Water resource requirements of corn-based ethanol

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Received 19 November 2007; revised 1 April 2008; accepted 4 June 2008; published 21 August 2008.

[1] Ethanol derived from fermentation of corn is a very water-intensive product with water to ethanol mass ratios of 927 to 1178 and volumetric ratios of 1174 to 1492 for the major rainfed corn-growing U.S. states of Illinois and Iowa and the leading irrigated corn-growing state of Nebraska, respectively. Over 99% of water requirements are for growing corn feed stocks, with 99% of that amount in Illinois and Iowa, occurring as evapotranspiration of rainfall in corn fields, and 60% as evapotranspiration of applied irrigation water in Nebraska. As a rough measure of water quality impacts, 65.5 g N, 23.8 g P, and 1.03 g of pesticides are applied, and 4.8 kg of soil is eroded per liter of ethanol produced. These results add to knowledge on corn-based ethanol's low net energy balance and high carbon footprint by demonstrating the high water resource intensity of corn-based ethanol production.

Citation: Mubako, S., and C. Lant (2008), Water resource requirements of corn-based ethanol, *Water Resour. Res.*, *44*, W00A02, doi:10.1029/2007WR006683.

1. Introduction

[2] Concerns over the future availability of and high prices for imported oil as a transportation fuel, along with rural economic development interests, have initiated a concerted effort to increase biofuel production [*Kopp*, 2006], especially ethanol. World ethanol production increased sixfold between 1982 and 2005 and continues to grow at an annual rate of 15% (C. Davis, March 2007 monthly update: Global biofuel trends, 2007, World Resources Institute, Washington, D.C., available at http://earthtrends.wri.org/updates/node/180). This is especially the case in the U.S. which, with the aid of a $0.51 per gallon subsidy, passed Brazil as the leading ethanol producing country in 2006 with corn, rather than sugarcane, as the dominant feed stock. Of the 19.3 billion L of biofuels produced in the U.S. in 2006, 98% was ethanol produced from corn [*National Research Council*, 2007]. Spurred by ethanol demand, U.S. farmers planted 90.5 million acres of corn in 2007, 15% more than in 2006 and the largest area devoted to corn since 1944 [*National Agricultural Statistics Service (NASS)*, 2007]. Ethanol supplied 2.4% of U.S. transportation fuel in 2006 utilizing 18% of all corn produced. If all U.S. corn production were to be converted to ethanol, it has been estimated that this would offset 12% of U.S. gasoline demand [*Hill et al.*, 2006].

[3] Simultaneously, a number of studies have analyzed the industrial ecology of ethanol. Early studies [*Ho*, 1989; *Pimentel*, 1991; *Keeney and DeLuca*, 1992; *Pimentel and Patzek*, 2005] found that corn-based ethanol yields net energy losses. However, *Hill et al.* [2006] found that, when the energy value of ethanol distillates as livestock feed are included in the analysis, ethanol production from corn yields 25% more energy than invested in its production. Nevertheless, the transformation of carbon-rich forests and grasslands into carbon-poor crop fields for the production of ethanol feed stocks makes ethanol more carbon intensive than petroleum-based gasoline per unit energy delivered [*Righelato and Spracklen*, 2007; *Searchinger et al.*, 2008]. In addition to its carbon footprint, expanded planting of corn reduces the delivery of other ecosystem services from agricultural landscapes [*Tilman et al.*, 2002; *National Research Council*, 2007]. The increased demand derived from ethanol also markedly increases prices for corn [*Baker and Zahniser*, 2006], thereby increasing costs of raising livestock, while it increases profits of corn growers and input suppliers. To further inform this literature, this paper focuses on the water resource requirements and water quality impacts of corn-based ethanol production, a relatively understudied aspect of the industrial ecology of biofuels [*Hill et al.*, 2006; *Kopp*, 2006; *Duffy and Correll*, 2006].

