002 (Table 1). The most notable soil-test P change was for the contour strip cropping where levels dropped to low and very low ranges by 2000. We suggest this was caused by greater P removal with the alfalfa hay than with corn grain (Sawyer et al., 2006) and that it serves as a reminder that when cropping systems are changed, soil-testing should be done consistently. The P fertilizer applications in 2001 and 2002 (Table 1) successfully increased soil-test P on summit and toeslope positions to very high levels (Sawyer et al., 2006), but soil-test P levels on the sideslope (Ida and Dow soils) remained very low throughout the rest of the study. Subtle erosion losses of P-rich surface particles and the higher pH associated with soils on that landscape position are two possible causes for the low P levels at those sites (Table 3).

Soil-test K was rated very high (Sawyer et al., 2006) for both watersheds when the conservation practices were implemented and generally remained there for the duration of this study because of the inherently high K in the minerals from which these soils are formed. However, as noted for soil-test P, K concentrations in Watershed 2 declined throughout the study, presumably because of greater K removal by the alfalfa biomass.

Perhaps the most notable soil fertility response was the change in late spring soil NO_3-N content and resultant decrease in fertilizer N (Table 1 and Figure 5) needed for corn within the 6-yr contour strip-crop rotation on Watershed 2. Previous studies showed a fairly uniform amount of NO_3-N throughout the top 90 cm of the soil profile in each of the DLRS watersheds every spring (Karlen et al., 1998). This was identified as a factor contributing to the leaching and loss of NO_3-N to groundwater and eventually surface water resources. By using the Late-Spring Nitrate Test (LSNT) to guide N fertilizer applications for the corn crop, the impact of crop rotation on available NO_3-N was documented (Figure 5) and much less fertilizer N was applied. This response was consistent with LSNT results for central Iowa reported by Dinnes et al. (2002).

The long-term average N fertilization rate for corn in Watershed 2 was 178 kg N ha^{-1} yr^{-1} and for 1996 our farmer-cooperator did not want to reduce the N rates compared to recent years (Karlen et al., 1999). This was agreed to for one year and explains why the 1997 anhydrous ammonia application was 30% less than that applied in 1996 (Table 1). Late-spring soil nitrate values were lower for 1998 and 1999 due to the abnormal amount of rainfall for March through June [252 and 243 mm more than the 1964 to 1995 average (364 mm), respectively]. Despite the lower levels of residual NO_3-N, the N fertilizer rates were reduced to less than 60% of the long-term average. The effects of having a perennial legume in the diversified crop rotation began to influence LSNT values in 2000 and became more pronounced in succeeding years (Figure 5). This resulted in N fertilizer applications that were reduced by 22 to 34% compared to the long-term average (Table 1). With fertilizer N prices increasing, incorporating legumes into a diversified crop rotation can have both environmental and economic benefits.

Nitrogen management within Watershed 1 was generally based on crop yield once our cooperator realized that historic N rates (Karlen et al. 1999) and the 1996 N rate exceeded annual crop removal by nearly 50%. By including N check strips, our cooperator reduced N fertilizer applications by 40% (Table 1) compared to the 1964 to 1995 average of 229 kg N ha^{-1}. Still, the total N application for 2000 through 2004 was 40% greater than that applied to corn on Watershed 2. Consistent with previous results (Karlen et al., 2006), this study shows numerous advantages for diversifying Midwestern cropping systems.

Crop Response

Corn yield averaged 9.5 and 9.3 Mg ha^{-1}, respectively, for the nine years that the no-tillage corn-soybean (Watershed 1) or no-tillage contour strip-crop (Watershed 2) evaluations were made. This was a substantial improvement compared to the 7.4 and 7.0 Mg ha^{-1} yield average for 1964 through 1995 (Karlen et al., 1999). The increased yield is partially attributed to improved genetics but also to the well-documented rotation effect (Karlen et al., 1994; 2006). Coupled with reduced fertilizer N input, this confirms that adoption of conservation practices and good agronomic management can have both environmental and economic benefits.

