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Energy Inputs for Corn Production in Wisconsin and Germany

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Abstract. Corn is one of the most important agricultural commodities in U.S. agriculture not least because of the expansion of ethanol production. The main purpose of this analysis is to quantify the total energy input used to produce corn in Wisconsin and to improve the quality of data and the methodology in the estimation. Therefore a comprehensive literature review was done. The calculation of the energy demand includes direct energy (for example fuel, electricity) and indirect energy (for example fertilizer, seed and machines). Data from the United States Department of Agriculture (USDA) are used to assess the development of the cultivation of corn over the last 30 years; especially the yields and the input of fertilizer in corn production are regarded.

Nitrogen fertilizer input decreased from 1980 to 1997 and then increased to 120 kg ha-1 again in 2005. Meanwhile corn yields increased steadily from nearly 6,500 kg ha-1 in 1980 to more than 9,000 kg ha-1 in 2005 (from 104 bu acre-1 to more than 143 bu acre-1). Our calculation of the energy inputs for corn grain production is about 1.7 MJ kg-1 with the embodied energy of Nitrogen fertilizer representing the largest single energy input

Keywords. Energy, corn production,

Introduction

Corn has always been an important crop in U.S. agriculture and the U.S. is the single largest corn producer in the world. The importance of corn as both a cash crop and energy source has increased with recent government programs to support the biofuels industry. The increasing acreage of corn is caused by favorable prices, driven by growing ethanol demand, and strong export sales. In 2002 corn was grown on over 25 percent of the U.S. cropland and represented more than 40 percent of the U.S. total annual commercial fertilizer use (Christensen, 2002). In 2007 U.S. farmers planted 37.9 million ha of corn, which is a 19% increase from 2006. About 333 million tons of corn grain was harvested in 2007 tons, or about 24% higher than the 2006 harvest (USDA, 2008a). This substantial increase demonstrates the importance of corn in the rapidly growing bio-fuels industry.

The U.S. corn yield per hectare has increased nearly eightfold over the last 100 years. The increase in per hectare corn yields before the 1970`s resulted mainly from increased application of agro-chemicals, especially nitrogen fertilizer. Increasing chemical inputs helped to increase corn yield per hectare, but reduced the corn yield per unit of fertilizer input (Wang et al., 2007). Concerns have been expressed in the scientific and agricultural communities about the environmental impact and energy efficiency of the rapidly growing corn-to-ethanol industry. Several research groups have investigated the energy efficiency of producing corn grain for ethanol production. Efficient energy use is an essential component of sustainable agricultural production because it reduces fossil fuel use, decreases air pollution and GHG emissions and can improve financial viability of agricultural production (Pervanchon et al. 2002). Energy accounting is a useful tool to characterise farming systems, quantify major inputs and identify promising strategies to improve energy efficiency and reduce environmental impacts.

The demand for ethanol has created a new market for corn. The expansion of the ethanol industry is seen by agricultural policymakers as a way of stabilizing farm income and reducing farm subsidies, while freeing the U.S. economy from its dependence on imported oil (Shapouri, 1995). Many studies have already been done on the energy balance of producing ethanol from corn grain (Pimentel, 1973; Pimentel, 1980; Pimentel 1991; Pimentel 2003, Wang et al. 1997; Shapouri et al., 2002; Patzek, 2004; Patzek, 2006; Graboski; 2002). The results of these studies differ mainly because of different choices of system boundaries for energy accounting and differing assumptions use to account for the energy value of by-products from ethanol production. Most of the studies include only primary energy inputs, partly because the indirect or embodied energy inputs, such as required to build farm vehicles, can be extremely difficult to quantify. Of the studies cited, only Pimentel attempted to quantify the energy embodied in the materials used to build farm machinery. The calculation of him is based on the manufacture from farm machinery in 1976 (Doering).

There are also differences among these studies related to assumptions about corn yields, fertilizer application, and fertilizer manufacturing technologies. Some studies rely on national averages while others use regionally specific values. It is clear that there are large regional differences in energy inputs for corn production due to cultural practices, climate and the need for irrigation and fertilizer use when corn production is integrated into animal agriculture. It is also clear that cultural practices have changed over time. It is therefore useful to examine cumulative energy inputs for corn production using regionally specific data representative of current cultural practices.

Objectives

The main purpose of this analysis is to quantify the total energy input used to produce corn grain considering current cultural practices in Wisconsin and using the latest available data. Wisconsin is one of the nine major corn producing states in the US. Cultural practices in Wisconsin differ from other corn producing regions as corn production is highly integrated into dairy production systems, therefore the application of both manure and commercial fertilizer is used, and does not employ irrigation as in drier regions of the country. Corn grown for grain is the focus of this investigation because of its importance in American agriculture and its intensive use of agricultural resources. We also compare the situation in Wisconsin with Germany, a similar climatic region in Europe, using the same calculation method.

