The Profitability and Risk of Long-Term Cropping Systems Featuring Different Rotations and Nitrogen Rates

Trenton F. Stanger,* Joseph G. Lauer, and Jean-Paul Chavas

Economic Analysis

ABSTRACT

Yield comparisons do not provide the appropriate basis for decision-making regarding cropping systems. The dominant factor influencing the adoption of cropping systems is economics. The objective of this 15-yr study was to evaluate the long-term effect of four N fertilization treatments on the economic returns of seven crop rotations in Wisconsin, based on annual market prices and production costs. The seven crop rotations were continuous corn (*Zea mays* L.) (CC), continuous alfalfa (*Medicago sativa* L.) (AA), corn-soybean [*Glycine max* (L.) Merr.] (CS), corn-alfalfa (CA), corn-corn-corn-alfalfa-alfalfa (CCCAA), corn-corn-oat (*Avena sativa* L.) with alfalfa seeding-alfalfa-alfalfa (CCOaAA), and corn-soybean-corn-oat with alfalfa seeding-alfalfa (CSCOaA). The four N treatments were 0, 56, 112, and 224 kg N ha^{-1} for the corn phase. Across all crop rotations, the average return was greatest for the 112 and 224 kg N ha^{-1} treatments, which returned on average \$32 and \$85 ha^{-1} more than the 56 and 0 kg N ha^{-1} treatments, respectively. Across all N rates, average returns were highest for the CS rotation. The CS rotation returned \$58 ha^{-1} more than the CSCOaA and CCOaAA rotations, \$129 ha^{-1} more than the CCCAA rotation and AA, \$224 ha^{-1} more than the CA rotation, and \$269 ha^{-1} more than CC. Under second degree stochastic dominance, the stochastically efficient treatments were CS at all N rates and CC at 224 kg N ha^{-1}. All other cropping systems were inefficient relative to these five treatments (i.e., they would not be chosen by a risk-averse decision maker). This research shows that the most profitable systems (CS) remain the most efficient when risk is taken into consideration. However, these results also show that when 224 kg N ha^{-1} is added, risk can be reduced for continuous corn. Individual circumstances will dictate the optimal choice among the efficient rotations.

Nitrogen has been considered as one of the best crop-input investments that a farmer can make in terms of return on dollars spent (Pikul et al., 2005); however, N is the most expensive nutrient for growing grain crops. Bundy et al. (1999) estimated that in the 12 states of the North Central United States, at least 3.3 million tonnes of N fertilizer was applied annually to corn at a cost of \$800 million. Nitrogen fertilizer is universally accepted as a key component to high corn grain yield and optimum economic return. Overapplication is more frequent since producers have an economic incentive to err more frequently in that direction. The cost of unneeded N fertilizer in areas of overapplication is less than the cost of lost yield potential in areas of under-application (Scharf et al., 2005).

Crop rotation has been shown to increase corn yield 5 to 30% and soybean yield from 8 to 16% compared to continuous production of either crop (Copeland et al., 1993; Crookston et al., 1991; Lund et al., 1993; Peterson and Varvel, 1989a, b; Singer and Cox, 1998a; West et al., 1996). Crop rotation has also been shown to improve N use efficiency by reducing requirements for external input of fertilizer N. Compared to CC, Kanwar et al. (1997) reduced fertilizer N inputs 17% for a CS rotation and reduced NO_3–N leaching loss through subsurface tile lines. Bruulsema and Christie (1987) found that a single-year of alfalfa or red clover (*Trifolium pretense* L.) was equivalent to corn yields obtained from applying 90 to 124 kg ha^{-1} of fertilizer N. Fox and Piekielek (1988) extended the evaluation period to 3 yr of alfalfa managed as hay and reported that there was no significant grain yield response to fertilizer N for first-year corn.

One result of increased crop yield and improved N use efficiency with crop rotation may be more favorable economics or net return to producers. Profit margins for production of most crops are very narrow, and producers seek sustainable cropping systems that provide consistent return on investment (Clegg and Francis, 1994). For example, when averaged for moldboard plow and chisel tillage systems in an Iowa study, Chase and Duffy (1991) reported a return to land, labor, and management for CC of \$351 ha^{-1} compared to \$363 ha^{-1} for CS. The CS rotation also required 17% less N fertilizer (168 vs. 202 kg ha^{-1}). In New York, Singer and Cox (1998b) reported greater net return for a CS rotation (\$250 ha^{-1}) than for CC (\$193 ha^{-1}) or a 3-yr soybean-wheat/

T.F. Stanger, Monsanto Company, 1920 Fifth St., Davis, CA 95616; J.G. Lauer, Dep. of Agronomy, 1575 Linden Dr., Univ. of Wisconsin, Madison, WI 53706; and J.P. Chavas, Dep. of Agricultural and Applied Economics, 427 Lorch St., Univ. of Wisconsin, Madison, WI 53706. Funded by CSREES project WIS0 142-4897. Received 17 Nov. 2006. *Corresponding author (trenton.floyd.stanger@monsanto.com).

Published in Agron. J. 100:105–113 (2008).
doi:10.2134/agronj2006.0322

AJ AGRONOMY JOURNAL 1908–2008

Abbreviations: AA, continuous alfalfa; CA, corn-alfalfa; CC, continuous corn; CCCAA, corn-corn-corn-alfalfa-alfalfa; CCOaAA, corn–corn–oat with alfalfa seeding–alfalfa–alfalfa; CS, corn–soybean; CSCOaA, corn–soybean-corn-oat with alfalfa seeding-alfalfa; FDSD, first-degree stochastic dominance; N, nitrogen; NASS, National Agricultural Statistics Service; SDSD, second-degree stochastic dominance. *Italics in a rotation code indicate the phase of the rotation under discussion.*

red clover-corn rotation (\$133 ha^{-1}) with reduced inputs. Katsvairo and Cox (2000) calculated that a CS rotation with reduced inputs returned \$99 ha^{-1} compared to \$12 ha^{-1} in CC with full inputs and chisel tillage. Zacharias and Grube (1984) reported that in an Illinois study, a soybean-corn-corn rotation had greater net returns (\$286 ha^{-1}) compared with a corn-soybean-wheat rotation (\$224 ha^{-1}) and continuous corn (\$188 ha^{-1}) in the presence of herbicides. Similarly, Hesterman et al. (1986) compared the profitability of CA, CC, and CS rotations and concluded that a CA rotation provided the greatest returns. They also concluded that to amortize alfalfa establishment costs over a longer period of time, the crop should be managed as forage rather than a green manure.

