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Energy output:input ratio of maize and sorghum management systems in eastern Nebraska

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Abstract

Crop management systems need to be designed to help farmers maintain economic profitability, while conserving external energy resources and farming in an environmentally responsible manner. The objective of this study was to determine the energy output:input ratio of several maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench.) management systems that are typical of eastern Nebraska, USA. Management variables were, (1) nitrogen (N) fertilization, (2) previous crop (cereal or legume), (3) tillage (none or traditional), (4) herbicide (none, banded, or broadcast), and (5) water (dryland, limited irrigation, or full irrigation). Eleven management systems were delineated from different combinations of the last four variables and compared at different levels of N fertilization. The energy output:input ratio ranged from 4.1 ± 0.5 in fully irrigated, broadcast herbicide, traditional tillage systems with cereal as previous crop and no N fertilizer to 11.6 ± 2.5 in dryland, broadcast herbicide, traditional tillage systems with legume as previous crop and no N fertilizer. The energy output:input ratio decreased with the addition of N fertilizer in all management systems, except in fully irrigated, continuous cereal systems. Management systems with legume as previous crop had a greater energy output:input ratio than those with cereal as previous crop. Under dryland conditions with traditional tillage, the energy output:input ratio was greater with herbicide usage than without. Dryland management systems had greater energy output:input ratios than systems with irrigation. The obvious short-term advantage of greater food production from irrigated agriculture using high levels of fossil fuel derived inputs must be balanced against the long-term costs to society of depleting a scarce and non-renewable energy resource. Rotation of cereals and legumes under dryland conditions in the western Corn Belt may be more sustainable for the future based on energy use efficiency because of lower fossil fuel requirements from N fertilizer and irrigation.

Keywords: Crop rotation; Irrigation; Legumes; Nitrogen fertilization; Tillage; Weed management

1. Introduction

Current, conventional agriculture is characterized by monoculture production of grain and fiber crops using specialized equipment and synthetically produced pesticides and fertilizers to reduce labor input (National Research Council, 1989). Fossil fuel derived energy embodied in machinery, fuel, and chemical inputs has replaced a large portion of the human labor input that was previously needed for agricultural production (DeWit, 1975). Fossil fuel energy resources are used to manufacture equipment, operate machinery, pump irrigation water, and produce fertilizers and pesticides. The average energy input for maize production in the

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USA has increased from about 10 000 MJ ha^{-1} in 1945 to over 30 000 MJ ha^{-1} in 1983 (Pimentel et al., 1973, 1990). Nitrogen fertilizer use has risen from 2.4 million t in 1960 to nearly 11 million t in 1981 (USDA, 1987). The percentage of area planted to maize in the USA that was treated with herbicides has increased from 11% in 1952 to 90% in 1976 (Hughes, 1980). Large fossil fuel driven machinery is common in agriculture in the USA today. Concomitant with these changes in external energy input, average USA maize production has increased from 2.4 Mg ha^{-1} in 1930 to 7.5 Mg ha^{-1} in 1991 (USDA, 1994). High yield production in the USA is often attributed to these changes in external energy inputs, although genetic improvement of crops is estimated to have accounted for at least half of the increase (Duvick, 1977; Jensen, 1978).

Intensive agricultural production with high fossil fuel derived energy inputs, however, has not developed without serious environmental consequences, including continued soil erosion and increased surface and groundwater contamination with pesticide residues and nitrate (National Research Council, 1989). Unintended losses of high-energy inputs of synthetically produced fertilizers and pesticides that are not used or needed by the crop decrease the energy efficiency of crop production systems. Society's growing concern with environmental degradation as a result of agricultural practices should be embraced by agronomists as a challenge to develop and improve crop management systems to decrease negative environmental impacts, increase energy efficiency, maintain economic viability, and improve sustainability beyond current high-input systems.

Management systems that meet the farmers' goal of sustainability have included approaches that attempt to reduce risk and diversify the farming operation (Flora, 1990). Crop rotations are integral to this strategy because they diversify labor input and income sources, reduce the risk of total crop failure, help maintain soil fertility, and reduce external energy inputs. Rotation of grain or forage legumes, capable of fixing atmospheric nitrogen (N), with cereal or fiber crops can maintain production levels with reduced reliance on energy intensive commercial fertilizers (Heichel and Barnes, 1984; Youngberg and Buttel, 1984). Additionally, crop rotations can reduce the incidence of insects and diseases (Bird et al., 1990) and weeds (Liebman and Janke, 1990) by disrupting pest life cycles and providing genetic diversity within a field over time. Growing crops with different growth characteristics may limit the build-up of crop-specific weed populations (Sumner, 1982).