2. Methods

[4] Water footprint refers to the volume of water used to produce a commodity [*Chapagain and Hoekstra*, 2007; *Zygmunt*, 2007]. The water footprint of ethanol comes from evapotranspiration of rainfall and irrigation water in fields where feed stock crops are grown and water withdrawn for use by ethanol plants. Each of these water inputs vary depending on growth conditions for feed stock crops as determined by climate, yields, crop species, production methods, farming technology, irrigation system efficiency, and water use efficiency at the ethanol plant. Ethanol production from corn also affects water quality through the application of fertilizers and pesticides and soil erosion that increases sediment loads. In assessing these forms of water use and water quality impacts, we focus on the two U.S. states with the greatest corn production (Illinois and Iowa) as well as the leading U.S. state in irrigated corn production (Nebraska). The study uses climatic and agricultural data from the 25-year period 1982–2006 (Table 1).

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0043-1397/08/2007WR006683

Table 1. Average Corn Yield and Production for Illinois, Iowa, and Nebraska for the Period 1982–2006[a]

State	Irrigation Status	Illinois	Iowa	Nebraska
Average yield (t/ha)	Irrigated	10.6	9.9	10.4
	Nonirrigated	10.2	9.2	5.9
Average area (ha)	Irrigated	126,308	48,998	1,971,860
	Nonirrigated	4,195,888	4,787,167	1,069,056
Average production (t/a)	Irrigated	1,338,865	485,080	20,507,344
	Nonirrigated	42,798,058	43,892,581	6,307,428
Total production (t/a)		44,136,923	44,377,661	26,814,772

[a]Derived from the *NASS* [2007] database and National Agricultural Statistics Service agriculture census (vol. 1, Geographic area series farm and ranch irrigation survey, 2002, U.S. Department of Agriculture, Washington, D. C., available at http://www.nass.usda.gov/Census/Create_Census_FRIS.jsp).

[5] The methodology followed is similar to the one used by *Hoekstra and Hung* [2005], *Chapagain et al.* [2006], and *Chapagain and Hoekstra* [2007] as part of an approach to quantify the water footprint of crop products. Soil type, climatic parameters, and other factors influence evapotranspiration from corn. The Penman-Monteith method described by *Allen et al.* [1994, 1998] for estimating reference crop evapotranspiration in mm/d, is the basis for the CROPWAT for Windows program developed by the Food and Agriculture Organization (FAO) [*Clark et al.*, 1998]. Evapotranspiration was calculated for each 10-day period as the lesser of precipitation or potential evapotranspiration from corn, added up for the length of the growing season. State-specific corn yield figures were obtained from the *NASS* [2002] database. Evapotranspiration of irrigation water for corn was determined from the actual amount applied in the three states as estimated by the Farm and Ranch Irrigation Surveys in the *NASS* [2002] database for the years 1992, 1997, and 2003, less return flows of 15% for sprinklers and 40% for gravity flow [*Brouwer et al.*, 1989; *NASS*, 2002].

[6] To estimate water quality impacts, we calculated the mean application of N, P, and pesticides using data published by *Hill et al.* [2006] and mean soil erosion per liter of ethanol produced using data from Natural Resources Conservation Service (National Resources Inventory, data tables on sheet and rill and wind erosion by state, 2003, U.S. Department of Agriculture, Washington, D. C., available at http://www.nrcs.usda.gov/Technical/NRI/maps/erosion.html). Also, following the *National Research Council* [2007], N, P, and pesticide applications and soil eroded per net energy gain in MJ were estimated.

3. Results

3.1. Water Footprint of Corn Feed Stocks

[7] Based on CROPWAT, the mean annual evapotranspiration of rainfall for corn is estimated as 338, 324, and 276 mm and the mean annual irrigation water applications on land where irrigation is used are 183, 152 and 294 mm for Illinois, Iowa, and Nebraska, respectively (Table 2, first and second rows). The later are adjusted for irrigation system efficiency to yield estimated evapotranspiration of irrigation water (third row). Multiplying the depth of evapotranspiration of rainfall and irrigation water in each state by the area of rainfed and irrigated corn in each state yields the volume of evapotranspiration from rainfall and irrigation in each state (Table 2, sixth and seventh rows). Results are similar in Illinois and Iowa (14.4 and 15.6 billion m^3/a, respectively); evapotranspiration is almost entirely from rainfall where less than 3% of corn area is irrigated. These results contrast with those in Nebraska where annual evapotranspiration from rainfall is smaller (2.95 billion m^3) and from irrigation is much larger (4.44 billion m^3). Dividing these totals by the mean corn production in tons (ninth row) yields estimates of evapotranspiration per ton of corn production (tenth row). Given that a cubic meter of water weighs 1 t, these estimates, ranging from 276 m^3 in Nebraska to 351 m^3 in Iowa, represent a dimensionless mass conversion ratio for