The merits of extended crop rotations that include forage or pasture crops have been debated for centuries (Karlen et al., 1994). Key benefits include increased carbon retention in the surface horizon and a more even distribution of labor needs and risk due to climate or market conditions than those involving only grain or fiber crops (Magdoff and van Es, 2000). Despite those benefits, the infrastructure developed and devoted to corn and soybean has resulted in a 500% increase in harvested area and 800% increase in soybean production between 1950 and 2003 (USDA-NASS, 2004). During that same period, oat production declined 90%, and although hay production increased because of better yields, the land area devoted to it decreased more than 15%. This occurred for several reasons including simplicity and similar equipment requirements as farm size increased, commodity programs that emphasized short-term profit, public and private research, and development efforts devoted to genetic improvement of corn and soybean, and increased food and industrial uses for both corn and soybean oils and various by-products (Karlen, 2004). Expansion of the simplified corn/soybean system has tremendous economic and world trade benefits because of the many products and materials developed from those crops (Karlen et al., 2006).

Although the net returns are often the most requested piece of data when crop rotation studies are reported to producers, very few experiments have provided that information, especially those that include both forage and grain crops (Singer et al., 2003). Farmers must select cropping systems based on expected market returns and risks associated with those returns (Young and Westcott, 1996). Cropping systems depend greatly on the mix and sequence of crops or crop rotations that farmers select (Francis and Clegg, 1990). Crop rotations, however, interact with management inputs (Riedell et al., 1998). An economic analysis of cropping systems that include different crop rotation and management inputs is important, because it helps in identifying the most profitable cropping systems based on current market prices.

An economic analysis should be the dominant factor for evaluating different cropping systems (Wesley et al., 1995) and assessing the riskiness of alternative rotations requires yield data on complete rotations over time (Meyer-Aurich et al., 2006). The objective of this study was to determine the economic profitability and risk based on annual market prices and production costs of 28 crop rotation by N treatments that feature seven crop rotations (CC, AA, CS, CA, CCCAA, CCOaAA, and CSCOaA) and four N treatments (0, 56, 112, and 224 kg N ha^{-1}) for the corn phase.

MATERIALS AND METHODS

A long-term cropping system study located in southwestern Wisconsin [University of Wisconsin Agricultural Research Station-Lancaster (42°50′ N, 90°47′ W; elevation 324 m above mean sea level)] near Lancaster was selected for this study. The site was originally established to evaluate crop rotation and N fertilization rate effects on crop yield and soil N mineralization, retention, and availability and was initiated in 1966 as a cooperative experiment (NC-157) among the University of Illinois, Iowa State University, University of Minnesota, and the University of Wisconsin. (Vanotti and Bundy, 1994a, 1995). This analysis evaluates the economic profitability and risk of crop rotation × N treatments during the last 15 yr (1990–2004) of this study.

The study was located on Rozetta silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs) soil. A randomized complete block in a split-plot design with two replications of 28 rotation by N rate treatments was established. Main plots consisted of seven crop rotations (CC, AA, CS, CA, CSCOaA, CCCAA, and CCOaAA). Subplots consisted of four N treatments (0, 56, 112, and 224 kg N ha^{-1}), for the corn phase. There were some changes in N rate since the study was initiated, but since 1977, the annual rates have not changed. To test the rotation effect each crop phase of every rotation is represented each year. To accommodate all possible crop phases of the rotations and four fertilizer treatments, 168 plots (6.1 by 9.1 m) were established in 1966. Thus, for CC, there was one plot within each replication, and for CS there was one corn plot and one soybean plot within each replication.

Nitrogen fertilizer treatments were broadcast by hand each spring as ammonium nitrate (NH_4NO_3). Tillage has varied over time. Corn following corn and oat and alfalfa seedbed preparation has always been fall chisel plowed followed by spring disking and cultimulching before planting. Corn following soybean has been no-till since 1994, while corn following alfalfa and soybean following corn have been no-till since 1999. Soil fertility samples were collected and analyzed every 3 yr, and uniform rates of P and K fertilizers were applied as needed to maintain optimum to high soil-test levels. Herbicides and cultivation were used for weed control as needed following best management practices. Cultivars varied over time but were always improved selections developed for the region. The alfalfa, which was seeded with oat, has not been harvested during the seeding year following oat harvest. For alfalfa that was independently established, two harvests were taken during the seeding year, except for rotations with 1-yr alfalfa, where the alfalfa was killed during the fall of the same year following a third cutting by plowing (before 1999) or through the use of appropriate herbicides (2000 onward). For rotations with 2 or 3 yr of alfalfa following establishment, three harvests were taken. The continuous alfalfa plots were established in 1977 and the prior rotation was a corn-oat with alfalfa seeding-alfalfa-alfalfa-alfalfa rotation with four N rates. Even though, no N treatments have been applied to AA, the established plots were maintained and will be reported separately in the analysis.

Profit associated with the various crop rotations was computed by estimating the variable and fixed costs of production as outlined by Duffy (1993–2004) and subtracting them from the potential income calculated using actual yields and the marketing year average Wisconsin crop prices received for those years from the NASS (National Agricultural Statistics Service) database. The potential impact of government support payments on cropping system choices was considered, but we chose not to use them for this analysis, as one of the goals of this research was to investigate cropping systems that do not rely on subsidies to be profitable. Production costs were estimated for each year using the actual cultural operations and equipment used, as listed in the field records. Pesticide and fertilizer rates have been adjusted to reflect what was actually applied on the various crops in the rotations. Sources for pesticide prices came from field records, NASS, and University of Wisconsin Extension specialists. Based on soil tests, lime was applied before the 1992 and 2004 growing seasons. Cost of lime was based on purchase price, spreading cost, and amounts applied, and then prorated over 10 yr to determine the cost per year (L.G. Bundy, personal communication, 2006). Crop insurance costs reflect the mix of multiple peril, revenue, and hail insurance, as well as noninsured acres. Labor has been treated as a fixed cost, since most labor on Wisconsin farms is supplied by the operator, family, or permanent hired labor. The hours per crop acre includes not only field work but also time for maintenance, travel, and other activities related to crop production. Equipment costs reflect a fleet consisting of both new and used machinery. Costs of machine operations were based on the 1989, 1996, 1998, and 2000 Crop Production Practices Survey conducted by the Iowa Agricultural Statistics Service (Duffy, 1993–2004). Data on oat straw which was removed following harvest was not kept. Straw yields were assumed to be 2,240 kg ha^{-1} according to Duffy (2004) and price based on the average auction price for straw from Weekly Indiana Hay and Straw Prices (Sept. 2000–Jan. 2004) at http://www.agry.purdue.edu/ext/forages/links.htm; verified 21 Sept. 2007.