As shown for long-term continuous corn in both watersheds (Karlen et al., 1999), the conservation practices did not overcome the substantial differences in yield among soils associated with the various topographic sampling positions (Table 4). For all crops, yields on sideslope (Ida and Dow) positions were much lower than either the summit (Monona) or toeslope (Napier and Kennebeck) positions. Reduced infiltration due to greater slope, greater long-term sheet and rill erosion, lower soil-test P, more alkaline pH, and lower soil organic matter are among the factors contributing to a lower yield potential (SCS, 1989) and measured yields on the sideslopes.

Economic Assessments

We used Iowa State University Extension's annually updated Ag Decision Maker accounting spreadsheets

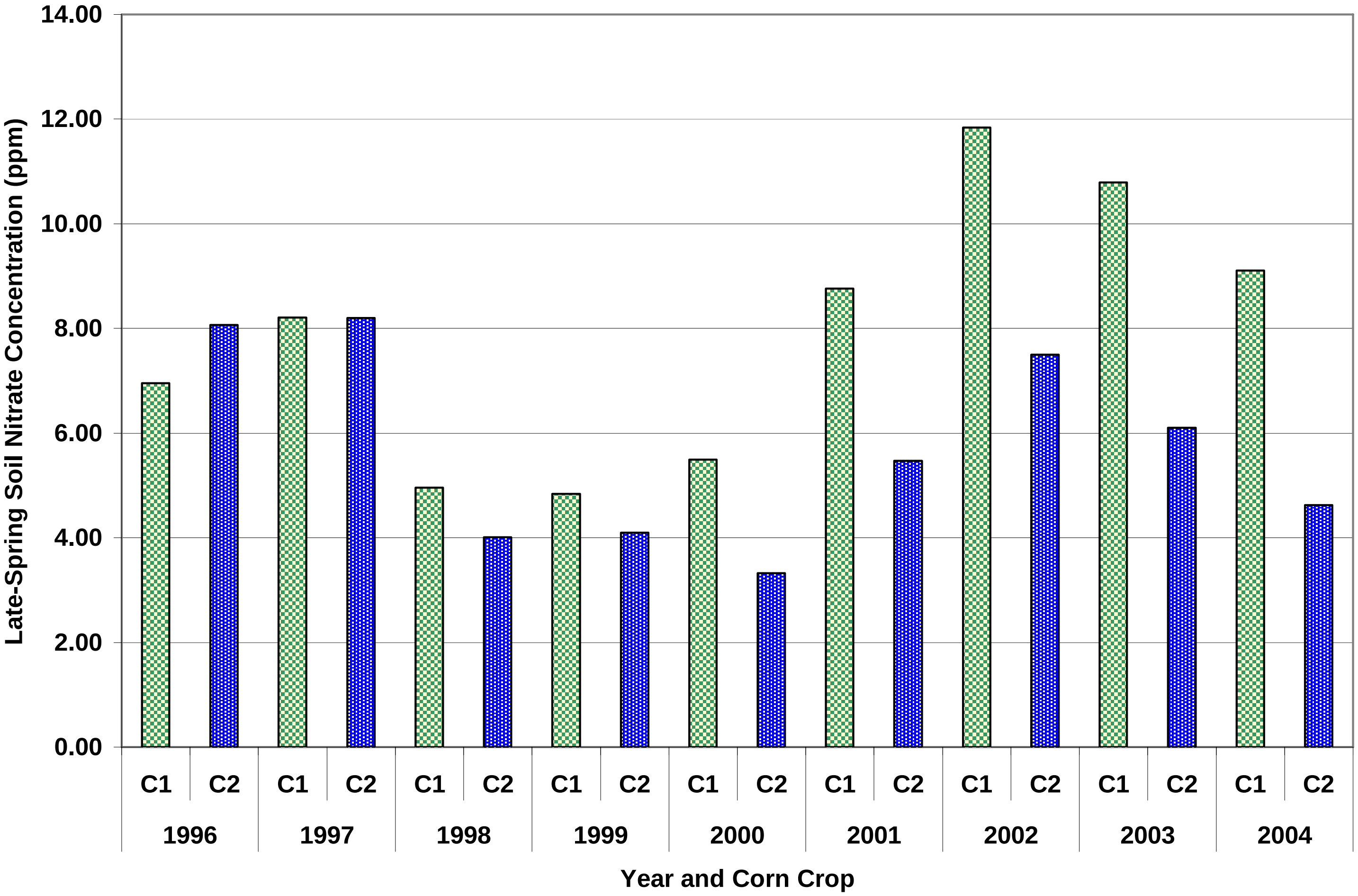

Figure 5. Average late-spring soil NO_3 concentrations from surface 60 cm soil samples for corn following alfalfa (C1) and corn following soybean (C2). Note that due to the cropping system transition, corn preceded both crops (C1 and C2) in 1996 and soybean preceded C1 in 1997 on Watershed 2.