Table 2. Determination of Corn Consumptive Use, Virtual Water Content of Corn, and Virtual Water Content of Ethanol in Illinois, Iowa, and Nebraska for the Period 1982–2006

	Illinois	Iowa	Nebraska
Mean evapotranspiration of rainfall for corn (mm/a)	338	324	276
Irrigation water applications (mm/a)	183	152	294
Evapotranspiration of irrigation water (mm/a)	155	129	225
Nonirrigated area planted to corn (ha)	4,195,888	4,787,167	1,069,056
Irrigated area planted to corn[a] (ha)	126,308 (2.9)	48,998 (1.0)	1,971,860 (65)
Volume of rainfall evapotranspiration by corn (million m^3/a)	14,182	15,510	2951
Volume of irrigation evapotranspiration by corn (million m^3/a)	196	63	4437
Volume of total evapotranspiration by corn (million m^3/a)	14,378	15,573	7388
Mean corn production (million t/a)	44.1	44.4	26.8
Volume of evapotranspiration per ton of corn produced (m^3)	326	351	276
Product ratio of tons of ethanol per ton of corn	0.299	0.299	0.299
Mass ratio average total water requirement for ethanol feedstocks (m^3/t)	1090	1174	923
Mass ratio average water requirement of rainfall for ethanol feedstocks (m^3/t)	1075	1169	369
Mass ratio average water requirement of irrigation for ethanol feedstocks (m^3/t)	15	5	554
Volumetric ratio average water requirement for ethanol feedstocks (m^3/t)	1381	1488	1170
Volumetric ratio average water requirement of rainfall for ethanol feedstocks (m^3/t)	1362	1482	468
Volumetric ratio average water requirement of irrigation for ethanol feedstocks (m^3/t)	19	6	702
Average water use in conversion of corn to ethanol at plants (m^3/t)	3.63	3.63	3.63
Average water footprint of ethanol (m^3/t) (mass ratio)	1094	1178	927
Average water footprint of ethanol (liters water/liter of ethanol) (volumetric ratio)	1385	1492	1174

[a]Percentage of corn area is given in parentheses.