Yield and profitability data were subjected to an analysis of variance using the PROC MIXED procedure (Littell et al., 1996) of SAS (SAS Inst., 2002). For determining the expected mean squares and appropriate F tests in the analysis of variance, random effects were year, rep(year), and rep by rotation (year). Least square means of the fixed effects were computed, and the PDIFF option of the LSMEANS statement was used to display the differences among least square means for comparison. This option uses Fisher's protected least significant difference, and comparison was conducted at $P \leq 0.05$. For calculating individual crop rotation by N rate standard errors, repeated measures analysis (SAS Inst., 2002) with a group effect was used.

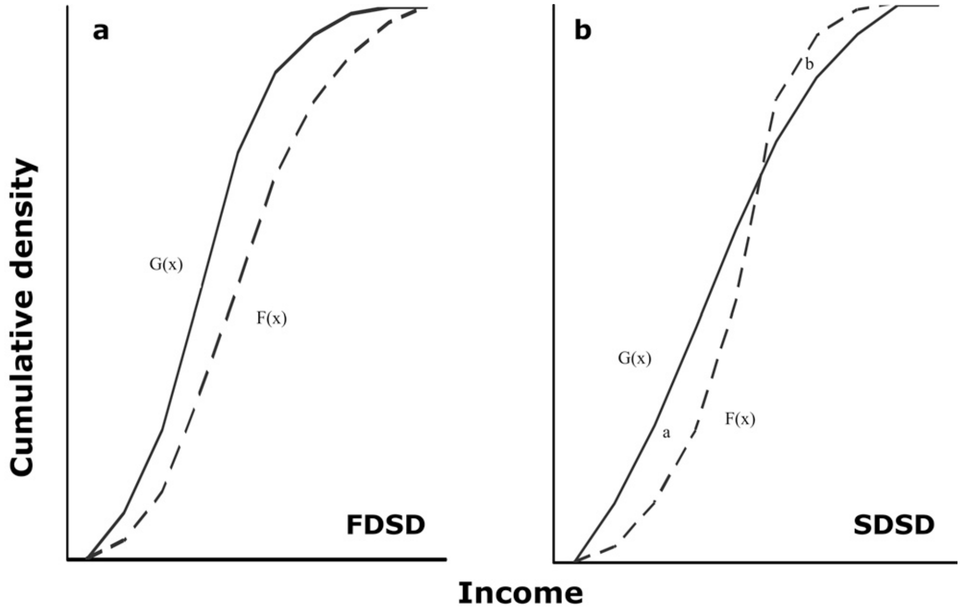

Fig. 1. Graphical representation of first-degree (FDSD) and second-degree (SDSD) stochastic dominance. F(x) and G(x) are cumulative density functions of two hypothetical rotation treatments.

To compare risk among the four N treatments by seven crop rotations, stochastic dominance analyses (Hanoch and Levy, 1969) were performed. Our approach was similar to Lowenberg-Deboer and Aghib (1999), who employed stochastic dominance to evaluate the economics of site-specific management. Using stochastic dominance, we complete a pair-wise ranking of net income from the treatments. Both first-degree stochastic dominance (FDSD) and second-degree stochastic dominance (SDSD) analyses were performed.

Stochastic dominance compares cumulative distributions of net income based on two observations about human nature: (i) most people prefer more to less, and (ii) most people prefer less risky outcomes (Lambert and Lowenberg-DeBoer, 2003). First-degree stochastic dominance assumes decision makers prefer more to less, and states that an alternative is preferred over others if it provides a higher outcome at every level of probability. A sufficient condition for one treatment, with cumulative density function F, to first-order dominate another treatment with cumulative density function G, is

$$F(x) \leq G(x), \text{ for all } x, \qquad [1]$$

with the inequality strictly holding over some domain of x (Hirshleifer and Riley, 1992). Equation [1] is graphically represented in Fig. 1a. As can be seen from the graph, for any given level of income x, the probability of incomes larger than x is higher for F than G. The decision maker will choose to take action associated with F as the cumulative density function of F always lies to the right of G (DeVuyst and Halvorson, 2004).

Second-order stochastic dominance assumes that the decision maker: (i) prefers more wealth to less and (ii) is risk averse. A sufficient condition for SDSD is

$$\int_{-\infty}^{y} F(x)dx \le \int_{-\infty}^{y} G(x), \text{ for all } y, \qquad [2]$$

with the inequality strictly holding for some domain of *y* (Hirshleifer and Riley, 1992). In Fig. 1b, SDSD is demonstrated. As the cumulative density functions given by *F* and *G* cross, clearly the condition for first-degree dominance fails. However, as long as the area labeled *a* is greater than or equal to the area labeled *b*, *F* is said to second-degree dominate *G*. While less intuitive than FDSD, SDSD considers the risk-averse nature of decision makers. That is all risk-averse decision makers would prefer *F* to *G* (DeVuyst and Halvorson, 2004).

Stochastic dominance tests were performed by covariate analysis of net income using the PROC MIXED procedure (Littell et al., 1996) of SAS (SAS Inst., 2002). The covariate was year. For determining the expected mean squares and appropriate *F* tests in the analysis of covariance, random effects were rep and rep by rotation. Repeated measures analysis (SAS Inst., 2002) with the compound symmetry variance structure was used to evaluate time and space effects on risk.

Table 1. Average crop yields for a crop sequence by N treatment study, 1990 to 2004, at Lancaster, WI.

Cropping sequence‡§¶	N rate, kg N ha^{-1}†			
	0	56	112	224
Corn		Mg ha^{-1}		
CA	8.5 l–o‡	9.8 e–h	10.4 a–e	10.7 ab
CC	3.3 u	5.6 t	8.2 nop	9.1 ijk
CCCAA	9.6 f–i	10.0 c–f	10.3 a–e	10.3 a–e
C**C**CAA	6.3 s	8.4 m–p	9.3 h–k	9.8 e–h
CC**C**AA	5.3 t	7.8 pq	9.0 i–l	9.6 f–i
CCOaAA	9.9 e–h	10.6 a–d	10.7 ab	10.8 a
C**C**OaAA	7.2 qr	8.9 j–m	9.4 g–j	9.9 e–h
CS	7.1 r	8.8 k–n	9.9 e–h	10.1 b–f
CSCOaA	9.4 g–j	10.2 b–f	10.6 abc	10.6 abc
CS**C**OaA	8.0 op	9.3 h–k	10.0 d–g	10.0 c–f
Oat				
CCOaAA	2.0 c	2.4 b	2.4 b	2.5 a
CSCOaA	1.9 c	2.1 b	2.2 b	2.6 a
Soybean				
CS	3.5	3.5	3.6	3.4
CSCOaA	3.4	3.6	3.5	3.6
Alfalfa				
AA	7.0 b	7.1 b	6.9 b	7.0 b
CA	4.2 c	4.2 c	4.4 c	4.6 c
CCC***A***A	4.1 c	4.0 c	4.2 c	4.2 c
CCCA***A***	8.6 a	8.5 a	8.8 a	8.7 a
CCOa***A***A	8.3 a	8.4 a	8.3 a	8.4 a
CCOaA***A***	8.6 a	8.6 a	8.5 a	8.5 a
CSCOaA	8.6 a	8.5 a	8.5 a	8.5 a

† N rates were applied to corn only.

