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The Contribution of Commercial Fertilizer Nutrients to Food Production

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ABSTRACT

Nutrient inputs in crop production systems have come under increased scrutiny in recent years because of the potential for environmental impact from inputs such as N and P. The benefits of nutrient inputs are often minimized in discussions of potential risk. The purpose of this article is to examine existing data and approximate the effects of nutrient inputs, specifically from commercial fertilizers, on crop yield. Several long-term studies in the USA, England, and the tropics, along with the results from an agricultural chemical use study and nutrient budget information, were evaluated. A total of 362 seasons of crop production were included in the long-term study evaluations. Crops utilized in these studies included corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], rice (*Oryza sativa* L.), and cowpea [*Vigna unguiculata* (L.) Walp.]. The average percentage of yield attributable to fertilizer generally ranged from about 40 to 60% in the USA and England and tended to be much higher in the tropics. Recently calculated budgets for N, P, and K indicate that commercial fertilizer makes up the majority of nutrient inputs necessary to sustain current crop yields in the USA. The results of this investigation indicate that the commonly cited generalization that at least 30 to 50% of crop yield is attributable to commercial fertilizer nutrient inputs is a reasonable, if not conservative estimate.

Modern high yield crop production and its associated inputs have come under intense scrutiny over the past several years. Concerns expressed often involve the widespread application of commercial crop nutrients and their possible effects on the environment (Ferber, 2001; Parry, 1998; Sharpley et al., 1999; Tilman et al., 2001). Food production for the expanding world population has required the development and application of new technology and an intensification of management to produce more food per unit of land. This new technology and intensified production often involve a greater need for commercial fertilizer nutrients to avoid nutrient depletion and ensure soil quality and crop productivity. The need for increased inputs correctly raises questions about associated risks. Potential risks are often widely publicized while the associated benefits of an abundant, affordable, and healthful food supply can be overlooked or understated. To judge any such practice or system, the risks must be evaluated in comparison with the benefits. While misuses of agricultural fertilizers have undoubtedly occurred and concerns about how fertilizers affect the environment have sometimes been overstated, the purpose of this article is not to address these issues but to provide evidence of the impact commercial fertilizers have had on agricultural production.

Several attempts have previously been made to estimate how much of the crop production in the USA is attributable to commercial nutrient inputs. These estimates usually range from about 30 to 50% for major grain crops (Nelson, 1990). Determining these estimates presents significant challenges, and assumptions are always required regardless of the approach taken. One difficulty that arises is that crops respond differently to application of a specific plant nutrient. For example, corn response to N fertilizer is much greater than the response of legumes such as soybean or peanut (*Arachis hypogaea* L.). The effort to measure yield response is further confounded by other factors such as variable soil fertility levels, climatic conditions, crop rotations, and changes in production practices that affect nutrient use efficiency. Nevertheless, it is possible to make meaningful estimates of the contribution of commercial nutrient inputs to crop yield.

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CHEMICAL USE STUDY

The impact of eliminating the use of several chemical inputs, including inorganic N fertilizer, on corn, cotton (*Gossypium hirsutum* L.), rice, barley (*Hordeum vulgare* L.), sorghum [*Sorghum bicolor* (L.) Moench], wheat, soybean, and peanut yields in the USA was investigated by Smith et al. (1990). The investigators used a modified Delphi procedure in this study, utilizing experts to pro-

Table 1. Estimated effect of eliminating N fertilizer on U.S. crop yields.

Crop	Estimated crop yield: Baseline†	Estimated crop yield: Without N fertilizer	Reduction from no N
	t ha^{-1}		%
Corn	7.65	4.52	41
Cotton	0.76	0.48	37
Rice	6.16	4.48	27
Barley	2.53	2.04	19
Sorghum	4.64	3.76	19
Wheat	2.15	1.81	16
Soybean	2.28	2.28	0
Peanut	2.55	2.55	0

† Baseline yields taken from 1987 USDA-ERS report.

vide yield and cost change estimates. Plant scientists were selected from major producing states for each crop analyzed. In arriving at the estimates for each scenario, the scientists were urged to draw on all available research and/or expertise. The 1987 production year was used as a baseline for estimating yield reductions.