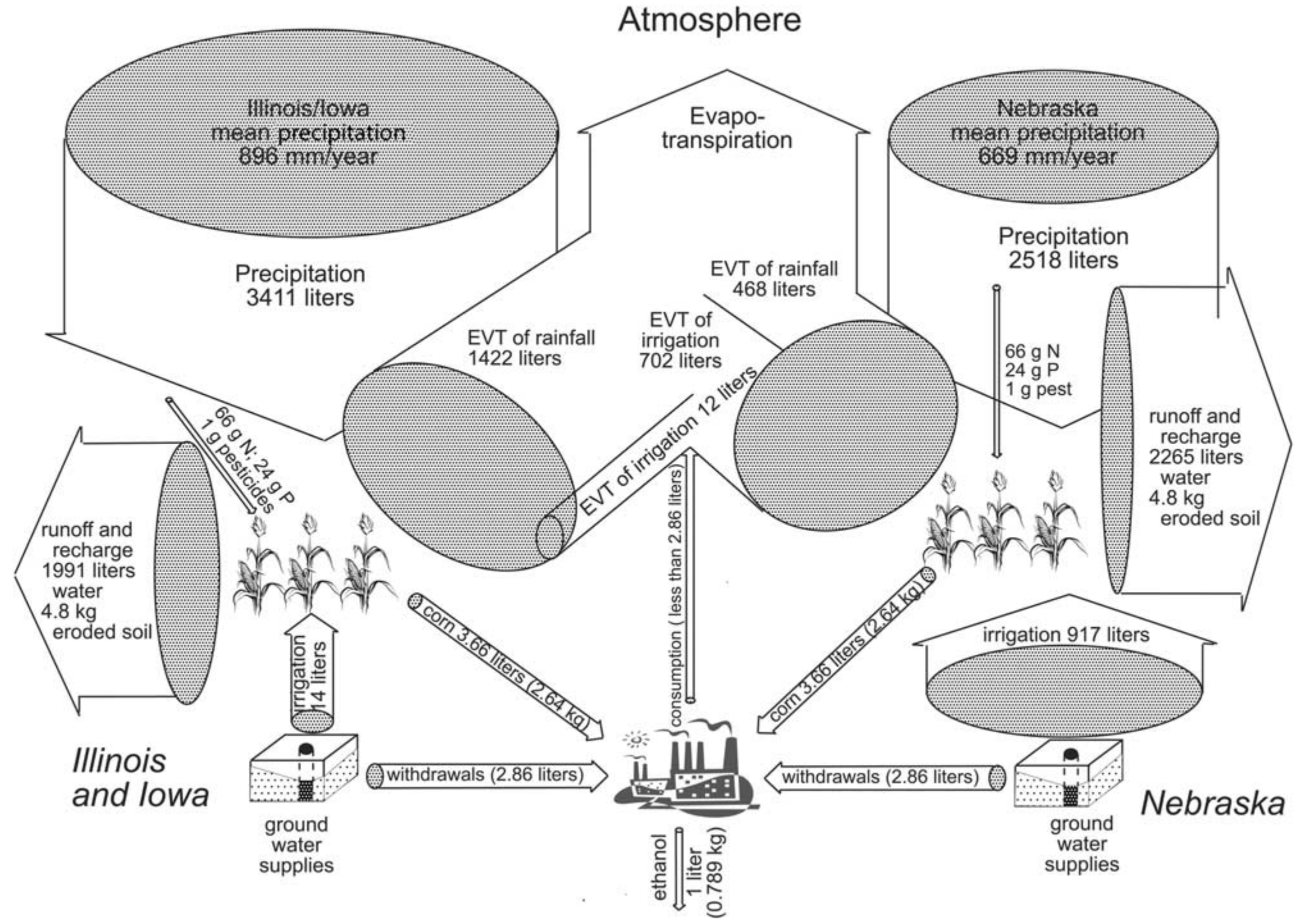

Figure 1. Water resource requirements and water quality impacts of 1 L of ethanol in the context of the hydrologic cycle. The cross-sectional area of each pipeline is roughly proportional to volumetric flow. The water footprint of ethanol is equal to evapotranspiration plus withdrawals for ethanol plants. Over 99% of this footprint is evapotranspiration from cornfields used as ethanol feedstock. In Illinois and Iowa this comes mostly from evapotranspiration of rainfall, while in Nebraska evapotranspiration of irrigation water is the largest component of the water footprint. In each case, N, P, and pesticides applied to, and soil eroded from, corn fields have water quality impacts.

water to corn. *Hoekstra and Chapagain* [2007] calculated the average virtual water content of corn in the U.S as 489 m^3/t. The numbers we calculate are somewhat smaller because of the use of actual irrigation water applied rather than hypothetical irrigation requirements and estimates of irrigation efficiencies based on actual methods applied in the study area.

3.2. Water Footprint of Ethanol

[8] A survey of eight studies [*Marland and Turhollow*, 1991; *Pimentel*, 1991, 2001, 2003; *Keeney and DeLuca*, 1992; *Morris and Ahmed*, 1992; *Shapouri et al.*, 1995, 2002] yields a narrow range of estimates of 0.37–0.40 L of ethanol per kilogram of corn with a mean of 0.38. Using 25.4 kg of corn per bushel [*Iowa State University Extension*, 2007] and an ethanol density of 0.789, corn is converted to ethanol at a product ratio of 0.299 t ethanol per ton of corn. Dividing the water to corn mass ratio by this product ratio yields water to ethanol mass ratios of 923, 1090, and 1174 for Nebraska, Illinois, and Iowa, respectively, of which 554, 15, and 5 are derived from irrigation (Table 2, 12th–14th rows). The corresponding water to ethanol volumetric ratios are 1170, 1381, and 1488 for Nebraska, Illinois, and Iowa, with 702, 19, and 6 L of evapotranspiration of irrigation water per liter of ethanol produced in those three states, respectively.