‡ Means followed by the same letter for the same crop are not significantly different ($P \le 0.05$).

§ C, corn; S, soybean; Oa, oat with alfalfa seeding; A, alfalfa.

¶ Italic indicates year of rotation for the corn crop being evaluated.

RESULTS AND DISCUSSION

Yields

Average yields by crop rotation by N rate for the 15-yr study (1990–2004) are compiled in Table 1. For first-year corn a significant rotation by N rate was observed. Within rotation sequences, yields were lowest at 0 kg N ha^{-1} and highest at 224 kg N ha^{-1} with yield increases of 2.2, 5.8, 0.7, 1.0, 3.0, and 1.2 Mg ha^{-1} for CA, CC, *C*CCAA, *C*COaAA, CS, and *C*SCOaA, respectively (Table 1). Within N treatments, first-year corn yields did not differ among the three 5-yr rotations (*C*CCAA, *C*COaAA, and *C*SCOaA) and yields were highest when following alfalfa or soybean and lowest for CC. Our results show improved first-year corn yields for rotations with less corn and more alfalfa. First-year corn yields were highest for *C*COaAA followed by *C*SCOaA, *C*CCAA, and CA which yielded 10.5, 10.2, 10.1, and 9.9 Mg ha^{-1}, respectively. These were followed by CS and CC which yielded significantly less at 9.0 and 6.5 Mg ha^{-1}, respectively.

These findings agree with Bolton et al. (1976), Higgs et al. (1976), and Welch (1976) who found that corn grown in rotation had higher yields than corn grown in monoculture, even in the presence of N, P, or K fertilizer levels that were not limiting yields. Corn grown in rotation with a legume receives more N than corn grown continuously with no fertilizer N. First year alfalfa can supply 134 to 168 kg N ha^{-1} for a subsequent corn crop (Bundy et al., 1990). However, if N is the only cause of yield differences between rotations, then these differences would be expected to disappear if more than adequate N is applied. It appears that N fertilizers do not substitute for crop rotation (Table 1).

Corn yields were also affected by rotation and N rate when the various rotations (CC, C*C*CAA, C*C*OaAA, and CS*C*OaA) were planted to a second-year corn (Table 1). For second-year corn a significant rotation by N rate was observed. Second-year corn yields were highest for CS*C*OaA followed by C*C*OaAA, C*C*CAA, and CC which yielded 9.3, 8.8, 8.4, and 6.5 Mg ha^{-1}, respectively. This difference was due to adding 1 yr of soybean between the first and second phases of corn in this rotation. Soybean can supply up to 45 kg N ha^{-1} for a subsequent corn crop (Bundy et al., 1990). Previous research has demonstrated that when corn is grown in rotation with soybean, it yields greater than CC (Baldock et al., 1981; Crookston et al., 1991; Meese et al., 1991; Porter et al., 1997; Pedersen and Lauer, 2002, 2003). Our data also suggests that alfalfa supplied a lower but still significant amount of the total N requirement of second-year corn in the rotation sequence; however, the effect of rotating corn for improved corn grain yield appears to have diminished when comparing the second year of corn with CC.

Corn yields were also affected by rotation and N rate when the various rotations (CC and CC*C*AA) were planted to third-year corn (Table 1). For third-year corn a significant rotation by N rate was observed.

Crop rotation did not affect oat yields (Table 1); however residual N left over from previous corn years did affect oat yields. Oat yields following a corn N treatment of 224 kg N ha^{-1} averaged 0.3 Mg ha^{-1} (11%) greater than the 112 and 56 kg N ha^{-1} treatments and 0.6 Mg ha^{-1} (23%) greater than the 0 kg N ha^{-1} treatment. Previous research (Dumenil, 1954; White et al., 1958; White and Pesek, 1959; Vanotti and Bundy, 1994b) also indicates that oat yields responded significantly to fertilizer N applied in previous growing seasons and that the response was correlated with soil NO_3–N resulting from previous N applications.

For first-year alfalfa a significant rotation by N rate was observed. This response varied by rotation treatment with yield increases for CA, CCC*A*A, and CCOa*A*A of 0.4, 0.2, and 0.2 Mg ha^{-1}, respectively, while for CSCOaA alfalfa yields decreased 0.1 Mg ha^{-1} with increasing N rates in corn (Table 1). In each N treatment, first-year alfalfa yields were greatest and did not differ among the two 5-yr rotations when alfalfa was seeded with an oat crop (CCOa*A*A and CSCOaA) and lowest when alfalfa was planted without a nurse crop. This was because for rotations CCOa*A*A and CSCOaA alfalfa was not harvested until the year following seeding and when alfalfa was planted without a nurse crop, alfalfa was harvested the seeding year. Across all N rates, first-year alfalfa yields did differ among the six rotations. First-year alfalfa yields were highest for CSCOa*A* and CCOa*A*A followed by AA which yielded 8.5, 8.4, and 7.0 Mg ha^{-1}, respectively. These were followed by CA and CCC*A*A which yielded significantly less at 4.3 and 4.1 Mg ha^{-1}, respectively. These results appear to be driven by the fact that alfalfa yields the seeding year are significantly less than those rotations using oats as a nurse crop the previous year. Alfalfa yields were only affected by rotation when the various rotations (AA, CCCA*A*, CCOaA*A*) were followed with a second-year of alfalfa (Table 1). Second-year alfalfa yields were highest for CCCA*A* followed by CCOaA*A* and lowest for AA, yielding 8.7, 8.5, and 7.0 Mg ha^{-1}, respectively.

Table 2. Average annual dollar-per-hectare production costs of corn by N rate, oat, soybean, and alfalfa at Lancaster, WI, 1990 to 2004.