Table 6. Economic assessment scenarios comparing averages for a multi-year (corn, soybean, corn, alfalfa, alfalfa, alfalfa) rotation with a two-year corn-soybean rotation on deep loess soils in western IA. [Price differences reflect costs or returns for the multi-year rotation (Watershed 2) minus those for the corn-soybean rotation (Watershed 1) [†]].

Year	Fixed Cost	Variable Cost	Total Cost	Gross Return	Net Return A[‡]	Net Return B[¶]
			--------------- US$ ha^{-1} ---------------			
			Scenario 1[§]			
2000	$40.22	-$164.99	-$124.78	-$286.92	-$121.92	-$162.14
2001	$71.47	-$139.28	-$67.82	-$275.93	-$136.65	-$208.12
2002	$76.2	-$71.64	$4.56	-$136.92	-$65.28	-$141.48
2003	$75.16	-$103.63	-$28.47	$17.08	$120.71	$45.55
2004	$73.31	-$136.70	-$63.39	-$140.80	-$4.10	-$77.41
			Scenario 2[§]			
2000	$31.16	-$111.85	-$80.69	-$82.21	$29.65	-$1.52
2001	$57.00	-$100.05	-$43.05	-$71.06	$28.99	-$28.01
2002	$60.64	-$77.37	-$16.73	-$25.62	$51.75	-$8.89
2003	$64.80	-$112.54	-$47.75	$18.62	$131.16	$66.37
2004	$64.99	-$112.94	-$47.95	-$35.84	$77.10	$12.11
			Scenario 3[§]			
2000	$32.32	-$111.21	-$78.89	$28.78	$139.99	$107.66
2001	$58.52	-$99.03	-$40.51	$104.47	$203.50	$144.98
2002	$60.79	-$77.28	-$16.49	-$9.81	$67.46	$6.67
2003	$64.97	-$112.42	-$47.45	$31.81	$144.23	$79.26
2004	$64.99	-$112.94	-$47.95	$53.41	$166.35	$101.37

[†] Analyses performed using methods outlined by ISU Extension Service bulletin FM-1712, except that actual land rent of $308.75 ha^{-1} ($125 ac^{-1}) was used for each crop.

[‡] Net return over variable costs

[¶] Net returns over total costs

[§] Scenario 1 uses measured corn and alfalfa yields, county average soybean yields, and 2007 costs and prices as a reference to current economic conditions; Scenario 2 uses measured corn and alfalfa yields, county average soybean yields with average NASS prices for 2000 through 2004; Scenario 3 uses measured corn yields and county average alfalfa and soybean yields with average NASS prices for 2000 through 2004.

(ISUE FM-1712) to calculate fixed, variable, and total costs as well as gross and net return (Table 6). The difference in costs and returns for the two conservation practices were computed by subtracting the values for the "standard" corn-soybean rotation (Watershed 1) from the values for the 6-yr rotation (Watershed 2). Therefore, any positive values indicate the costs or returns were greater for the extended rotation. For our first Scenario (Table 6), we used 2007 costs and prices, hand-collected corn and alfalfa yield measurements, and county average soybean yields. This showed gross returns for Watershed 2 that were lower than for Watershed 1 except in 2003 when corn and alfalfa yields were very good in Watershed 2 (data not presented) and the required amount of fertilizer N was lower (Table 1) because of carry-over from alfalfa and soybean crops.

For Scenario 2, we used the same yield measurements as Scenario 1, but instead of 2007 prices, we used the average price for the five years (2000-2004) (Table 5). This resulted in the extended rotation (Watershed 2) showing a positive return over variable costs for all five years and a positive return over total costs in the final two (2003 and 2004). For Scenario 3, the goal was to assess the economic potential of a multi-year rotation, so the hand-measured corn yields and County average alfalfa and soybean yields were used. This resulted in a positive net return over both variable and total costs for all five years for Watershed 2.