The proportion of total energy inputs invested in irrigation and synthetically produced fertilizers and pesticides for maize production in the USA has risen from 11% in 1945 to 38% in 1970 to 64% in 1983 (Pimentel et al., 1973, 1990). Greater control over these high-energy inputs has been targeted as one way to increase energy efficiency. Setting alternative yield goals based upon economics or energy efficiency rather than maximum yield can reduce N fertilizer requirements (Hanson et al., 1988). Rotation of cereals with legumes can reduce the amount of N fertilizer required to attain optimal yields (Heichel and Barnes, 1984; Hanson et al., 1988) and limit the need for pesticides (Bird et al., 1990). Limiting irrigation to a schedule based on available soil moisture has been recommended as a means to conserve water and energy (Kranz et al., 1992). Limited data are available, however, to characterize fully energy efficiency in different agricultural regions, especially when management practices vary widely within a region.

One approach to evaluating energy efficiency is to design trials together with farmers as full participants in the research process (Franzluebbers and Francis, 1991). Our objective was to determine the energy output:input ratio of maize and sorghum production systems in eastern Nebraska that varied in N fertilizer, previous crop, tillage, herbicide, and water management.

2. Methodology

Thirty-eight farmers in 14 counties of eastern Nebraska participated in 86 nitrogen fertilizer trials on their farms as part of a University of Nebraska Cooperative Extension program during 1988–1990. Farm operations were small to medium-sized grain production systems typical of the area, with 85% of the farms having a livestock operation in conjunction with crop production. Selection criteria and participatory activities of farmers are described by Franzluebbers and Francis (1991). The long-term average rainfall in the area varies from 610 mm year^{-1} in the west to 840 mm year^{-1} in the east.

Fifty-nine percent of the trials were conducted with only two N rates. One rate was a control without N fertilizer application after planting. The second N fertilizer rate was selected by the farmer and averaged 62 kg ha^{-1}, ranging from 11 to 112 kg ha^{-1}. The remaining 41% of the trials were conducted with three to six N rates (one rate always as a control without N fertilizer after planting). The maximum N fertilizer application rate in these latter trials averaged 114 kg ha^{-1}, and ranged from 67 to 180 kg ha^{-1}.

Timing and type of N fertilizer application were selected by each farmer, and included (1) preplant as gaseous ammonia or dry mixture with P and/or K, (2) at planting as dry or liquid mixture, (3) at cultivation as liquid mixture, or (4) at sidedressing as liquid mixture or gaseous ammonia. Fertilizer was applied by the farmer in long, narrow strips ranging from four to 20 rows wide (3–20 m) and 117–930 m long. Where N fertilizer application was not normally practiced by participating farmers because of long-term rotation that provided soil N, fertilization of experimental plots within farmers' fields was performed by the project coordinator (24% of trials). A detailed methodological description and report on grain yield response to N fertilizer were described by Franzluebbers et al. (1994).

Planting occurred during late April to late May for maize and early June for sorghum. All management practices other than N fertilization were under the control of each farmer, including type of tillage, planting, weed and insect management, and irrigation. Maize and grain sorghum were harvested with the farmer's equipment and grain was weighed on a portable field scale in most cases. The small plots fertilized by the project coordinator and some of the long strips were harvested by hand after physiological maturity. These subplots were one or two rows that were 6–8 m long.

Replication of each N rate within a trial varied from none (8% of trials) to seven. Mean values of the energy output:input ratio for each N fertilizer rate within replicated trials and values obtained from unreplicated trials comprised the total data set. Individual trials were, therefore, considered as replications within each management system (Stroup et al., 1993).

Previous crop in each trial was a cereal or a legume. Cereal previous crops included maize, sorghum, oat (*Avena sativa* L.), or rye (*Secale cereale* L.). Legume previous crops included soybean (*Glycine max* L. Merr.), alfalfa (*Medicago sativa* L.), sweet clover (*Melilotus officinalis* Lam.), oat/clover (*Trifolium pratense* L.), or first year cereal after alfalfa.