	Production costs							
							Alfalfa	
	Corn				Oat	Soybean	First year	Second year
N rate, kg N ha^{-1}†	0	56	112	224				
Input	$ ha^{-1}							
Machinery‡	157	179	186	190	164	100	175	184
Seed	95	95	95	95	32	62	119	0
Fertilizer	46	68	91	137	58	37	79	85
Chemical§	120	120	120	120	15	100	33	19
Misc.¶	103	105	107	110	57	86	94	95
Total	522	569	600	652	325	384	500	382

† N rates were applied to corn only.
‡ Include field operations, handling, hauling, drying (corn), and baling (oat and alfalfa).
§ Herbicides and insecticides.
¶ Including costs on interest on operating capital, insurance, and labor costs.

Cost, Profitability, and Risk

Costs of production varied among the various crops with the highest cost associated with corn at 224 kg N ha^{-1} (Table 2). Oat had the lowest production costs, which were 50% of the cost associated with corn production using the highest N rate. Production costs of soybean and first- and second-year alfalfa were higher than for oat. Higher corn production costs were mostly attributed to seed, fertilizer, and chemical costs that were relatively higher than for the other crops (Table 2). Meyer-Aurich et al. (2006) reported similar findings with corn having the highest associated costs. However, they reported soybean with the lowest production costs, which were 60% less than the costs associated with corn production, compared to our results of 53% less. Higher first-year alfalfa costs were due to seed costs when compared to the second-year alfalfa.

Average returns to land using average annual crop prices are found in Table 3. For first-year corn a significant rotation by N rate was observed. For all rotations sequences, average returns were not like grain yields that increased with increasing N rate (Table 1). Average returns for CA were highest at 56 and 112 kg N ha^{-1} averaging \$73 ha^{-1} (26%) more than the 0 and 224 kg N ha^{-1} treatments. The highest returns in the *C*CCAA rotation were at 0, 56, and 112 kg N ha^{-1} averaging \$52 ha^{-1} (18%) more than the 224 kg N ha^{-1} treatment. For the *C*COaAA rotation the 56 kg N ha^{-1} treatment averaged \$55 ha^{-1} (18%) more than the 224 kg N ha^{-1} treatment. In the CS rotation the 112 kg N ha^{-1} treatment averaged \$61 ha^{-1} (23%) and \$156 ha^{-1} (59%) more than the 56 and 0 kg N ha^{-1} treatments, respectively. The highest return in the *C*SCOaA rotation was at 112 kg N ha^{-1} treatment which averaged \$50 ha^{-1} (16%) more than the 224 kg N ha^{-1} treatments (Table 3). Across all crop rotations, the average return was greatest for the 112 kg N ha^{-1} treatment, which returned on average \$35 ha^{-1} (13%) more than the 56 and 224 kg N ha^{-1} treatments and \$101 ha^{-1} (38%) more than the 0 kg N ha^{-1} treatment. Across all N rates, average returns for first-year corn were highest for the *C*COaAA, *C*SCOaA, and *C*CCAA rotations. The *C*COaAA rotation returned \$52 ha^{-1} (17%) more than the CA rotation, \$107 ha^{-1} (35%) more than the CS rotation and \$309 ha^{-1} (one-fold) more than CC (Table 3). One reason why CC had the lowest average returns was because it is the only cropping system that still uses an annual fall chisel plow tillage treatment, while corn following soybean and corn following alfalfa have been no-till since 1994 and 1999, respectively. However, Liu and Duffy (1996) and Singer and Cox (1998b) both reported greater returns for corn following soybean compared with CC both under a chisel tillage system.

A significant rotation by N rate interaction was observed for second-year corn. Average returns for the C*C*CAA and C*C*OaAA rotations were greatest at 56, 112, and 224 kg N ha^{-1} averaging \$155 ha^{-1} (82%) and \$106 ha^{-1} (51%) more than the 0 kg N ha^{-1} treatment, respectively. The highest return in the CS*C*OaA rotation was at 112 kg N ha^{-1} treatment which averaged \$74 ha^{-1} (27%) more than the 0 and 224 kg N ha^{-1} treatments (Table 3). Across all crop rotations, the average return was greatest for the 112 kg N ha^{-1} treatment, which returned on average \$29 ha^{-1} (12%) more than the 56 kg N ha^{-1} treatment and \$127 ha^{-1} (55%) more than the 0 kg N ha^{-1} treatment, but was not significantly different from the 224 kg N ha^{-1} treatment. Across all N rates, average returns for first-year corn were highest for the CS*C*OaA rotation. The CS*C*OaA rotation averaged \$64 ha^{-1} (28%) more than the *C*COaAA and *C*CCAA rotations (Table 3).

Table 3. Average annual dollar-per-hectare returns to land by crop, N rate, and cropping system at Lancaster, WI, 1990 to 2004.

		Phase							
Rotation†	N rate‡	First year corn	Second year corn	Third year corn	Oat	Soybean	First year alfalfa	Second year alfalfa	Average
	kg N ha^{-1}	$ ha^{-1} (SE§)							
AA	0						142 (62)		142 (54)
	56						154 (64)		154 (56)
	112						135 (62)		135 (54)
	224						138 (62)		138 (54)
CA	0	206 (44)					−177 (66)		12 (45)
	56	267 (41)					−176 (66)		46 (47)
	112	286 (46)					−164 (66)		61 (46)
	224	200 (47)					−150 (66)		55 (45)
CC	0	−211 (48)							−211 (41)
	56	−61 (43)							−61 (42)
	112	118 (49)							118 (44)
	224	147 (44)							147 (39)
CCCAA	0	288 (40)	34 (51)	−56 (52)			−186 (66)	310 (57)	78 (39)
	56	287 (39)	163 (55)	117 (44)			−188 (66)	310 (57)	138 (38)
	112	285 (46)	205 (48)	189 (46)			−179 (66)	327 (57)	165 (38)
	224	235 (46)	199 (48)	185 (45)			−175 (66)	318 (59)	152 (38)
CCOaAA	0	309 (39)	102 (49)		63 (24)		127 (53)	306 (69)	181 (36)
	56	332 (39)	200 (50)		95 (24)		140 (53)	306 (69)	215 (36)
	112	314 (40)	215 (49)		100 (24)		130 (54)	295 (69)	211 (36)
	224	274 (40)	206 (49)		108 (24)		137 (54)	302 (69)	205 (36)
CS	0	107 (43)				325 (32)			216 (40)
	56	202 (40)				338 (34)			270 (38)
	112	263 (40)				353 (33)			308 (37)
	224	229 (47)				315 (36)			275 (36)
CSCOaA	0	272 (40)	177 (59)		54 (24)	312 (33)	153 (54)		194 (36)
	56	299 (39)	244 (59)		68 (24)	358 (34)	145 (53)		223 (36)
	112	310 (39)	274 (48)		78 (23)	331 (33)	147 (53)		228 (36)
	224	259 (41)	223 (59)		113 (24)	349 (34)	145 (53)		218 (36)
LSD (Rotation, 0.05)		34.2	35.7	–	NS¶	NS	67.2	NS	38.5
LSD (N rate, 0.05)		16.4	23.7	43.3	13.0	NS	NS	NS	24.5
LSD (R by N, 0.05)		47.7	47.6	–	NS	NS	60.0	NS	66.4

† C, corn; S, soybean; Oa, oat with alfalfa seeding; A, alfalfa.