Methods

A comprehensive literature review was undertaken to investigate previous calculation methods and data sources. The energy inputs for corn production were assessed for both direct and indirect energy consumption. Direct energy use is in the form of tractor fuel and electricity used on the farm. Indirect energy includes inputs for manufacturing machinery and other production inputs such as fertilizers, herbicides, pesticides and seed . This estimation neglects the solar energy input and energy from human labour.

The used method to determine the energy input in the procedure corn production bases on the VDI guideline 4600 "Cumulative energy demand- terms, definitions, methods of calculation" (VDI, 1997). "The cumulative energy demand (KEA) states the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good or which maybe attributed respectively to it in causal relation. This energy demand represents the sum of the cumulative energy demands for the production (KEA_H), for the use (KEA_N) and for the disposal (KEA_E) of the economic good:

$KEA_H = KEA_N + KEA_N + KEA_E$

The direct energy inputs and indirect energy inputs were estimated for Wisconsin conditions based on existing macro level data sources and confirmed with farm survey data. Data from the United States Department of Agriculture (USDA) were used to assess trends in cultural practices over the last 27 years; especially relating to the yields and fertilizer inputs. USDA-NASS maintains a historical database that provides yield, planted and harvested acreage, fertilizer and chemical input data at the state level. Data for corn cultivation practice in Germany were taken from the data collection of the KTBL (2006). It includes data from farms in Germany as well as for typical cultivation practices.

Data is presented for each input as well as the cumulative energy demand expressed in MJ of energy input per kg of corn grain produced. The mass of corn grain produced is expressed in kilograms per hectare (1 hectare = 10000 m^2 or 2.47 acres). One bushel is defined as 56 pounds or 25.4 kg of corn grain with moisture content of 15 percent by weight. Table 1 gives an overview of the energy equivalents used in these calculations.

The energy efficiency of the production of nitrogen fertilizer has been improved by 30% over the last 60 years (Patzek, 2006). Because of a major technological advancement in the fertilizer industry, the U.S. farmers have gained substantial real energy-saving benefits in terms of nitrogen and phosphate over the last 20 years (Shapouri et al., 2002). The energy input for nitrogen fertilizer in 1980 was 54.43 MJ kg^{-1} N and decreased to 47 MJ kg^{-1} N in 1994, according to Patzek (2004). The calculations for nitrogen fertilizer used in our study incorporate changes in N application rates and corn production as well as changes in the energy used to produce N fertilizer in the U.S.

Our calculations include the energy inputs for producing hybrid corn seed, almost universally used for corn production in the U.S. Diesel was the fuel assumed to be used for tillage and other field operations. The following higher heating value energy equivalents for the calculation of 1980 were used for gasoline (42.32 MJ L^{-1}), LPgas (32.25 MJ L^{-1}) and diesel (47.78 MJ L^{-1}) (Cervinka, 1980). Standard densities of liquid fuels used in this work are: 0.74 kg L^{-1} for gasoline; 0.58 kg L^{-1} for LP gas and 0.84 kg m^{-3} natural gas (Patzek, 2004).

An energy equivalent for machinery of 109 MJ kg^{-1} (Pimentel, 1992) was used for this analysis. The indirect energy input for tractors and field machines is difficult to quantify. Variations in energy inputs for machinery include the intensity of machinery use on individual farms, the date and location of machinery manufacture and the useful life of the machinery. Completely neglecting energy inputs for buildings and machinery can lead to higher errors than the possible under- or overestimate because of an inexact energy equivalent (Kalk and Hülsbergen, 1996). Furthermore, the energy inputs for machinery inputs ultimately represent a small percentage of total energy input and it is useful to estimate its relative importance. We therefore included an approximate value for machinery inputs in our calculations. For the disposal of agricultural machinery the recommended average specific energy input of $KEA_E = 0.5$ MJ kg^{-1} is used (Scholz and Kaulfuß, 1995).

The energy input of the disposal of expandable materials and consumable is ignored because these materials are generally fully consumed or converted and no details are available on this respectively.

The electricity fuel mix of Wisconsin and Germany is nearly similar. For both calculations the energy equivalent of 10.3 MJ kWh $^{-1}$ (GEMIS, 2006; Mge, 2008) is used.

The calculation of the energy input for machines as well as the calculation of the cumulative energy demand of the production of corn for grain in Germany was done with the farm and environmental management system REPRO (reproduction of organic soil matter). The REPRO software allows the analysis and evaluation of environmental impacts. As distinguished from other approaches, it reflects systemic consideration and the description of interrelated mass and energy fluctuations at the farm level (Hülsbergen, 2003).