[9] To these figures must be added water use in ethanol plants. Estimates of water use per liter of ethanol at production plants in the U.S. are few. In their study of ethanol plants in Minnesota, *Keeney and Muller* [2006] find a wide range, but a mean use of 5.8 L in 1998 declining to 4.2 L in 2005 per liter of ethanol produced. They emphasize that ethanol plants do not need treated, potable water from municipal supplies. *U.S. Department of Agriculture* [2007] calculates 2.74 L and *Owens* [2007] estimates 3.63 L. The *National Research Council* [2007] also estimates 3.63 L withdrawn of which 39% or 1.43 L is consumed in cooling towers and the drying process; these last figures are adopted for this study.

[10] Withdrawals at ethanol plants constitute less than 1% of overall water use. Ethanol plant use increases mass ratios slightly to 927, 1094, and 1178 and volumetric ratios to 1174, 1385, and 1492 for Nebraska, Illinois, and Iowa, respectively. Water and other inputs per liter of ethanol are summarized diagrammatically in Figure 1 in the context of

Table 3. Water Quality Effects of Ethanol Production as Measured by N, P, and Pesticides Applications and Soil Erosion

	N	P	Pesticides	Erosion[a]
Application rate (kg/ha)[b]	146.1	53.1	2.3	10,620
Application rate (kg/t corn produced)[c]	15.46	5.62	0.243	1124
Application (kg) per ton ethanol produced	51.71	18.80	0.814	3759
Mass ratio of N, P, pesticides, and erosion to ethanol	0.052	0.019	0.0008	3.76
Application rate (g/L ethanol)	65.54	23.83	1.03	4764
Application rate (g) per MJ net energy gain[d]	15.53	5.65	0.24	1129

[a]Based on Natural Resources Conservation Service (National Resources Inventory, data tables on sheet and rill and wind erosion by state, 2003, U.S. Department of Agriculture, Washington, D. C., available at http://www.nrcs.usda.gov/Technical/NRI/maps/erosion.html) average sheet and rill plus wind erosion rates for all cultivated cropland in 1997 in Illinois, Iowa, and Nebraska. Note that corn generally has an erosion rate about 20% less than soybeans but substantially higher than wheat and alfalfa, the other primary crops grown in the study area states. Average erosion rates for corn are therefore close to those for all cultivated cropland in Illinois, Iowa, and Nebraska.
[b]Source: *Hill et al.* [2006].
[c]Based on 9.45 t/ha calculated from Table 2.
[d]Based on 21.1 MJ/L ethanol and 1.25 net energy balance [*Hill et al.*, 2006].

the hydrologic cycles for Iowa and Illinois, where, because of relatively reliable rainfall, only a small proportion of corn is irrigated, and for Nebraska, where irrigation represents the majority of water supplies used in the production of ethanol from corn.

3.3. Water Quality Impacts of Corn-Based Ethanol

[11] While fertilizer and pesticide applications, soil erosion rates, and delivery ratios vary over space and time, we calculated mean applications and soil erosion per liter of ethanol produced and, following the *National Research Council* [2007], per MJ of net energy gain as a rough measure of the water quality impacts of ethanol production (Table 3). Using N, P, and pesticide application rates per hectare of corn of 146.1, 53.1, and 2.3 kg, respectively [*Hill et al.* 2006], average corn yield of 9.45 t per hectare (calculated from Table 1), the product ratio of 0.299, and the density of ethanol of 0.789, we calculated that 65.5 g N, 23.8 g P, and 1.03 g of pesticides are applied per liter of ethanol produced. At a rate of 10.6 t/ha, 4.8 kg of soil are eroded per liter. Using 21.1 MJ as the energy value per liter of ethanol and a net energy balance of 1.25 [*Hill et al.* 2006], application rates of 15.53 g N, 5.65 g P, and 0.24 g of pesticides and 1.13 kg of eroded soil are required per net MJ of energy gain from ethanol.