‡ N rates were applied to corn only.

§ Standard Error as calculated by PROC MIXED.

¶ NS, not significant.

This was due to higher yields when corn followed soybean in the CS*C*OaA rotation (Table 1).

A significant rotation by N rate was observed for first-year alfalfa. The highest return for the AA rotation was for the 56 kg N ha^{-1} treatment which averaged $18 ha^{-1} (12%) more than the 112 kg N ha^{-1} treatment. Whereas, due to establishment costs and low yields (Table 1), the smallest return in the CA rotation was at 224 kg N ha^{-1} treatment which lost $26 ha^{-1} (18%) more than the 0 and 56 kg N ha^{-1} treatments (Table 3). Across all N rates, average returns for first-year alfalfa were positive for the AA, CCOa*A*A, and CSCOa*A* rotations, which average $141 ha^{-1}, while those rotations, CA and CCC*A*A, which were not continuous or followed a nurse crop year, averaged $–174 ha^{-1} (Table 3).

Overall net returns were affected by rotation, with the magnitude of the rotation response affected by applied N rates. Overall returns for CC had highest returns at 112 and 224 kg N ha^{-1} averaging $269 ha^{-1} (two-fold) more than the 0 and 56 kg N ha^{-1} treatments. These results show that CC is not profitable using <112 kg N ha^{-1}. The highest returns in the CCCAA rotation were at 112 and 224 kg N ha^{-1} averaging $81 ha^{-1} (51%) more than the 0 kg N ha^{-1} treatment. In the CS rotation the 112 kg N ha^{-1} treatment averaged $92 ha^{-1} (30%) more than the 0 kg N ha^{-1} treatment, however it was not found to be significantly different from the 56 and 224 kg N ha^{-1} treatments. Across all crop rotations, the average return was greatest for the 112 and 224 kg N ha^{-1} treatments, which returned on average $32 ha^{-1} (19%) more than the 56 kg N ha^{-1} treatment and $85 ha^{-1} (49%) more than the 0 kg N ha^{-1} treatment. Across all N rates, average returns were highest for the CS rotation. The CS rotation returned $58 ha^{-1} (22%) more than the CSCOaA and CCOaAA rotations, $129 ha^{-1} (48%) more than the CCCAA rotation and AA, $224 ha^{-1} (84%) more than the CA rotation, and $269 ha^{-1} (one-fold) more than CC (Table 3). Our results were similar with Chase and Duffy (1991) and Katsvairo and

Cox (2000) where they reported that CC had the least net returns and a CS rotation had the highest net returns among rotations in a chisel tillage system.

Stochastic dominance analysis of net income per hectare was conducted across systems. First degree stochastic dominance analysis failed to identify any cropping system dominating the others. The reason is that the distribution functions of net income from any two systems were found to cross (as illustrated in Fig. 1b). Given this result, we proceeded to conduct second degree stochastic dominance, under the assumption that decision makers are risk averse. Twenty-eight empirical distributions were used to compare and evaluate alternative cropping systems (Lowenberg-Deboer and Aghib, 1999). The empirical distribution was obtained by combining yield, prices, and cost for each system over the 15-yr study period. This generates a consistent estimate of the true underlying distributions, providing a basis for a stochastic dominance evaluation of profitability across cropping systems under risk (Pope and Ziemer, 1984). Stochastic dominance has the advantage of generating relative ranking without imposing a parametric structure on the distribution functions. For example, it does not require a normal distribution (Buccola, 1986). As such, using empirical distributions provides an appropriate basis for a stochastic dominance analysis of net returns across cropping patterns.

The selection of rotation and N rates by a producer depends on the net returns of the whole system and not just individual components in isolation of the other elements. When choosing among cropping systems, producers are often faced with a trade-off between increases in annual net returns and increases in income variability or financial risk. As producers become increasingly risk averse, they tend to choose cropping systems that display lower income variability (Meyer-Aurich et al., 2006).

Of the 28 crop rotation by N rate treatments, five were found to be second-degree stochastically efficient (in the sense that they were not dominated by any other cropping systems). The five stochastically efficient treatments were CS at all N rates and CC at 224 kg N ha^{-1} (data not shown). All other cropping systems were inefficient when compared to these five treatments. All other treatments were dominated by at least one other treatment. This means that these dominated treatments would not be chosen by any risk-averse decision maker. To the extent that most decision makers are risk averse, this provides useful information on the economic performance of the various cropping patterns. This is likely due to establishment costs related to alfalfa (machinery, seed, and fertilizer; see Table 2), higher overall prices for corn and soybean when compared to oat and alfalfa, or due to lower yield variability associated with corn and soybean when compared to oat and alfalfa.

This research shows that the most profitable systems (CS) remain the most efficient when risk is considered. According to Meyer-Aurich et al. (2006), the diversification of the rotation reduces production risk in contrast to planting corn continuously. Similar findings have been observed by Helmers et al. (2001), where they compared a CS rotation with corn and soybean planted continuously and found that production risk was reduced when the crops were planted in rotation, even though yield variance was higher in the rotated crops than for the sole crops planted continuously. Zentner et al. (2002) also found that crop diversification reduces business risk for wheat-based crop rotations in western Canada. According to Helmers et al. (2001), the benefit of crop rotations in reducing risk involves three distinct influences. First, conventionally practiced rotations involve diversification, an offsetting phenomenon where low returns in 1 yr for one crop are combined with relatively high returns from a different crop. Second, rotation cropping is generally thought to reduce yield variability compared with monoculture practices. Finally, rotations, as opposed to monoculture cropping, may result in overall higher crop yields as well as reduced production costs. However, in addition to these facts, these results also show that when 224 kg N ha^{-1} is added, risk can be reduced for continuous corn, by reducing yield variability.