Many other factors including crop quality, oil content, feed value, and nutritional characteristics are necessary for a complete economic assessment, but in general, this study suggested that diversified rotations can be profitable on deep loess soils. As shown by the three scenarios, however, the economic returns are dominated by crop yield and price. This means that optimum management must be used for all crops (including the forages) within a diversified rotation, if the system is to be more profitable than current grain crops. Another alternative is to begin assigning economic value to all of the benefits (i.e. soil, water, and air quality; wildlife habitat, carbon sequestration, etc.) that can be obtained from more diversified cropping systems. Fortunately, better management of forage crops may become easier for regional producers to justify as opportunities for producing lignocellulosic feedstock for bioenergy and bioproducts begin to emerge.

SUMMARY AND CONCLUSIONS

This study quantifies effects of two conservation practices – no-tillage corn and soybean or no-tillage contour strip-cropping with a corn-soybean-corn-alfalfa rotation – on surface runoff, soil fertility, and crop yields when imposed on deep-loess soils. Although three of the most intensive rainfall events in the 40 yr history of the DLRS occurred after these practices were imposed, no-tillage plus contour strip-cropping reduced runoff from those events by more than 50% compared to no-tillage alone. This suggests that using more diverse crop rotations can reduce the potential for flooding in agricultural watersheds. For runoff-producing rainfall events of 75 mm d^{-1} (3.0 in d^{-1}) or less, the no-tillage C-S rotation showed an 18% increase in average annual runoff compared to conventional tillage, whereas the no-tillage six-year rotation showed a decrease in annual runoff of 22%. By using LSNT recommendations for the no-tillage plus contour strip-cropping system, fertilizer N applications were reduced by 22 to 34% compared to the long-term average (178 kg N ha^{-1}), thus demonstrating a significant economic savings for the producer and reducing the potential for leaching of excess N. Improved genetics and better management improved average corn yield by 2 Mg ha^{-1} compared to the long-term average for continuous corn (7.2 Mg ha^{-1}) on these two field-scale watersheds.

Economic assessments showed that with good agronomic management, multi-year crop rotations can be competitive with corn-soybean rotations. Based on these results, we conclude that adopting conservation practices that include diversified crop rotations, reduced or no-tillage operations, and well-managed agronomics, may be profitable for land owners/operators and provide positive environmental benefits to taxpayers who are supporting the conservation programs.

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APPENDIX

Table A1. Additional published research addressing soil properties, hydrology, nutrient responses, pesticides, and soil quality at the Deep Loess Research Station near Treynor, IA USA.

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Table A2. Pesticide applications and rates for Watershed 1 and 2 corn production for the period 1996 - 2004.

	Pre-Emergence Applications		Post-Emergence Applications	
Year	Trade Name	Rate	Trade Name	Rate
1996	Dual II[†]	2.9 l ha^{-1}	Basagran[§]	1.8 l ha^{-1}
	Counter CR[‡]	8.2 kg ha^{-1}		
1997	Dual II	3.0 l ha^{-1}	Basagran	2.3 l ha^{-1}
	Roundup Ultra[¶]	1.8 l ha^{-1}	Accent[#]	46.2 g ha^{-1}
1998	Dual II Magnum[††]	2.0 l ha^{-1}	Accent	46.2 g ha^{-1}
	Weedone[‡‡]	1.2 l ha^{-1}	Hornet[§§]	168 g ha^{-1}
	Roundup Ultra	1.2 l ha^{-1}		
1999	Dual II Magnum	1.2 l ha^{-1}	Accent	49.7 g ha^{-1}
	Weedone	1.2 l ha^{-1}	Hornet	175.0 g ha^{-1}
	Gramoxone Extra[¶¶]	1.9 l ha^{-1}		
2000	Dual II Magnum	1.8 l ha^{-1}	Accent	44.8 g ha^{-1}
	Weedone	1.2 l ha^{-1}	Hornet	168 g ha^{-1}
	Touchdown[##]	1.5 l ha^{-1}		
2001	Axiom[†††]	1.3 kg ha^{-1}	Distinct[‡‡‡]	392.1 g ha^{-1}
	Roundup Ultra	1.4 kg ha^{-1}	Accent (W2[§§§] only)	56.0 g ha^{-1}
2002	Axiom	1.3 kg ha^{-1}	Distinct	378.1 g ha^{-1}
	Roundup Ultra	1.4 kg ha^{-1}	Accent (W2 only)	56.0 g ha^{-1}
2003	Roundup WeatherMax[¶¶¶]	1.5 kg ha^{-1}	Calisto[††††]	210.0 g ha^{-1}
	Define[###]	1.4 kg ha^{-1}	Atrazine[‡‡‡‡]	0.37 kg a.i[§§§§] ha^{-1}
2004	Roundup WeatherMax	1.1 kg ha^{-1}	Calisto	210.0 g ha^{-1}
	Define	1.4 kg ha^{-1}	Atrazine	0.37 kg a.i. ha^{-1}