[12] The final step in estimating the water resource and water quality impacts of ethanol is to multiply these ratios by past and future ethanol production levels. The water consumed in producing the 16.217 billion L of ethanol produced in the U.S. in 2005, using the range of volumetric ratios for the three states studied, was 19.1–24.2 $\times$ 10^{12} L (10^9 m^3). To produce this quantity of ethanol, 1.06 million t N, 386,000 t P, and 16,700 t of pesticides were applied in the production of corn feed stocks, and 77 million t of soil were eroded. The 2005 Energy Policy Act goal of 7.5 billion gallons (28.38 billion L) of renewable fuel to be used in gasoline by 2012, if completely reliant on corn-based ethanol, would consume 33.3–42.3 $\times$ 10^{12} L (10^9 m^3), require applications of 1.86 million t of N, 676,000 t P, and 29,200 t of pesticides, and result in 135 million t of soil eroded.

4. Discussion and Conclusions

[13] Ethanol is a very water-intensive product with mass ratios (927–1128) and volumetric ratios (1174–1492) exceeded by few other products. For example, among plant products, tea (9205) (world average) and cotton (2535–5733) (U.S), are among the most water intensive while chicken (2389) and beef (13,193) exceed the mass ratio of ethanol [*Hoekstra and Chapagain*, 2007]. In assessing the effect of this water intensity on regional water resources, the source from which water inputs are obtained must be taken into consideration. In particular, over 99% of the water requirements of ethanol are used in growing corn as a feed stock. Despite the substantial water quality impacts of ethanol plants [*National Research Council*, 2007], water quality concerns are also concentrated on corn fields where inputs of N, P, and pesticides and soil erosion rates are higher than for any other rural land use in the states studied, except for soil erosion rates on soybean fields.

[14] The net effect on water resources of ethanol production depends upon the land uses that it replaces, but determining this precisely is a difficult exercise beyond the scope of this paper. Nevertheless, some comparisons can be drawn. *Searchinger et al.* [2008], in calculating the net carbon effects of ethanol production, estimates that for every hectare devoted to corn for ethanol production, 0.84 ha of new land, primarily forest, savannah and grassland in Brazil, China, India, and the U.S., are brought into cultivation. U.S. lands now cultivated for soybeans, wheat, and hay, as well as pasture for livestock grazing and lands currently enrolled in the Conservation Reserve Program are also likely candidates for growing corn as an ethanol feedstock. A comparison of annual potential evapotranspiration, N, P, and pesticide applications, and erosion rates per hectare on these land uses shows that water quality impacts of corn are higher than all alternative land uses except for soil erosion rates for soybeans. Irrigated corn also places additional net demands on water resources in competition with municipal and industrial supplies and other potentially irrigated crops. This is especially the case in Nebraska and other states that rely on aquifers with falling water tables, such as the Ogallala, or that compete with neighboring states for water supplies from interstate rivers. For rainfed corn, ethanol production can either increase or decrease available water supplies (e.g., streamflow) depending upon the land use that it replaces. For comparison, according to data available in CROPWAT, average annual potential evapotranspiration per hectare for corn in the study area is 697 mm, more than for wheat (456 mm), but less than for

soybeans (733 mm), alfalfa (1003 mm) or pasture (1211 mm), the other primary rural land uses in the study area states.

[15] Based on these analyses, we conclude that the very slight gain in energy independence achieved through current and anticipated corn-based ethanol production is achieved at a high cost to water resources where corn is irrigated and at a high cost to water quality wherever corn feed stocks are grown. Combined with its negative net effects on greenhouse gas emissions [*Searchinger et al.*, 2008] and low net energy balance [*Hill et al.*, 2006], these water resource costs call into question the continued subsidization and expansion of corn-based ethanol production, especially where irrigation is required.

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