Table 1. Values used for the energy equivalence of inputs

Item	Energy equivalent	References
Machinery	108 MJ kg $^{-1}$	Kalk & Hülsbergen, 1996
Gasoline	46.7 MJ kg $^{-1}$	Patzek, 2004
Diesel	39.6 MJ l $^{-1}$	Reinhardt, 1993
LP gas	50.0 MJ kg $^{-1}$	Patzek, 2004
Natural gas	55.5 MJ kg $^{-1}$	Patzek, 2004
Nitrogen	35.3 MJ kg $^{-1}$	Appl, 1997
Phosphate	36.2 MJ kg $^{-1}$	Kaltschmitt & Reinhardt, 1997
Potassium	11.2 MJ kg $^{-1}$	Hülsbergen, 2003
Seeds	104 MJ kg $^{-1}$	Patzek, 2006
Herbicides	288 MJ l $^{-1}$	Green, 1987
Pesticides	196 MJ l $^{-1}$	Hülsbergen, 2003
Electricity	10.3 MJ kWh $^{-1}$	GEMIS, 2006

Results and Discussion

Development of corn farming in Wisconsin

Wisconsin farmers planted 64 million ha of corn in 2007, an 11% increase from 2006. Of those acres planted, 1.32 million ha were harvested for grain (USDA, 2008a). A historical look at the development of the cultivation of corn for grain from 1980 to 2007 is presented in Figure 1. Yield/ha trends increased steadily during that time. The yield occurring in 2005 and the large downward spikes in 1988 (drought year) and 1993 (flood year) were caused by poor weather conditions.

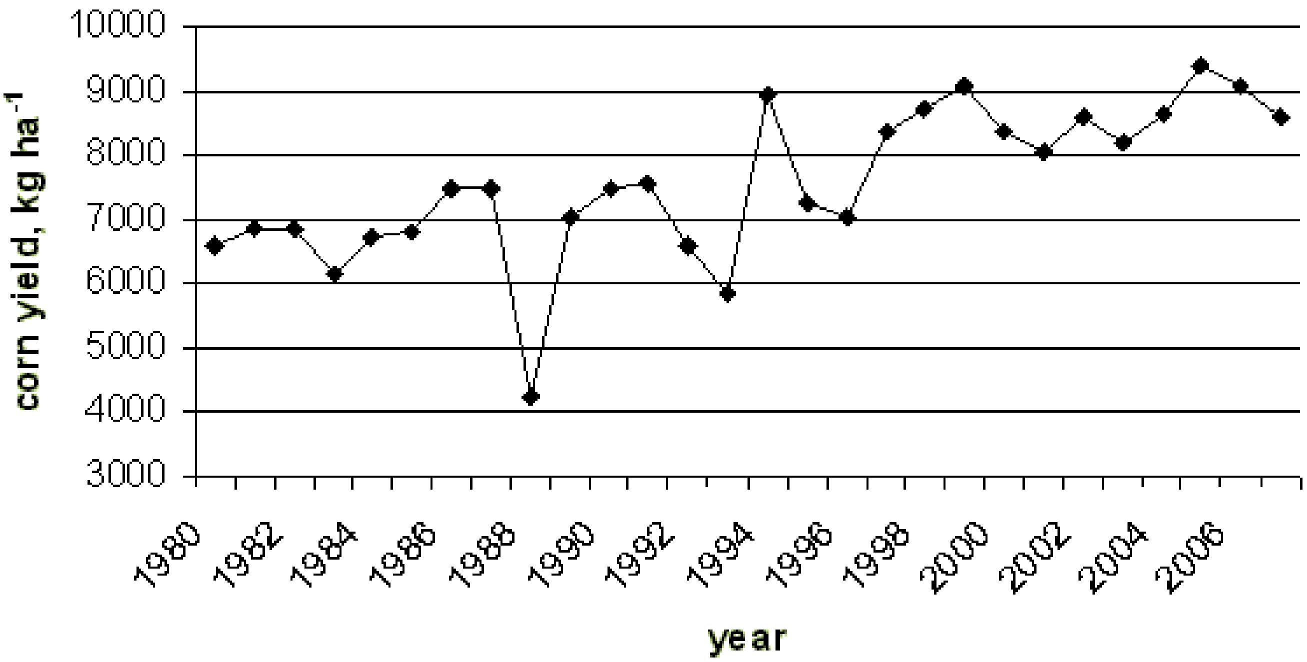

Figure 1. Development of the yields of corn in Wisconsin from 1980 to 2007 (USDA, 2007a)

Nitrogen fertilizer use in Wisconsin peaked in 1981 and then decreased by about 30% in 1997 but has been increasing since then to its previous maximum level (figure 2). The decline in fertilizer use was due in part to increased cost of fertilizer production due to the energy crisis of the early 1980′s.