[†] Metolachlor herbicide: 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide

[‡] Terbufos insecticide: *S*-[[(1,1-dimethylethyl)thio]methyl] *O,O*-diethyl phosphorodithioate

[§] Bentazon herbicide: 3-(1-methylethyl)-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide

[¶] Glyphosate herbicide, isopropylamine salt: *N*-(phosphonomethyl)glycine compound with 2-propanamine (1:1)

[#] Nicosulfuron herbicide: 2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide

[††] S-Metolachlor herbicide: 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide

[‡‡] 2,4-D herbicide: (2,4-dichlorophenoxy)acetic acid

[§§] 18.5% flumetsulam + 60% clopyralid salt herbicide: *N*-(2,6-difluorophenyl)-5-methyl[1,2,4]triazolo[1,5-*a*]pyrimidine-2-sulfonamide 3,6-dichloro-2-pyridinecarboxylic acid

[¶¶] Paraquat herbicide: 1,1′-dimethyl-4,4′-bipyridinium

[##] Sulfosate (Glyphosate + Trimesium) herbicide: trimethylsulfonium *N*-[(hydroxyphosphinato)methyl]glycine

[†††] Flufenacet + Metribuzin herbicide: *N*-(4-fluorophenyl)-N-(1-methylethyl)-2-[[5-(trifluoromethyl)-1,3,4-thiadiazol-2-yl]oxy]acetamide-4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one

[‡‡‡] Dicamba + diflufenzopyr herbicide: 3,6-dichloro-2-methoxybenzoic acid-2-[1-[[[(3,5-difluorophenyl)amino]carbonyl]hydrazono]ethyl]-3-pyridinecarboxylic acid

[§§§] Applied only in Watershed 2 corn production strip areas

[¶¶¶] Glyphosate (potassium salt) herbicide: *N*-(phosphonomethyl)glycine monopotassium salt

[###] Flufenacet herbicide: *N*-(4-fluorophenyl)-N-(1-methylethyl)-2-[[5-(trifluoromethyl)-1,3,4-thiadiazol-2-yl]oxy]acetamide

[††††] Mesotrione herbicide: 2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione

[‡‡‡‡] Atrazine herbicide: 6-chloro-*N*-ethyl-*N′*-(1-methylethyl)-1,3,5-triazine-2,4-diamine

[§§§§] a.i. = active ingredient

Table A3. Pesticide applications and rates for Watershed 1 and 2 soybean production for the period 1996 - 2004.

	Pre-Emergence Applications		Post-Emergence Applications	
Year	Trade Name	Rate	Trade Name	Rate
1996	Dual II[†]	2.9 l ha^{-1}	Classic[‡]	8.5 g ha^{-1}
			Manifest[§]	4.2 l ha^{-1}
1997	Roundup Ultra[¶]	2.1 l ha^{-1}	Pursuit[#]	0.33 kg ha^{-1}
	Dual II	2.9 l ha^{-1}	Status[††]	0.69 l ha^{-1}
1998	Roundup Ultra	2.0 l ha^{-1}	Pursuit	0.32 kg ha^{-1}
	Dual II	2.1 l ha^{-1}		
1999	Dual II Magnum[‡‡]	1.0 l ha^{-1}	Pursuit	0.30 kg ha^{-1}
	Touchdown[§§]	0.7 l ha^{-1}	Prestige[¶¶]	2.0 l ha^{-1}
2000	Dual II	1.2 l ha^{-1}	Fusion[##]	0.7 l ha^{-1}
	Touchdown	0.9 l ha^{-1}	Pinnacle[†††]	9.8 g ha^{-1}
			Pursuit	0.10 kg ha^{-1}
2001	None		Roundup Ultra	1.5 l ha^{-1}
			Roundup Ultra	1.5 l ha^{-1}
2002	None		Roundup[‡‡‡]	2.4 kg ha^{-1}
			Roundup	2.2 kg ha^{-1}
2003	Roundup	1.5 kg ha^{-1}	Roundup	1.5 kg ha^{-1}
2004	None		Roundup	1.5 kg ha^{-1}