The choice between the stochastically dominant cropping systems of CS at all N rates and CC at 224 kg N ha^{-1} is driven by several factors. This includes the degree of risk aversion of the producer. Note that the degree of risk aversion may vary across decision makers (e.g., depending on their wealth, credit availability, age, and familiarity/experience with these cropping systems). Individual circumstances will dictate the optimal choice among the efficient set (DeVuyst and Halvorson, 2004). This choice is further influenced by the joint distribution of yields and prices. Our analyses are based on historical prices and yields. So we have determined the ex-post ranking of cropping systems. For a decision maker, expected yields and prices are used to make decisions. If past yields and prices are judged to be good predictors of future outcomes, our analyses are appropriate. If not, a formal expectations model is needed to generate forecasted yields and prices (DeVuyst and Halvorson, 2004).

CONCLUSIONS

Previous research from this long-term field study evaluated yield differences in crop rotations and N rates. Current findings agree with past research that crop rotation improves yields relative to monoculture, even in the presence of N, P, or K fertilizer levels that were not limiting yields. However, yield comparisons do not provide the appropriate basis for economic decision-making regarding cropping systems. Overall net returns were affected by rotation, with the magnitude of the rotation response affected by applied N rates. Across all crop rotations, the average return was greatest for the 112 and 224 kg N ha^{-1} treatments. Across all N rates, average returns were highest for the CS rotation followed by CSCOaA, CCOaAA, CCCAA, AA, CA, and CC. The crop rotations with the highest net returns were calculated without inclusion of government payments. Inclusion of government payments would have further substantiated our results by improving the economic return to corn, soybean, and oat. Under second degree stochastic dominance, the stochastically efficient treatments were CS at all N rates and CC at 224 kg N ha^{-1}. All other cropping systems were inefficient relative to these five treatments (i.e., they would not be chosen by a risk-averse decision maker). This research shows that the most profitable systems (CS) remain the most efficient when risk is taken into consideration. However, these results also show that when 224 kg N ha^{-1} is added, risk can be reduced for continuous corn. Individual circumstances will dictate the optimal choice among the efficient rotations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Tim Wood for his technical support and providing us with the historical information necessary to complete this paper; Jung Won Mun and Nicholas Keuler for their statistical advising and assistance in data analysis; and to the associate editor and reviewers for the helpful comments. Funding for this research and publication was provided from the USDA Cooperative State Research, Education and Extension Service (CSREES) project WIS0 142-4897.

REFERENCES

Baldock, J.O., R.L. Higgs, W.H. Paulson, J.A. Jackobs, and W.D. Shrader. 1981. Legume and mineral N effects on crop yields in several crop sequences in the Upper Mississippi Valley. Agron. J. 73:885–890.

Bolton, E.F., V.A. Dirks, and J.W. Aylesworth. 1976. Some effects of alfalfa, fertilizer, and lime on corn yield rotation on clay soil during a range of seasonal moisture conditions. Can. J. Soil Sci. 56:21–25.

Bruulsema, T.W., and B.R. Christie. 1987. Nitrogen contribution to succeeding corn from alfalfa and red clover. Agron. J. 79:96–100.

Buccola, S.T. 1986. Testing for nonnormality in farm net returns. Am. J. Agric. Econ. 68:334–343.

Bundy, L.G., K.A. Kelling, and L. Ward Good. 1990. Using legumes as a nitrogen source. Bull. A3517. Univ. of Wisconsin Coop. Ext. Serv., Madison.

Bundy, L.G., D.T. Walters, and A.E. Olness. 1999. Evaluation of soil nitrate tests for predicting corn nitrogen response in the North Central Region. North Central Reg. Res. Publ. 342. Wisconsin Agric. Exp. Stn., Univ. of Wisconsin, Madison.

Chase, C.A., and M.D. Duffy. 1991. An economic analysis of the Nashua tillage study: 1978–1987. J. Prod. Agric. 4:91–98.

Clegg, M.D., and C.A. Francis. 1994. Crop management. p. 135–156. *In* J.L. Hatfield and D.L. Karlen (ed.) Sustainable agricultural systems. CRC Press, Boca Raton, FL.

Copeland, P.J., R.R. Allmaras, R.K. Crookston, and W.W. Nelson. 1993. Corn-soybean rotation effects on soil water depletion. Agron. J. 85:203–210.

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113.

DeVuyst, E.A., and A.D. Halvorson. 2004. Economics of annual cropping versus crop-fallow in The Northern Great Plains as influenced by tillage and nitrogen. Agron. J. 96:148–153.

Duffy, M.D. 1993–2004. Estimated costs of crop production in Iowa. Coop. Ext. Serv., FM 1712. Iowa State Univ., Ames.

Dumenil, L. 1954. Residual effect of nitrogen fertilizer applied to corn on the yields of succeeding corn or oats crops. p. 28–29. *In* Agronomy abstracts. ASA, Madison, WI.

Fox, R.H., and W.P. Piekielek. 1988. Fertilizer N equivalence of alfalfa, birdsfoot trefoil, and red clover for succeeding corn crops. J. Prod. Agric. 1:313–317.

Francis, C.A., and M.D. Clegg. 1990. Crop rotations in sustainable production systems. p. 107–122. *In* C.A. Edwards et al (ed.) Sustainable agricultural systems. Soil and Water Conserv. Soc., Ankeny, IA.

Hanoch, G., and H. Levy. 1969. The efficiency analysis of choices involving risk. Rev. Econ. Stud. 36:335–346.

Helmers, G.A., C.F. Yamoah, and G.E. Varvel. 2001. Separating the impacts of crop diversification and rotations on risk. Agron. J. 93:1337–1340.

Hesterman, O.B., C.C. Sheaffer, and E.I. Fuller. 1986. Economic comparisons of crop rotations including alfalfa, soybean, and corn. Agron. J. 78:24–28.

Higgs, R.L., W.H. Paulsen, J.W. Pendleton, A.F. Peterson, J.A. Jakobs, and W.D. Shrader. 1976. Crop rotations and nitrogen: Crop sequence comparisons on soil of the driftless area of southwestern Wisconsin, 1967–1974. Res. Bull. R2761. Univ. of Wisconsin. College of Agric. and Life Sci., Madison.

Hirshleifer, J., and J.G. Riley. 1992. The analytics of uncertainty and information. Cambridge Univ. Press, Cambridge, UK.

Kanwar, R.S., T.S. Colvin, and D.L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. J. Prod. Agric. 10:227–234.

Karlen, D.L. 2004. Cropping systems: Rain-fed maize-soybean rotations of North America. p. 358–362. *In* R.M. Goodman (ed.) Encyclopedia of plant and crop science. Marcel Dekker, New York.

Karlen, D.L., E.G. Hurley, S.S. Andrews, C.A. Cambardella, D.W. Meek, M.D. Duffy, and A.P. Mallarino. 2006. Crop rotation effects on soil quality at three Northern Corn/Soybean Belt locations. Agron. J. 98:484–495.