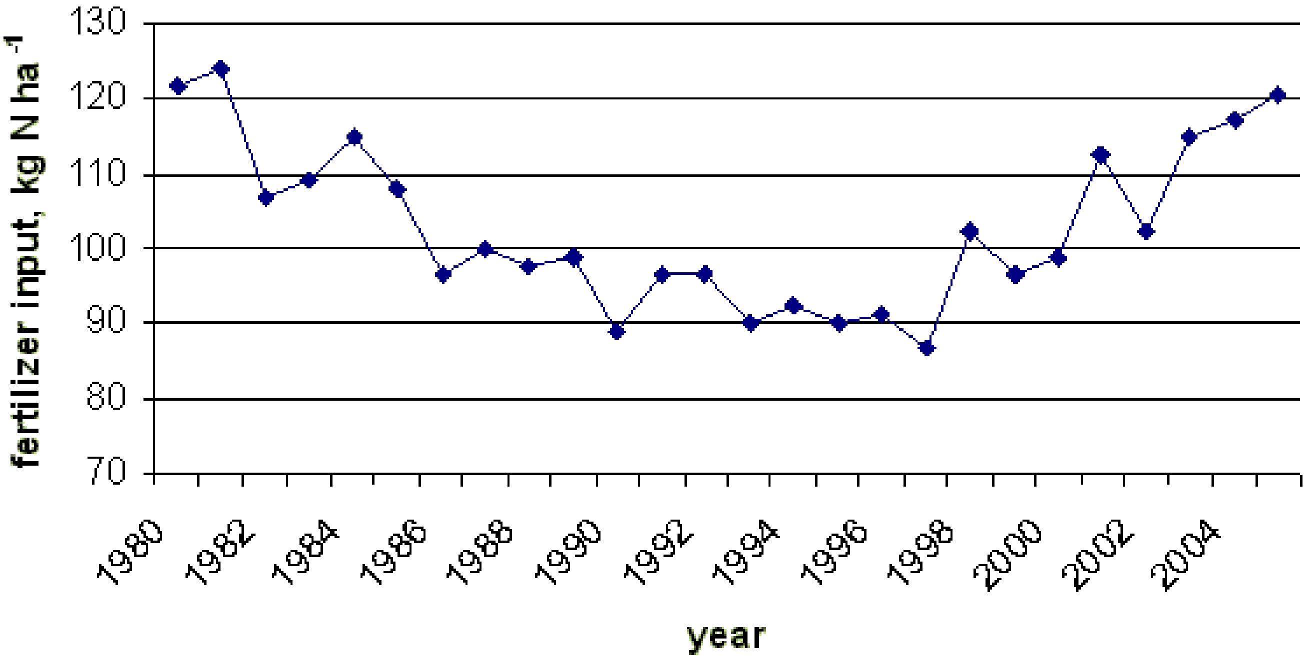

Figure 2. Use of nitrogen fertilizer from 1980 to 2005 in Wisconsin (USDA, 2007b)

Corn yields did not increase proportionally to the use of nitrogen fertilization. Yields trended upward from 1980 to 1997 (with exception of the two bad years 1988 and 1993) while input of nitrogen fertilizer decreased in that period of time. The use of phosphate (figure 3) and potassium (figure 4) decreased steadily over the period from 1980-2005.

Increased corn yields without the corresponding increase of fertilizer (and energy inputs) indicate that farm resources were being used more efficiently from 1980 to 1997. In addition to the lower inputs of fertilizer, the manufacture of agricultural chemicals became more energy efficient. Energy savings in nitrogen fertilizer production and use is especially important because it has in average a higher energy requirement than phosphate and potassium fertilizers.