[†] Metolachlor herbicide: 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide

[†] Chlorimuron herbicide: 2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]benzoic acid

[§] Sethoxydim + Bentazon + Acifluorfen herbicide:
2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one
3-(1-methylethyl)-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide
5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid

[¶] Glyphosate herbicide, isopropylamine salt: *N*-(phosphonomethyl)glycine compound with 2-propanamine (1:1)

[#] Imazethapyr herbicide: 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid

[††] Acifluorfen herbicide: 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid

[‡‡] S-Metolachlor herbicide: 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide

[§§] Sulfosate (Glyphosate + Trimesium) herbicide: trimethylsulfonium *N*-[(hydroxyphosphinato)methyl]glycine

[¶¶] Sethoxydim herbicide: 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one

[##] Fenoxaprop-P-ethyl + fluazifop-P-butyl herbicide:
ethyl (2*R*)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoate
butyl (2*R*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate

[†††] Thifensulfuron herbicide: 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid

[‡‡‡] Glyphosate herbicide: *N*-(phosphonomethyl)glycine

Table A4. Pesticide applications and rates for Watershed 2 alfalfa production for the period 1996 - 2004.

Pesticide Applications			
Year	Crop Year	Trade name	Rate
1997	A1-3[†]	Lorsban[‡]	1.25 l ha^{-1}
	A3	Roundup[§]	3.6 l ha^{-1}
1998	A3	Roundup	5.0 l ha^{-1}
1999	A1-3	Warrior[¶]	150 g ha^{-1}
	A3	Roundup	3.5 l ha^{-1}
	A3	2,4-D[#]	2.4 l ha^{-1}
2000	A3	Roundup	5.3 l ha^{-1}
2001	A1, A2	Poast[††]	2.3 l ha^{-1}
	A1, A2	Nufos[‡‡]	2.3 l ha^{-1}
	A3	Sentry[§§]	3.6 l ha^{-1}
	A3	Gly Star Plus[¶¶]	5.5 l ha^{-1}
2002	A1, A2	Poast	2.3 l ha^{-1}
	A1, A2	Nufos	2.3 l ha^{-1}
	A3	Sentry	3.6 l ha^{-1}
	A3	Gly Star Plus	5.5 l ha^{-1}
2003	A1, A2	Poast	2.2 l ha^{-1}
	A3	Sentry	3.6 l ha^{-1}
	A3	Gly Star Plus	5.5 l ha^{-1}
2004	A3	Sentry	3.6 l ha^{-1}
	A3	Gly Star Plus	5.5 l ha^{-1}

[†] A1-A2-A3: first year alfalfa, second year alfalfa, and third year alfalfa, respectively

[‡] Chlorpyrifos insecticide: *O,O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate

[§] Glyphosate herbicide: *N*-(phosphonomethyl)glycine

[¶] Lambda-cyhalothrin insecticide: *rel*-(*R*)-cyano(3-phenoxyphenyl)methyl (1*S*,3*S*)-3-[(1*Z*)-2-chloro-3,3,3-trifluoro-1-propenyl]-2,2-dimethylcyclopropanecarboxylate