Tillage system among trials was traditional or no tillage. Traditional tillage systems comprised conventional and conservation tillage. A survey of eastern Nebraska farmers indicated that 85% of those questioned were using some form of conservation tillage system (Jones and Dickey, 1989), which includes no-till, till-plant, ridge-till, disk, or chisel-plow. No tillage systems were defined separately from traditional tillage systems, although only 2% of farmers surveyed used this system.

Weed control among trials consisted of (1) tillage only without herbicides, (2) banded herbicide application at the time of planting, and (3) broadcast herbicide application.

Water management of trials was characterized as (1) dryland with no supplemental irrigation, (2) limited irrigation to prevent drought stress during critical periods of plant development, and (3) full irrigation throughout the growing season.

Number of field operations and associated fuel use are summarized in Table 1. Energy consumption was calculated from crop production practices used by the farmers using published unit values for inputs (White, 1974). Field operations ranged from four in no-till and ridge-till to nine with chisel-plow tillage. Energy use was expressed in diesel fuel equivalence of 42 MJ l^{-1}. Fuel required to apply N fertilizer (83 MJ per application ha^{-1}) was added to the energy in N fertilizer (50 MJ kg^{-1} N; Lockeretz, 1980). The energy embodied in herbicides (other than application) was assumed to be 446 MJ ha^{-1} for band application, 893 MJ ha^{-1} for broadcast application with disk tillage, and 1122 MJ ha^{-1} for broadcast application with no tillage. These values reflect the different types and amounts of herbicides typically used for these systems (USDA, 1980). The energy required to pump irrigation water (41 MJ ha^{-1} mm^{-1}; Dvoskin et al., 1977) was calculated for full irrigation (508 mm assumed) and limited irrigation (254 mm assumed). Manure (249 MJ ha^{-1}, including energy for collection, transportation, and spreading) or phosphate fertilizer application (353 MJ ha^{-1}; Lockeretz, 1980) was assumed for all trials at a rate of 6.1 kg P ha^{-1}. Soil insecticide application (767 MJ ha^{-1}; Pimentel, 1980) was assumed for all trials conducted with maize following maize and sorghum following sorghum. All management systems were assumed to have equal energy invested in machinery (4159 MJ ha^{-1}), transportation (140 MJ ha^{-1}), and seeds (1295 MJ ha^{-1}) (Pimentel, 1980). The energy output of maize grain was assumed to be 15 MJ kg^{-1} (Pimentel and Burgess, 1980), and sorghum grain was assumed to contain 14 MJ kg^{-1} (Bukantis, 1980).

Mean energy output:input ratio of each management system was regressed upon N fertilizer rate using the GLM procedure of SAS (Statistical Analysis Systems Institute Inc., 1985). Means of energy input and energy output:input ratio without N fertilizer application among management systems were declared significantly different at $P \leqslant 0.1$.

3. Results and discussion

Energy inputs, excluding N fertilizer and its application, for different crop management systems as influenced by previous crop, tillage, weed control, and water management ranged from 7729 to 30 107 MJ ha^{-1} (Table 2). Management systems with legume as previous crop had energy inputs equal to 13% lower than management systems with cereal as previous crop, primarily because of decreased need for insecticide application to the cereal in rotation. Under dryland conditions, traditional tillage systems with broadcast herbicide had 11% greater energy input than no-till systems with broadcast herbicide. Fuel consumption was 48% less with no-till than with traditional tillage and broadcast herbicide application (Table 1). However, the assumption was made that no-till systems required 26% greater energy invested in herbicides (USDA, 1980). Weed control with traditional tillage using no herbicides or using banded application decreased energy input by 12% compared with traditional tillage with broadcast herbicide (Table 2). Energy inputs in irrigated management systems were two to three times greater than in dryland management systems as a result of the large cost of pumping.