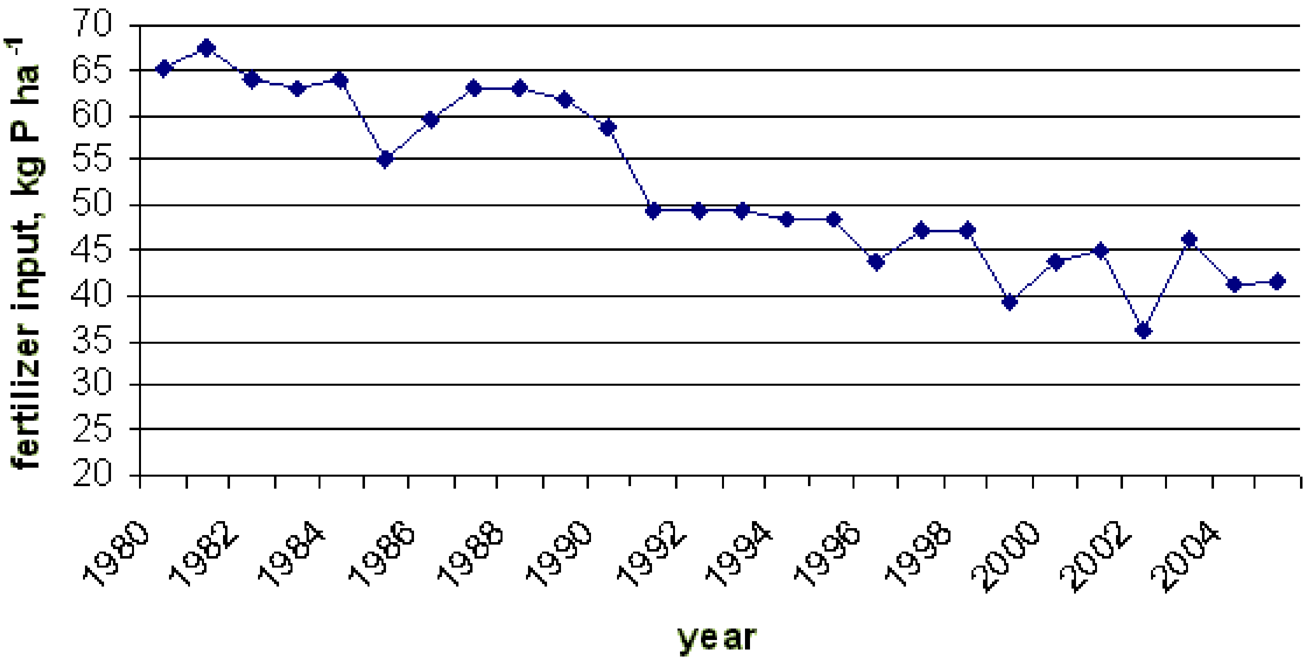

Figure 3. Use of phosphate fertilizer in Wisconsin from 1980 to 2005 (USDA, 2007b)

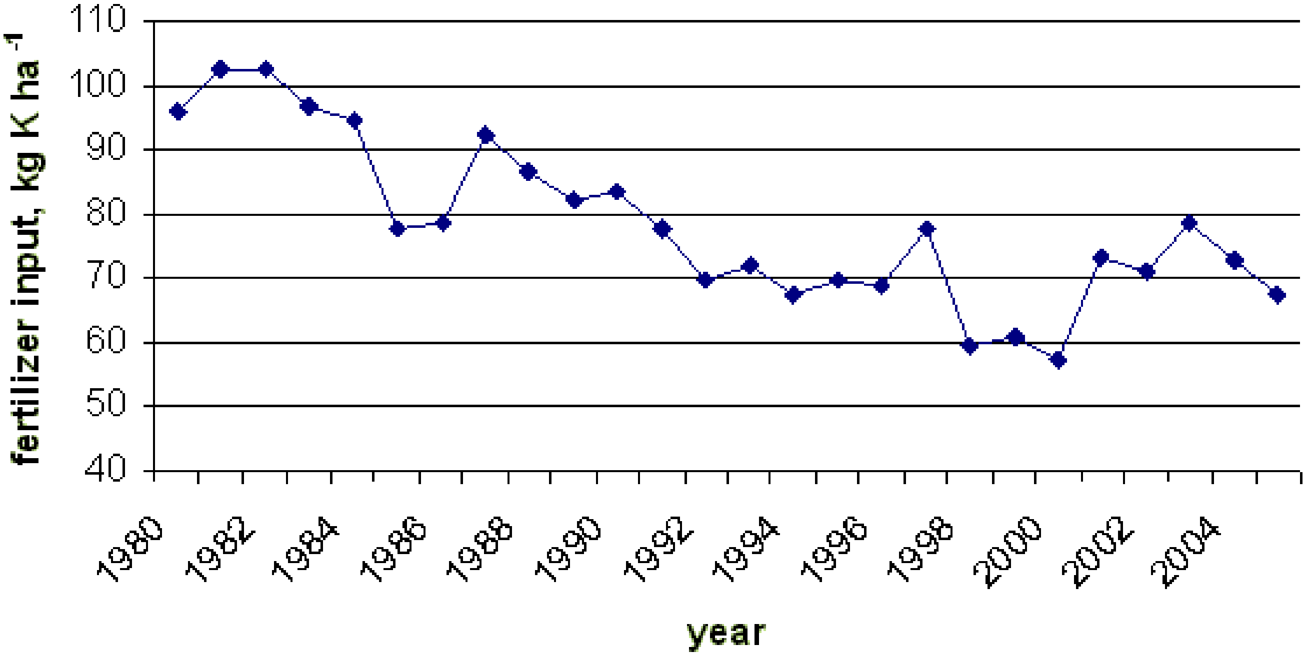

Figure 4. Potassium used on corn from 1980 to 2005 in Wisconsin (USDA, 2007b)

Why did Wisconsin farmers start using more nitrogen fertilizer after 1997? The marginal value of increased corn production compared to the marginal cost of increased nitrogen fertilizer is part of the reason. The cost fertilizers from 1998 to the present are presented in table 2.