The estimated effect of eliminating N fertilizer is shown in Table 1. Average U.S. corn yield was predicted to decline by 41% without N fertilizer, or in other words, N fertilizer was responsible for 41% of corn yield. The elimination of N in cotton production resulted in an estimated yield reduction of 37%. The average estimated reduction in yield from elimination of N fertilizer on the six nonleguminous crops analyzed was 26%. Had the effects of other nutrient inputs such as P and K been measured, the estimated yield reductions would have probably been greater.

LONG-TERM STUDIES

One comprehensive approach to estimating how much yield for the major crops is attributable to fertilizer inputs is by comparing yields of unfertilized controls to yields produced with fertilization over a period of many years. There are several long-term studies being conducted throughout the world that provide useful data for this approach. Some of the following long-term study examples use continuous cropping systems, which may not reflect the norm for the region (e.g., continuous wheat in Missouri); nevertheless, these data are valuable since they enable the comparison of fertilized to unfertilized production of a single crop over a long period of time.

The Magruder Plots (Oklahoma State University)

Oklahoma State University scientists have studied wheat yield response to fertilization since the late 1800s (Oklahoma State Univ., 2000). The Magruder Plots, located in Stillwater, OK, were established in 1892 and are the oldest continuous wheat soil fertility research plots in the Great Plains and are among the oldest continuous soil fertility plots in the world. The nutrient input treatments have changed since the plots were established, with yearly inorganic fertilizer applications commencing in 1930. The inorganic N source was sodium nitrate ($NaNO_3$) from 1930 to 1946 when it was changed to ammonium nitrate (NH_4NO_3). Annual N application rates have ranged from 37 to 67 kg N ha^{-1}. The early inorganic P source was ordinary superphosphate (9% P, 12% S) but was replaced by triple superphosphate (20% P) in 1968. The P rate throughout the study has been constant at 15 kg P ha^{-1}. When averaged over 71 yr, N plus P fertilizer has been responsible for 40% of wheat yield (Fig. 1).

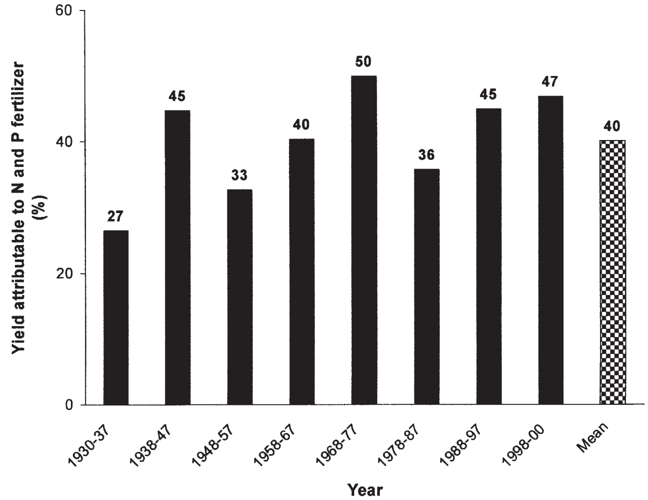

Fig. 1. Wheat yield attributable to inorganic N and P fertilizer from N plus P treatments from 1930 to 2000 in the Oklahoma State University Magruder plots.

The Sanborn Field (University of Missouri)

The Sanborn Field at the University of Missouri was initiated in late 1888 to demonstrate the value of rotations and manure in crop production. Several changes have been made to the field since its establishment, with the introduction of commercial fertilizer in 1914 (Missouri Agric. Exp. Stn., 2004). Changes in management of the field have made long-term evaluation of the effects of nutrient inputs difficult with some crops. However, the effect of nutrients in continuous wheat plots maintained since 1889 is easily evaluated by comparing the "full fertility" plot to the control. Nutrient (N, P, and K) application rates and sources in the full fertility plot have varied through the years but were considered adequate for each year. Figure 2 shows the effect of nutrient inputs on wheat grain yield from 1889 to 1998. Nutrient inputs were responsible for an average of 62% of wheat grain yield over the 100-yr period (S.J. Troesser, personal communication, 2003).