Average cereal (i.e. maize and sorghum) yields in the 11 management systems ranged from 3.6 ± 1.5 Mg ha^{-1} in dryland, no herbicide, traditional tillage systems with legume as previous crop and no N fertilizer to 8.7 ± 2.1 Mg ha^{-1} in fully irrigated, broadcast herbicide, traditional tillage systems with legume as previous crop and no N fertilizer (Table 2). The highest average yields under dryland were with full herbicide, traditional tillage systems with legume as previous crop and no N fertilizer (6.6 ± 1.4 Mg ha^{-1}, Table 2). Irrigation increased grain yield per hectare from 20% to 140% compared with dryland conditions, but required a much greater energy input to obtain this level of productivity. Energy output:input ratios of dryland management systems were 50–180% greater than those of fully irrigated management systems. Farm policies that regulate grain production, especially surplus feed grains, should consider the much larger fossil-fuel

Table 1
Number of field operations and associated fuel consumption in l ha^{-1} (White, 1974) for different types of maize and sorghum management systems in eastern Nebraska

Field operation	Traditional tillage														No tillage			
	No herbicide										Banded herbicide				Broadcast herbicide			
	A		B		C		D		E		F		G		H		I	
Plow	1	17.1	1	10.5		NA	1	7.2		NA		NA		NA		NA		NA
Disk	2	14.5	2	14.5	2	14.5		NA		NA	2	14.5		NA	2	14.5		NA
Herbicide		NA		NA		NA		NA		NA		NA		NA	1	1.9	2	4.0
Plant	1	5.9	1	5.9	1	5.9	1	5.9	1	5.9	1	5.9	1	5.9	1	5.9	1	5.9
Rotary hoe	1	1.6	2	3.3	2	3.3	2	3.3	2	3.3		NA		NA		NA		NA
Cultivate	2	7.9	2	7.9	2	7.9	2	7.9	2	7.9	2	7.9	2	7.9	2	7.9		NA
Harvest	1	11.8	1	11.8	1	11.8	1	11.8	1	11.8	1	11.8	1	11.8	1	11.8	1	11.8
Total	8	58.7	9	53.9	8	43.4	7	36.1	6	28.9	6	40.1	4	25.6	7	42.0	4	21.7

A, moldboard plow; B, chisel plow; C, disk till; D, sweep plow, ridge till; E, ridge till; F, disk till; G, ridge till; H, disk till; I, no till.

Table 2
Average energy input and output ($MJ\ ha^{-1}$), grain yield ($Mg\ ha^{-1}$) and regression parameters relating energy output:input ratio to N fertilizer rate ($kg\ ha^{-1}$) for different maize and sorghum management systems

Management system				Number of trials	Grain yield ($Mg\ ha^{-1}$)	Energy input ($MJ\ ha^{-1}$)	Regression parameters		
Water[a]	Herb[b]	Till[c]	PC[d]				Intercept[e]	Linear	Quadratic
D	N	T	C	9	3.7	7902	7.0 ± 2.1	−0.0020	−0.00057
D	N	T	L	32	3.6	7874	6.9 ± 2.8	−0.0364	NA[f]
D	B	T	C	7	4.2	7839	8.1 ± 1.1	−0.0277	NA
D	B	T	L	6	4.8	7729	9.3 ± 2.6	−0.0449	NA
D	F	N	C	2	4.6	9057	7.7 ± 0.3	−0.0016	−0.00015
D	F	N	L	9	5.1	7865	9.7 ± 2.6	−0.0417	NA
D	F	T	C	4	4.9	9332	7.9 ± 2.6	−0.0253	−0.00027
D	F	T	L	4	6.6	8539	11.6 ± 2.5	−0.0600	NA
L	B	T	L	2	7.9	17 786	5.7 ± 1.1	−0.0172	NA
F	F	T	C	3	8.2	30 107	4.1 ± 0.5	0.0027	−0.00001
F	B	T	L	8	8.7	29 149	4.5 ± 1.1	−0.0051	NA

[a]Water: D, dryland; L, limited irrigation (254 mm $year^{-1}$); F, full irrigation (508 mm $year^{-1}$).
[b]Herbicide: N, no herbicide; B, banded herbicide; F, full, broadcast herbicide.
[c]Tillage: T, traditional tillage; N, no tillage.
[d]Previous crop: C, cereal; L, legume.
[e]Intercept, mean energy output:input ratio without N fertilizer ± standard deviation.
[f]NA, not applicable.

derived energy inputs that are required to produce equal quantities of grain with less land area. In addition, policies that subsidize production to balance supply and demand of grain should consider the availability of land, energy inputs, and labor in order to make sound economic and environmental decisions that will benefit all sectors of society in the long term.