Table 2. U.S. Average Fertilizer Prices by Year (per ton) (USDA, 2008c)

Year	Nitrogen	Phosphate	Potassium
2007	495	485	310
2006	362	324	273
2005	332	299	245
2004	276	266	181
2003	261	243	165
2002	191	221	164
2001	280	236	170
2000	200	233	165
1999	176	255	168
1998	195	253	163
1997	257	257	152

Additionally a shift in cultivation of corn as a monoculture might be an explanation for the disproportionate increase in N-fertilization versus corn yields from 1997 until 2005. Khan et al. (2007) come to this conclusion and they argue that the intensive use of nitrogen fertilizers in modern agriculture is motivated by the economic value of high grain yields. Increasing nitrogen application is believed to benefit the soil by building organic carbon up to some level, but too much nitrogen does the opposite. The usual one-size-fits-all method was intended to minimize the risk of nitrogen deficiency as insurance for high yields. But the typical result is over-fertilization, because of the assumption that the fertilizer supplies more nitrogen than the soil. The opposite is predominantly true, especially for the highly productive soils which receive the highest nitrogen rates (Khan et al., 2007).

Nutrient management decisions (e.g. the amounts and form of nutrients used, the timing of fertilizer application as well as the application method) influence how much of the applied nutrient is used by the corn, how much is stored as a residual in the soil, and how much becomes available as a potential water and air pollutant. The survey results of Christensen (2002) indicate that the use of nutrient testing techniques in corn production vary among the different corn producing regions in the US. In Lake States, 36% of corn acreage received a soil or plant tissue test, but only 11% received a nitrogen test. In the entire US nutrient management techniques such as soil testing, applying all nitrogen at or after planting, and precision agriculture technologies were used on 20 to 30 percent of the corn acreage. Special conservation measures for nitrogen were used on less than 10 percent of corn acreage.

Cumulative energy demand in corn farming in Wisconsin

The energy inputs for corn production vary with the method of production and the level of mechanization. Pimentel (1980) calculated energy demand for the production of corn using data from 1980 or earlier. These numbers are still used in some of the recent literature. Our study compares the estimate of energy demand for producing corn in 1980 with more recent data representing practices in Wisconsin today.

In 1980 the cumulative energy demand for corn for grain in Wisconsin was estimated at 3.30 MJ kg $^{-1}$ with corn production levels of 6,604 kg ha $^{-1}$. Energy inputs for drying increased this value to 3.88 MJ kg $^{-1}$. An important part on this energy demand is the energy input for N-fertilizers. The intensive energy demand for the production of N-fertilizer has a negative influence on the energy balance (see table 3).

Table 3: Cumulative energy demand (KEA) corn for grain production, Wisconsin 1980

Item.	Quantity ha $^{-1}$	References	1980
			KEA MJ ha $^{-1}$
Machinery (kg)	55	Pimentel, 1980	6023
Diesel (l)	56.36	Pimentel, 1980	2693
Nitrogen (kg)	122	USDA, 2007a	6640

Phosphate (kg)	65.3	USDA, 2007a	2364
Potassium (kg)	95.6	USDA, 2007a	1071
Seeds (kg)	16	Pimentel, 1980	1644
Herbicides (l)	4.61	Pimentel, 1980	1328
Pesticides (l)	-	-	-
Insecticides	3.92	Pimentel, 1980	929
Natural Gas (m^3)	-	-	-
Gasoline (l)	41.66	Pimentel, 1980	1763
LP gas (l)	25.18	Pimentel, 1980	812
Electricity (kWh)	35.82	Pimentel, 1980	369

The average corn yield in 1994 was 8,954 kg ha $^{-1}$ while the cumulative energy demand 1.65 MJ kg $^{-1}$ (including drying 1.88 MJ kg $^{-1}$). Table 4 gives an overview of the energy inputs for corn in 1994.

Table: 4: Cumulative energy demand (KEA) corn grain production, Wisconsin 1994

Item.	Quantity ha $^{-1}$	References	1994
			KEA MJ ha $^{-1}$
Machinery (kg)	13.4	Hülsbergen, 2003	1454
Diesel (l)	84.15	Shapouri et al., 2002	3332
Nitrogen (kg)	92.3	USDA, 2007a	4338
Phosphate (kg)	48.4	USDA, 2007a	1752
Potassium (kg)	67.5	USDA, 2007a	756
Seeds (kg)	22	Patzek, 2006	2262
Herbicides (l)	3.07	Wang, 1997	884
Pesticides (l)	-	-	-
Insecticides	0..22	Wang, 1997	52

Natural Gas (m^3)	18.9	Shapouri et al., 2002	880
Gasoline (l)	18.70	Shapouri et al., 2002	646
LP gas (l)	28.05	Shapouri et al., 2002	1
Electricity (kWh)	50	Shapouri et al., 2002	515

In 2005 the average yield of corn in Wisconsin was 9,398 kg ha $^{-1}$ (USDA, 2007a) and our estimated cumulative energy demand was 1.54 MJ kg $^{-1}$ (results summarized in Table 5). Energy inputs of irrigation were neglected in this study, because only 7% of the corn land in Wisconsin is irrigated (USDA, 2006). Nitrogen fertilizer comprised the largest single primary energy input for producing corn grain with 26% of the total KEA. Diesel fuel for field operations is the next most important factor with 21% of the total KEA.