The Morrow Plots (University of Illinois)

Another long-term study is being conducted at the University of Illinois. Various crops, rotations, and fertility treatments have been evaluated in the Morrow Plots since 1876 (Univ. of Illinois Ext., 2004). Early fertility treatments included manure, rock phosphate, bone meal phosphate, and limestone. In 1955, commercial fertilizer treatments were imposed that combined N from urea, P from superphosphate, K from muriate of potash, and lime. An evaluation of continuous corn grain yields (Fig. 3) from the no-fertilizer control and

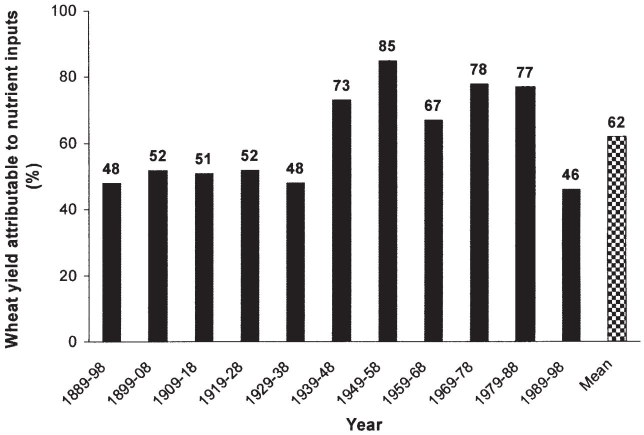

Fig. 2. Wheat yield attributable to nutrient inputs from 1889 to 1998 in the University of Missouri Sanborn Field plots.

the fertilizer (N–P–K) + lime treatment revealed that on average from 1955 to 2000 (45 yr), 57% of yield was attributable to the fertilizer + lime treatment (H.F. Reetz, personal communication, 2003). Interestingly, the yield loss from omitting these inputs more than doubled after the first 5 yr.

Long-Term Corn and Grain Sorghum Study (Kansas State University)

A long-term irrigated study in western Kansas has examined the effect of various N (0 to 225 kg N ha^{-1} in 45-kg increments) and P (0 and 20 kg P ha^{-1}) fertilizer rates on yields of corn and grain sorghum. Through 40 yr (1961 to 2000) of this study, N and P fertilization resulted in an average yield increase of 44% for corn and 31% for sorghum (Schlegel, 1990, 1991, 2000). The data shown in Table 2 summarize the 40-yr average yields for both crops for each fertility treatment and percentage of yield attributable to fertilization. These data illustrate the importance of adequate and balanced nutrient inputs in crop production. An alternate approach to estimating the contribution of fertilizer to yield would be to examine the economic optimum rates of N and P. The economic optimum N rate for corn in this study was 180 kg ha^{-1}, and in most years for sorghum, it was 90 kg ha^{-1} (Schlegel, 2000). Phosphorus fertilizer (20 kg P ha^{-1}) was necessary to maximize profit for both crops. The 40-yr averages for percentage of yield attributable to fertilizer at the economic optimum rates for N and P were 60% for corn and 38% for grain sorghum.

The Broadbalk Experiment (Rothamsted, England)

The research site at Rothamsted (40 km north of London) is among the oldest continuous field experiments in the world. Winter wheat has been grown continuously on all or part of the Broadbalk experiment since 1843, and on many plots, the treatments have remained unchanged. When the experiment started, the field had been in arable cropping for several decades, and soil organic matter levels were relatively low. Organic matter levels declined slightly over the next 20 yr where no fertilizer was applied and increased slightly where N (145 kg N ha^{-1}), P (33 kg P ha^{-1}, 35 since 1974), and K (89 kg K ha^{-1}) were applied. Over many decades, N fertilizer (with P and K) was responsible for 62 to 66% of wheat yield compared with P and K alone (Fig. 4). In recent years, as the yield potential of wheat varieties has increased, N has contributed 76 to 82% of the yield.

Between 1970 and 1995, with high-yielding varieties of winter wheat grown continuously and receiving 96 kg N ha^{-1}, the effect of omitting P has been to decrease yield, on average, by 44% while omitting K has decreased yield by 36%. Since 1968, other arable crops have been grown in rotation with wheat on part of the Broadbalk experiment each year. For potato (*Solanum tuberosum* L.) grown between 1968 and 1994, applying N at 145 kg ha^{-1} (with P and K) resulted in a 60% yield increase while omitting K decreased yield by 51%. Nitrogen (145 kg ha^{-1}) increased the yield of corn silage dry matter by 77% when applied with P and K (A.E. Johnston, personal communication, 2003).