Karlen, D.L., G.E. Varvel, D.G. Bullock, and R.M. Cruse. 1994. Crop rotations for the 21st century. Adv. Agron. 53:1–45.

Katsvairo, T.W., and W.J. Cox. 2000. Economics of cropping systems featuring different rotations, tillage, and management. Agron. J. 92:485–493.

Lambert, D.M., and J. Lowenberg-DeBoer. 2003. Economic analysis of row spacing for corn and soybean. Agron. J. 95:564–573.

Littell, R.C., G.A. Milliken, W.W. Stroup, and W.W. Wolfinger. 1996. SAS system for mixed models. SAS Institute Inc., Cary, NC.

Liu, S., and M.D. Duffy. 1996. Tillage systems and profitability: An economic analysis of the Iowa MAX program. J. Prod. Agric. 9:522–527.

Lowenberg-Deboer, J., and A. Aghib. 1999. Average returns and risk characteristics of site specific P and K management: Eastern Corn Belt on-farm trial results. J. Prod. Agric. 12:276–282.

Lund, M.G., P.R. Carter, and E.S. Oplinger. 1993. Tillage and crop rotation affect corn, soybean, and winter wheat yields. J. Prod. Agric. 6:207–213.

Magdoff, F., and H. van Es. 2000. Crop rotations. p. 99–108 *In* Building soils for better crops. 2nd ed. Sustainable Agric. Publ., Univ. of Vermont, Burlington.

Meese, B.G., P.R. Carter, E.S. Oplinger, and J.W. Pendleton. 1991. Corn/soybean rotation effect as influenced by tillage, nitrogen, and hybrid/cultivar. J. Prod. Agric. 4:74–80.

Meyer-Aurich, A., K. Janovicek, W. Deen, and A. Weersink. 2006. Impact of tillage and rotation on yield and economic performance in corn-based cropping systems. Agron. J. 98:1204–1212.

Pedersen, P., and J.G. Lauer. 2002. Influence of rotation sequence and tillage system on the optimum plant population for corn and soybean. Agron. J. 94:968–974.

Pedersen, P., and J.G. Lauer. 2003. Corn and soybean response to rotation sequence, row spacing, and tillage system. Agron. J. 95:965–971.

Peterson, T.A., and G.E. Varvel. 1989a. Crop yield as affected by rotation and nitrogen rate. I. Soybean. Agron. J. 81:727–731.

Peterson, T.A., and G.E. Varvel. 1989b. Crop yield as affected by rotation and nitrogen rate: III. Corn. Agron. J. 81:735–738.

Pikul, J.L., Jr., L. Hammack, and W.E. Riedell. 2005. Corn yield, nitrogen use, and corn rootworm infestation of rotations in the Northern Corn Belt. Agron. J. 97:854–863.

Pope, R.D., and R.F. Ziemer. 1984. Stochastic efficiency, normality, and sampling errors in agricultural risk analysis. Am. J. Agric. Econ. 66:31–40.

Porter, P.M., J.G. Lauer, W.E. Lueschen, J.H. Ford, T.R. Hoverstad, E.S. Oplinger, and R.K. Crookston. 1997. Environment affects the corn and soybean rotation effect. Agron. J. 89:441–448.

Riedell, W.E., T.E. Schumacher, S.A. Clay, M.M. Ellsbury, M. Pravecek, and P.D. Evenson. 1998. Corn and soil fertility responses to crop rotation with low, medium, or high inputs. Crop Sci. 38:427–433.

SAS Institute. 2002. SAS release 9.1. The SAS Inst., Cary, NC.

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron. J. 97:452–461.

Singer, J.W., C.A. Chase, and D.L. Karlen. 2003. Profitability of various corn, soybean, wheat, and alfalfa cropping systems. Available at www.plantmanagementnetwork.org/pub/cm/research/2003/profit/ [verified 25 Sept. 2007]. Crop Management doi: 10.1094/CM-2003-0130-01-RS.

Singer, J.W., and W.J. Cox. 1998a. Agronomics of corn production under different crop rotations in New York. J. Prod. Agric. 11:462–468.

Singer, J.W., and W.J. Cox. 1998b. Economics of different crop rotations in New York. J. Prod. Agric. 11:447–451.

USDA-National Agricultural Statistics Service. 2004. Historical track records. Available at www.usda.gov/nass/pubs/trackrec/croptr04.pdf (assessed 1 May 2006; verified 21 Sept. 2007). USDA-NASS, Washington, DC.

Vanotti, M.B., and L.G. Bundy. 1994a. Corn nitrogen recommendations based on yield response data. J. Prod. Agric. 7:249–256.

Vanotti, M.B., and L.G. Bundy. 1994b. Frequency of nitrogen fertilizer carryover in the humid Midwest. Agron. J. 86:881–886.

Vanotti, M.B., and L.G. Bundy. 1995. Soybean effect on soil nitrogen availability in crop rotations. Agron. J. 86:676–680.

Welch, L.F. 1976. The Morrow plots: Hundred years of research. Ann. Agron. 27:881–890.

Wesley, R.A., L.G. Heatherly, C.D. Elmore, and S.R. Spurlock. 1995. Net returns from eight nonirrigated cropping systems on clay soil. J. Prod. Agric. 8:514–520.

West, T.D., D.R. Griffith, G.C. Steinhardt, E.J. Kladivko, and S.D. Parsons. 1996. Effect of tillage and rotation on agronomic performance of corn and soybean: Twenty-year study on dark silty clay loam soil. J. Prod. Agric. 9:241–248.

White, W.C., L. Dumenil, and J. Pesek. 1958. Evaluation of residual nitrogen in soils. Agron. J. 50:255–259.

White, W.C., and J. Pesek. 1959. Nature of residual nitrogen in Iowa soils. Soil Sci. Soc. Am. Proc. 23:39–42.

Young, C.E., and P.C. Westcott. 1996. The 1996 US Farm Act in creases market orientation. USDA-ERS Agric. Info. Bull. 726. U.S. Gov. Print. Office, Washington, DC.

Zacharias, T.P., and A.H. Grube. 1984. An economic evaluation of weed control methods used in combination with crop rotation: A stochastic dominance approach. North Cent. J. Agric. Econ. 6:113–120.

Zentner, R.P., G.P. Lafond, D.A. Derksen, and C.A. Campbell. 2002. Tillage method and crop diversification: Effect on economic returns and riskiness of cropping systems in a Thin Black Chernozem of the Canadian Prairies. Soil Tillage Res. 67:9–21.