Energy output:input ratios of management systems without N fertilizer ranged from 4.1 ± 0.5 in fully irrigated, broadcast herbicide, traditional tillage systems with cereal as previous crop to 11.6 ± 2.5 in dryland, broadcast herbicide, traditional tillage systems with legume as previous crop (Table 2). These values of energy output:input ratio under both irrigated and dryland conditions are about twice as large as those reported previously for maize and sorghum production in Nebraska (Bukantis, 1980; Pimentel and Burgess, 1980). Pimentel and Burgess (1980) and Bukantis (1980) assumed that as much as 16–35% of the total energy input came from N fertilizer, which drastically reduced the energy output:input ratios in their energy budgets. The on-farm data reported here indicate that N fertilizer management can be optimized, such that the percentage of energy invested in N fertilizer can be very low. The availability of N from residual soil nitrate and previous cropping history must be considered in order to improve energy efficiency, improve economic returns on N fertilizer investment, and reduce environmental stress caused by excessive NO_3 that may leach to groundwater supplies and/or that may denitrify causing an increase in harmful greenhouse gas. Residual soil nitrate to a depth of 1 m averaged 106 kg N ha^{-1} with cereal as previous crop, but only 76 kg N ha^{-1} with legume as previous crop (Franzluebbers et al., 1994).

In all management systems except fully irrigated, broadcast herbicide, traditional tillage, and cereal as previous crop (FFTC), the average energy output:input ratio decreased with N fertilizer application. The energy input of added N fertilizer was greater than the energy produced in additional grain. In the FFTC management system, the energy output:input ratio increased up to 187 kg N ha^{-1} and beyond that level the ratio decreased. With a legume as previous crop, the energy output:input ratio decreased more with N fertilizer application than in systems with cereal as previous crop (Table 2). This was a result of a greater relative yield level without N fertilizer when a legume was previous crop compared with when a cereal was previous crop (Franzluebbers et al., 1994).

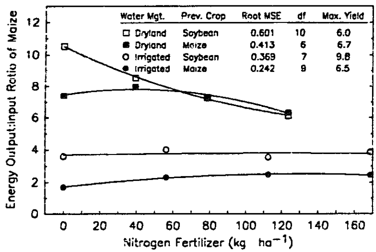

Fig. 1. Examples of energy output: input ratio of maize in response to N fertilizer as affected by previous crop and water management system.

Typical examples of energy output:input ratio of maize production in response to N fertilizer with respect to previous crop and water management are illustrated in Fig. 1 from two trials at different locations. With soybean as previous crop, the energy output:input ratio was greatest without N fertilizer. With maize as previous crop, however, the maximum energy output:input ratio occurred at 34 kg N ha^{-1} for the dryland site and 112 kg N ha^{-1} for the irrigated site.

Twenty percent of the trials increased in energy output:input ratio with the application of N fertilizer when a cereal was previous crop, while only 5% of the trials increased in energy output:input ratio when a legume was previous crop. Even though the average response of the energy output:input ratio decreased with N fertilization when cereal was the previous crop, those trials with a positive response to N fertilizer had an exceptionally low initial N level (residual soil nitrate to a depth of 1 m plus preplant or starter fertilizer) (Franzluebbers et al., 1994). Only when the initially available N level was low relative to grain yield (i.e. less than 0.01 kg N kg^{-1} grain) did the energy output:input ratio of maize following a cereal respond to fertilizer N.

The infrequent occurrence of increased energy efficiency with N fertilization demonstrates the importance of setting realistic yield goals and carefully interpreting soil test information when determining N fertilizer needs for cereals, especially in rotation with legumes. The results of these trials indicate that the energy output:input ratio for eastern Nebraska maize and sorghum producers can be expected to increase with N fertilizer application only when grain yield is severely limited by initially available N. Fertilizer recommendations based on energy considerations may not be appealing with cheap supplies of fossil fuels presently available, but will have greater importance in the future if fossil fuel supplies become increasingly expensive and there is more competition among industrial, domestic, and agricultural sectors. Historically, the low cost of N fertilizer and lack of regulations and concern about ground and surface water contamination led to economic decisions based on short-term net returns to the individual producer. Energy output:input ratios and environmental consequences of excessive N use might limit application rates in the future.