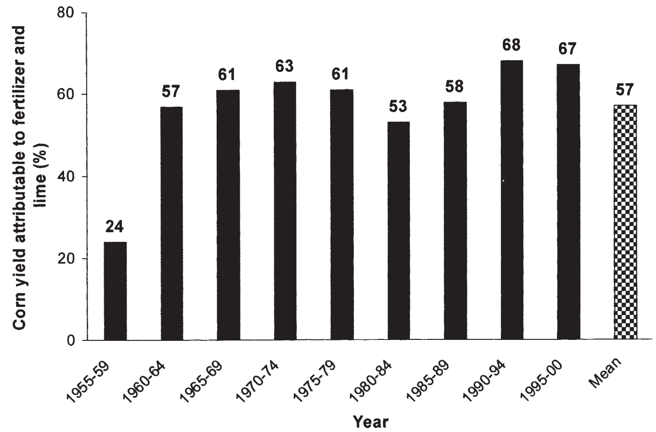

Fig. 3. Continuous corn yield attributable to N, P, and K fertilizer and lime over 46 yrs in the University of Illinois Morrow plots.

Research from the Tropics

The rate of early deforestation in the Amazon Basin had been conservatively estimated as 1.2 million ha per

Table 2. Effect of N and P fertilizer on 40-yr average (1961 to 2000) irrigated corn and grain sorghum yields and percentage yield attributable to fertilization in western Kansas.

Fertilizer applied		Grain yield		Yield due to fertilizer	
N	P	Corn	Sorghum	Corn	Sorghum
— kg ha^{-1} —		— t ha^{-1} —		— % —	
0	0	4.27	3.94	–	–
0	20	4.50	4.02	5	2
45	0	6.39	5.04	33	22
45	20	7.43	5.95	43	34
90	0	7.25	5.71	41	31
90†	20	9.10	6.34	53	38
135	0	7.33	5.51	42	28
135	20	10.06	6.58	58	40
180	0	7.77	5.70	45	31
180‡	20	10.63	6.74	60	42
225	0	7.94	5.87	46	33
225	20	10.58	5.87	60	33

† Economic optimum N rate for sorghum.
‡ Economic optimum N rate for corn.

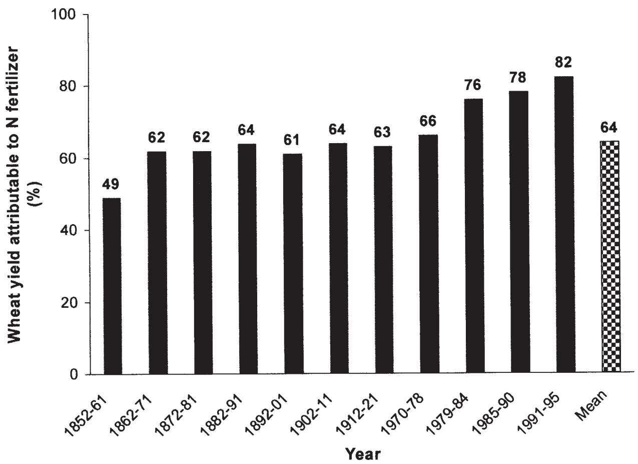

Fig. 4. Winter wheat grain yield attributable to N fertilizer with adequate P and K compared with P and K alone (Broadbalk, Rothamsted). The years between 1921 and 1969 were not included in the summary because part of the experiment was fallowed each year to control weeds. From 1970, the periods shown represent averages for individual varieties until replaced by newer varieties.

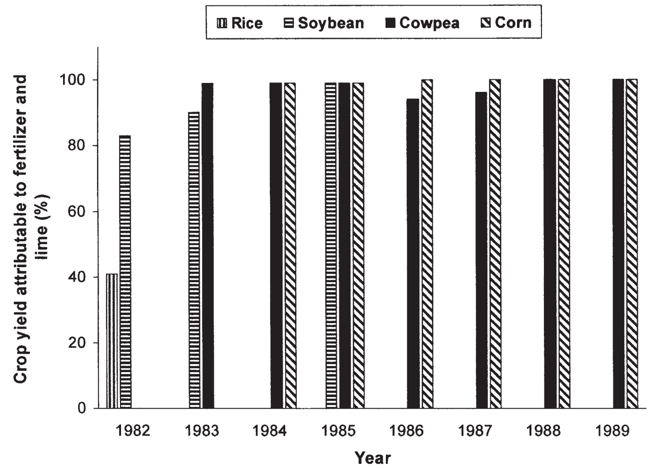

Fig. 5. Contribution of fertilizer (N, P, and K) and lime to the yield of 17 consecutive crops (rice, soybean, cowpea, and corn) during 8 yr of cultivation after slash-and-burn clearing of an Oxisol in the Amazon of Brazil.