[#] 2,4-D herbicide: (2,4-dichlorophenoxy)acetic acid

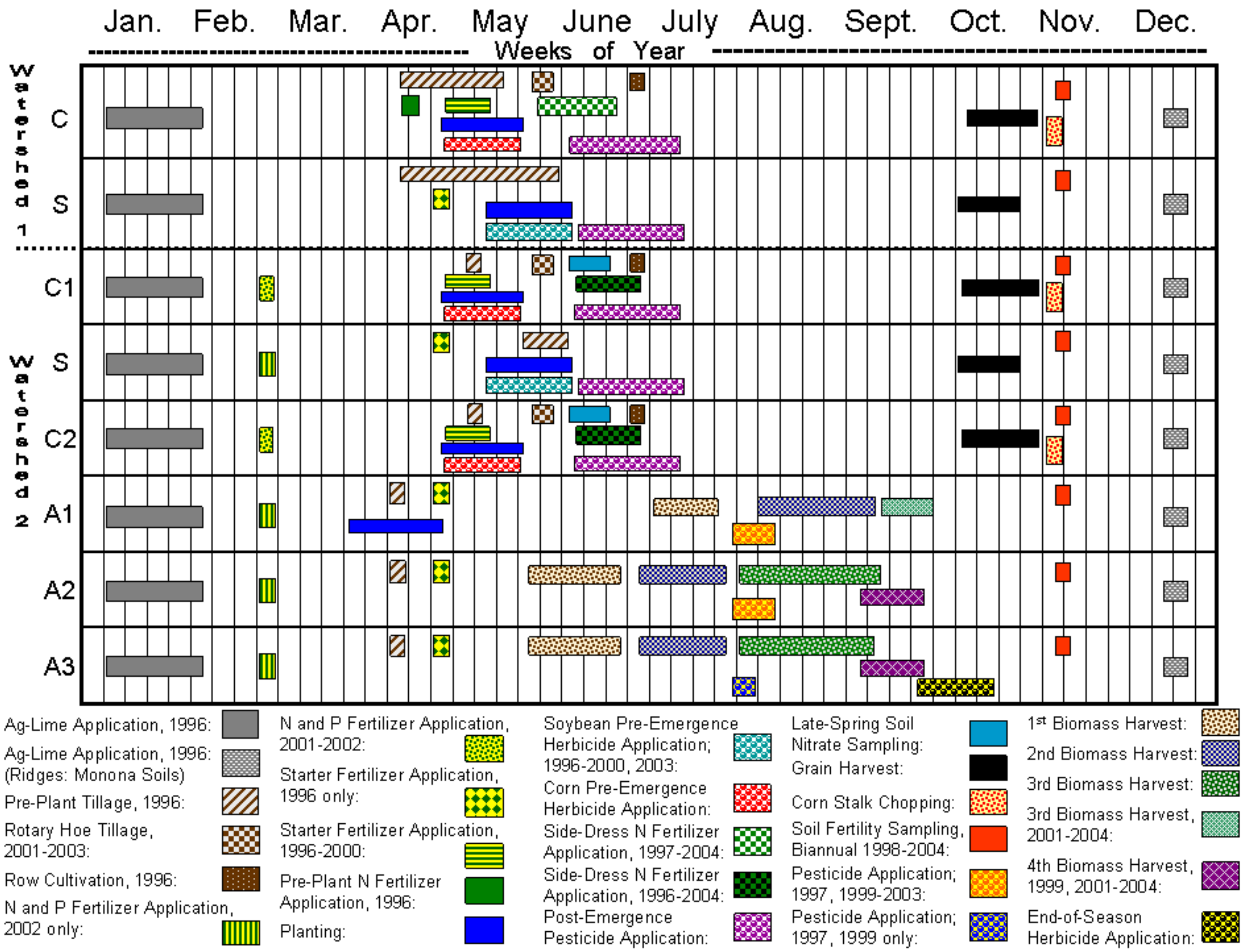
[††] Sethoxydim herbicide: 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one

[‡‡] Chlorpyrifos insecticide: *O,O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate

[§§] 2,4-D amine 4 herbicide: 2,4-D, dimethylamine salt

[¶¶] Glyphosate, isopropylamine salt herbicide: *N*-(phosphonomethyl)glycine compound with 2-propanamine (1:1)

Appendix Figure A1. Time ranges for field operations used for the crop rotations on Watersheds 1[†] and 2[‡] from 1996 through 2004.



[†] Watershed 1 cropping system: Corn – Soybean (C-S)

[‡] Watershed 2 cropping system: Corn – Soybean – Corn – Alfalfa – Alfalfa – Alfalfa (C1-S-C2-A1-A2-A3)