With legume as previous crop, the energy output:input ratio without N fertilizer was 6% greater than with cereal as previous crop when averaged across all dryland management systems. Greater cereal yield in rotation without N fertilizer (Franzluebbers et al., 1994) contributed to the increase in energy output:input ratio. In Nebraska, Peterson et al. (1990) reported a maximum energy output:input ratio of 6.1 from maize in an irrigated maize/soybean/wheat (*Triticum aestivum* L.) rotation without N fertilizer, but only 4.7 in continuous maize requiring 120 kg N ha^{-1}. Heichel (1978, 1980) also observed higher energy output:input ratios in several different rotation sequences compared with continuous cropping systems. Energy output:input ratio was 4.5 for conventionally managed continuous maize in Iowa, but ranged from 5.7 to 7.6 in various rotated crop sequences that were managed organically (Pimentel et al., 1983).

It is important to note that these energy output:input ratios are based on a single year's energy budget to raise a crop of maize or grain sorghum. To measure adequately the long-term energy efficiency of crop rotation systems would require data collection over several years for all crops in the sequence, including the legumes in rotation with cereals. This multi-year energy budget would reveal more clearly which system was more energy efficient, and would be more realistic for evaluation of the total system. Such a comparison was beyond the scope of this study, but warrants further research. As examples, the energy output:input ratios of soybean production in different states vary from 1.8

in Georgia, 2.4 for irrigated soybean in Nebraska, 3.5 in Ohio, and 4.5 in Illinois (Scott and Krummel, 1980). The corresponding energy output:input ratios of maize production were reported to be 2.1 in Georgia, 1.8 for irrigated maize in Nebraska, 4.2 in Ohio, and 4.6 in Illinois (Pimentel and Burgess, 1980). These authors also report an energy output:input ratio of 3.1 for dryland maize production in Minnesota. Heichel and Martin (1980) reported values of 2.8 for establishment-year oat/alfalfa and 7.2 for 2–3 year alfalfa stands in Minnesota. It appears that legume phases of a rotation sequence may be more energy efficient than the maize phase, especially when considering that the energy efficiency values for cereal and legume crops would probably be higher in rotation than in monoculture.

The energy output:input ratio did not differ between traditional tillage and no tillage systems with broadcast herbicide under dryland conditions. The greater energy input of traditional tillage systems was associated with a proportional increase in energy output of grain. Maintenance of high energy output:input ratios with NT with the potential for reduced soil erosion compared with traditional tillage systems could increase the long-term benefit to the nation's soil and water resources for agricultural, utility, and recreational use.

With legume as previous crop under dryland conditions, management systems with herbicide (i.e. banded or broadcast application) had greater energy output:input ratios than without use of herbicides, despite the greater energy input of management systems with herbicides. This may have been a result of decreased weed competition in management systems with herbicides that led to increased grain yields. This was apparent during 1988 and 1989 when precipitation was less than normal at many locations and competition for water by weeds could have been severe in management systems without herbicides.

Dryland management systems had significantly greater energy output:input ratios than irrigated management systems, because of the 200–300% greater energy input required for pumping irrigation water. The difference in energy input between fully irrigated and dryland management systems would require that 1466 kg ha^{-1} more maize or 1562 kg ha^{-1} more sorghum be produced under irrigation to balance the additional energy invested in pumping costs. This has occurred in the past, when irrigated maize yields have been 3200 ± 750 kg ha^{-1} greater than dryland yields from 1970–1986 (Nebraska Agricultural Statistics, 1972–1986). However, because the energy input of fully irrigated systems was three to four times greater than that of dryland systems, an equivalent energy output:input ratio between these water management regimes could not occur, except under very adverse conditions (e.g. drought, heat stress) that would restrict dryland yields.

4. Summary

Energy inputs of maize and sorghum production systems in eastern Nebraska were greatest in irrigated management systems. Energy output:input ratios decreased with N fertilizer application in all management systems, except with cereal as previous crop and low initially available N. Energy output:input ratios for cereals were (1) greater with a legume compared with a cereal as previous crop, (2) were not different between traditional and no tillage, (3) were greater with herbicide use compared with no herbicides, and (4) greater under dryland compared with irrigated conditions. These results have important implications for farmers' future decisions on management practices as energy costs rise and environmental concerns about agriculture intensify.

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