year and was associated mainly with shifting cultivation and pasture establishment (Hecht, 1982). Shifting cultivation involves land clearing by slashing and burning the existing vegetation, planting several food crops, and abandoning the land to forest regrowth after 1 or 2 yr of cropping because of rapid declines in productivity. The use of nutrient inputs in the tropics is critical to increasing the longevity of production from these fields and thereby decreasing the rate of further clearing of existing forest.

Fertilizer requirements for continuous production of grain crops after initial slash-and-burn clearing of rainforest vegetation were studied for 8 yr on an Oxisol near Manaus, Brazil (Cravo and Smyth, 1997) and for 15 yr on an Ultisol near Yurimaguas, Peru (Alegre et al., 1991). Both sites contained replicated control treatments, which never received fertilizer or lime, and fertilized treatments where lime and fertilizer inputs for each crop were based on soil test and plant analyses data for the preceding crops. Fertilizer and lime inputs were frequently adjusted during the course of the experiments to account for declining native soil nutrient supply and residual effects from prior fertilization. In Brazil, 17 consecutive crops were grown in a succession containing upland rice, soybean, cowpea, and corn. In Peru, 33 consecutive crops were grown in a succession that included upland rice, soybean, and corn. Fertilization began with the first crop in Brazil and the second crop after land clearing in Peru.

The effects of fertilization and lime on crop yields are shown in Fig. 5 for the Brazil site and Fig. 6 for the Peru site. Yields attributed to fertilizer and lime inputs (i.e., yield where inputs were used minus yield of zero input control) at both sites were less than 40% in the first crop fertilized after slash-and-burn clearing but increased to over 80% in subsequent crops. After the second crop, yields attributable to fertilizer and lime were never below 90%.

The use of nutrient inputs in tropical regions clearly has the potential for dramatic positive impact. Large areas of the tropics are dominated by highly weathered soils with limited nutrient reserves for crop growth. Therefore, fertilization is imperative if production from cleared land is to be continued for more that just a few cropping cycles. Furthermore, extending the productivity of previously cleared land in these regions has the potential to preserve substantial natural forest resources.

NUTRIENT BUDGETS

Since the role of nutrients in maintaining high crop yields is clearly established, the question of how much of the current crop nutrient needs can be satisfied from readily available organic sources should be addressed. Partial nutrient budgets (Fixen and Johnston, 2002) can help answer this question. Tables 3 and 4 contain information on N, P, and K budgets for the USA and the

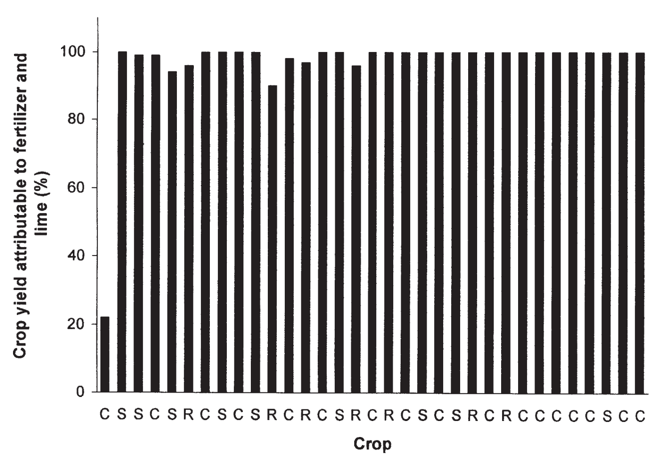

Fig. 6. Contribution of fertilizer (N, P, K, S, Mg, and micronutrients) and lime to the yield of 33 successive crops of corn (C), soybean (S), and rice (R), during 15 yr (1972 to 1987) of cultivation after slash-and-burn clearing of an Ultisol in the Amazon of Peru.

Table 3. Partial N budgets for the USA and the six major corn-producing states in the USA. All values are averages of 1998 to 2000 crop years except recoverable manure nutrients, which are estimates for 1997.