Common practice in Wisconsin is to maximize biomass drying in the field before harvest so that there is usually little or no energy is required for drying corn. 1996 was an unusual year in that natural drying was limited and the corn crop had a high moisture content and the energy inputs for drying was abnormally high (Shapouri et al., 2002). Including the energy input for drying the corn for grain in 1996 increased the total KEA to 1.76 MJ kg $^{-1}$.

Table 5. Cumulative energy demand (CED) corn for grain production, Wisconsin 2005.

Item.	Quantity ha $^{-1}$	References	2005
			KEA MJ ha $^{-1}$
Machinery (kg)	13.4	Hülsbergen, 2003	1454
Diesel (l)	84.15	Shapouri et al., 2002	3332
Nitrogen (kg)	120.37	USDA, 2007a	4249
Phosphate (kg)	41.6	USDA, 2007a	1506
Potassium (kg)	67.5	USDA, 2007a	756
Seeds (kg)	22	Patzek, 2006	2262
Herbicides (l)	2.97	According to Kim & Dale 2004	855
Pesticides (l)	0.16	According to Kim & Dale 2004	33
Insecticides	0.02	USDA, 2006	5
Natural Gas (m^3)	18.9	Shapouri et al., 2002	880

Gasoline (l)	18.70	Shapouri et al., 2002	646
LP gas (l)	28.05	Shapouri et al., 2002	1
Electricity (kWh)	50	Shapouri et al., 2002	515

The KEA of producing one kilogram of corn grain in Wisconsin in 2005 was about 40% lower than it was in 1980. One reason for increased yields in 2005 versus 1980 is the use of improved hybrid seed, also resulting in energy demand per kg of corn. In 2005 Wisconsin farmers used about the same amount of N-fertilizer per ha as in 1980, while N-fertilizer use in 1994 was about 25% less than in 2005. If there had not been improvements in the energy inputs for nitrogen fertilizer production (35.3 MJ kg $^{-1}$ in 2005 compared to 47 MJ kg $^{-1}$ in 1994) the energy demand per kg of corn grain would be higher in 2005 than in 1994.

Cumulative energy demand corn for grain in Germany

The area is planted for corn for grain in Germany is only one fourth of the total in Wisconsin, and the cultivation of corn for grain has a lower market importance in Germany. Corn yield per hectare in Germany have increased by about up to 40% over the last 25 years with similar yields to those in Wisconsin (Figure 5).

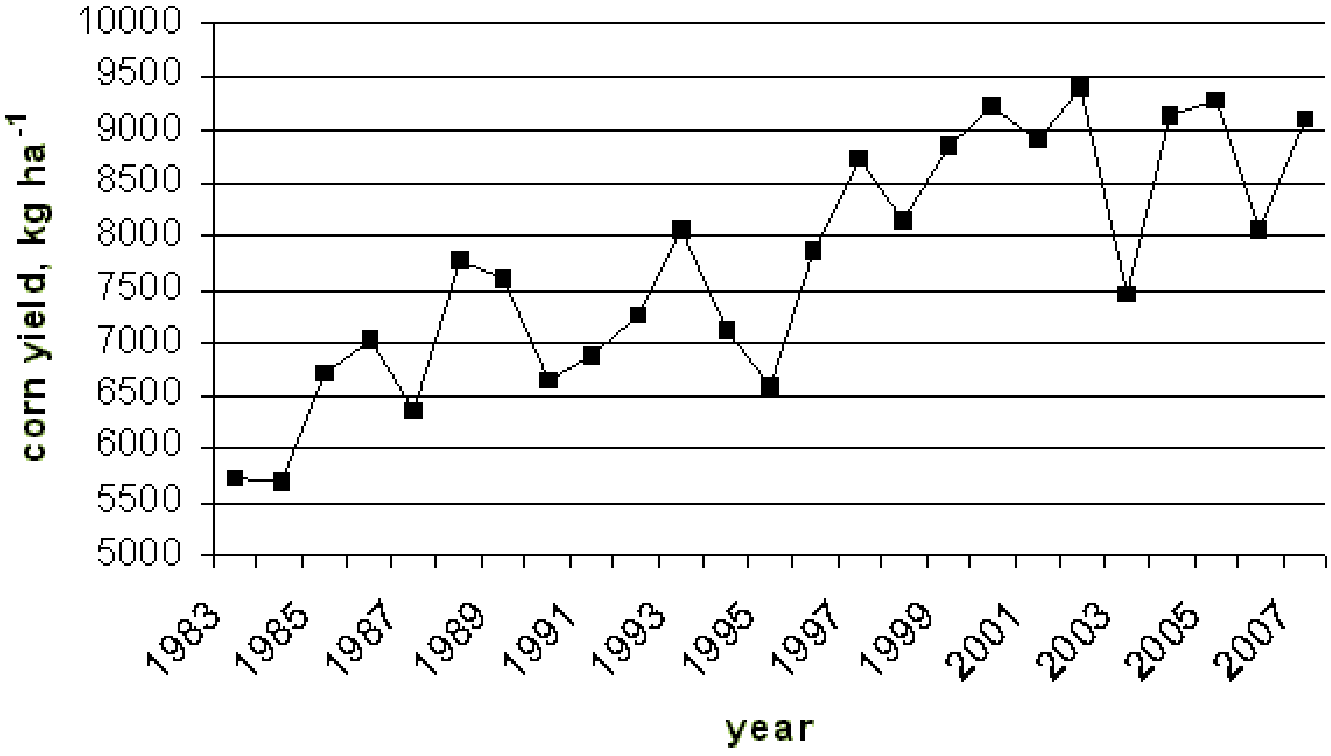

Figure 5: Development of the yields of corn for grain in Germany 1983-2007

In 2006 the corn yield in Germany averaged 9,330 kg ha $^{-1}$. The KEA of corn for grain production is calculated from KTBL-data (2006), which describes typical cultivation practices in

Germany. Table 6 shows the energy inputs in the production of corn grain in Germany. The cumulative energy demand for growing corn for grain in Germany is 1.43 MJ kg^{-1}. Because of the climate conditions in Germany artificial drying of the corn is necessary and results in substantial energy use and including this drying energy increases the KEA to 2.69 MJ kg^{-1}.

Table 6. Cumulative energy demand (CED) corn for grain production, Germany 2006.

Item.	Quantity ha^{-1}	References	KTBL, 2006
			KEA MJ ha^{-1}
Diesel (l)	79	Hülsbergen, 2003	3130
Nitrogen (kg)	145.6	KTBL, 2006	5140
Phosphate (kg)	60	KTBL, 2006	2170
Potassium (kg)	26.6	KTBL, 2006	300
Seeds (kg)	25	Hülsbergen, 2003	770
Herbicides (l)	1.5	Sunreg, 2008	430
Insecticides (l)	0.038	Sunreg, 2008	100
Machinery (kg)	13.4	Hülsbergen, 2003	1454
Electricity (kWh)	175.8	KTBL, 2006	1811
Fuel oil (l)	250.8	KTBL, 2006	9981

Conclusion

Energy efficiency of corn production in Wisconsin has improved in some respects and not in others over the past 25 years. This analysis provides some indication of areas in which the energy efficiency of corn production can be improved. Improved energy efficiency in the production of N-fertilizer has been a major contributor to reducing the energy intensity of corn production. Wisconsin’s farmers made substantial reduction in the amount of N-fertilizer applied to corn fields from 1980 to 1997. These reductions have been largely reversed from 1997 to 2005. With N-fertilizer composing the largest single energy input for producing corn, its careful management is essential in improving the energy intensity of corn production. Wisconsin farmers have demonstrated that they are capable of maintaining corn yields with substantially less N-fertilizer than is being used now, presumably through best management practices such as site-specific assessment of soil N availability, crop rotations and accounting for the nutrients available in animal manure. These management practices provide additional benefits by reducing the negative consequences of soil organic matter deterioration by over-fertilization. Nutrient management is an essential aspect of energy-efficient, economical and sustainable corn production.

Corn yields in Wisconsin and Germany are in the same range. Fertilizer use on German corn fields is slightly higher than in Wisconsin. The energy demand for the production of corn grain is slightly lower in Germany than in Wisconsin if the energy inputs for drying are neglected (1.43 MJ kg $^{-1}$ in Germany versus 1.54 MJ kg $^{-1}$ in Wisconsin). When drying energy is included the energy demand for corn production is considerably higher than in Wisconsin (2.69 MJ kg $^{-1}$ in Germany versus 1.54 to 1.76 MJ kg $^{-1}$ in Wisconsin).

Further investigations should be done for other major corn production states in the U.S. as these results may not apply to other regions that do not have a substantial level of animal agriculture in proximity to corn producing area. These results present useful information for Wisconsin corn farmers who are motivated to reduce the energy intensity and carbon footprint of their farm operations.

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