Region	Crop removal	Legume fixation	Applied fertilizer	Recoverable manure	Balance†
	Mt				
USA	14.6	7.1	11.2	1.2	4.9
Six leading corn states	6.6	3.8	4.0	0.2	1.5

† Fixation + fertilizer + manure − removal.

six leading corn-producing states in the USA. The leading corn states (Illinois, Indiana, Iowa, Minnesota, Nebraska, and Ohio) are included separately because of their dominance in U.S. nutrient cycles. It is important to point out that national and regional nutrient budgets can involve considerable uncertainty because of the inability to accurately determine all inputs and outputs on a large scale, hence, the term "partial budget" is used. Nevertheless, budgets can offer useful insight into the balance between nutrient inputs and outputs in crop production and are thus generally instructive.

Nitrogen removal in the harvested portion of crops in the USA amounts to about 75% of N inputs from the sources evaluated (fertilizer, recoverable manure, legume fixation) (Table 3). Of the estimated total N input, legume and recoverable manure N contribute about 36 and 6%, respectively. If crops recovered all of the legume and recoverable manure N, it would account for only about 57% of the total N removed. Thus, at the current national crop production level, N removal exceeds N inputs by legumes and manures by 43%. Of course, without inorganic commercial N fertilizer, U.S. crop production would be substantially reduced, and the N removal in Table 3 would not have been achieved.

The budget data in Table 3 reveal that more N is applied than is removed by crop harvest in the USA. However, significant strides have been made in recent years in improving crop N management and use. For example, the apparent fertilizer N use efficiency of corn in the USA has trended upward since about the mid 1970s. In 1980, a kilogram of N fertilizer produced 42 kg of corn while in 2000, it produced 57 kg…an increased efficiency of over 35% (Fixen and West, 2002). This increase is likely attributable to several factors, including changes in genetics, tillage, and water and nutrient management practices.

Table 4 shows partial budgets for P and K in the USA and the six leading corn-producing states in the USA. The table also shows P and K removal/use ratios with and without recoverable manure. The comparison is made since most U.S. crop production does not receive manure because of the relatively confined geographic production of recoverable manure. Recoverable manure P represents only about 30% of P removed in the U.S. crop harvests while manure K accounts for only 20% of national K removal. Therefore, the majority of P and K removed in yearly crop harvest in the USA must come from commercial fertilizer sources or from finite soil reserves. Additionally, over time, crop removal will deplete finite soil reserves of P and K if not replenished by an external source such as commercial fertilizer.

Taken together and recognizing the uncertainty discussed previously in such estimates, it seems that without commercial fertilizer N, P, and K, crop production in the USA would decline at least 50% over time. Declines would be less for some soils and cropping systems and more for others. The primary point here is that readily available organic sources of nutrients are inadequate to maintain current crop production levels in the USA.

SUMMARY

The data from the long-term studies discussed in this paper represent 362 seasons of crop production. Significant variation in crop response to fertilizer inputs depends on crop species, soil conditions, climate, geographical location, and other factors. All of these variables are integrated into the long-term harvested yields. These data all support the oft-cited generalization that at least 30 to 50% of crop yield is attributable to commercial fertilizer nutrient inputs, and that is probably a conservative estimate.

Commercial fertilizers make up the majority of nutrient inputs necessary to sustain current crop yields, with available organic sources, native soil reserves, and biological N fixation supplying the remainder. Using these inputs efficiently and in concert is essential in today's agriculture and will be even more important in years to come. To produce the nutritious food supply needed to meet the demands of a growing and more affluent world population, the appropriate and effective use of nutrients supplied from commercial fertilizers is imperative.

Table 4. Partial P and K budgets for the USA and the six major corn-producing states in the USA. All values are averages of 1998 to 2000 crop years except recoverable manure nutrients, which are estimates for 1997.

Nutrient	Region	Crop removal	Applied fertilizer	Recoverable manure	Balance†	Removal/use ratios w/o manure	Removal/use ratios w/ manure
		Mt					
P	USA	2.26	1.74	0.65	0.13	1.30	0.95
	six leading corn states	1.02	0.60	0.17	−0.25	1.71	1.33
K	USA	7.28	3.81	1.43	−2.04	1.91	1.39
	six leading corn states	2.49	1.55	0.38	−0.57	1.62	1.30

† Fixation + fertilizer + manure − removal.

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