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New perspectives on the energy return on (energy) investment (EROI) of corn ethanol

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Abstract Research on corn ethanol is overly focused on whether corn ethanol is a net energy yielder and, consequently, has missed some other fundamental issues, including (1) whether there is significant error associated with current estimates of the EROI of corn ethanol, (2) whether there is significant spatial variability in the EROI of corn ethanol production, (3) whether yield increases will translate linearly to increases in EROI, (4) the extent to which assumptions about co-product credits impact the EROI of corn ethanol, and (5) how much of the ethanol production from biorefineries is net energy. We address all of these concerns in this research by: (1) performing a meta-error analysis of the calculation of EROI, (2) calculating the EROI for 1,287 counties across the United States, and (3) performing a sensitivity analysis for the values of both yield and co-products within the calculation of EROI. Our results show that the average EROI calculated from the meta-error analysis was 1.07 ± 0.2, meaning that we are unable to assert whether the EROI of corn ethanol is greater than one. The average EROI calculated across 1,287 counties in our spatial analysis was 1.01, indicating that the literature tended to use optimal values for energy inputs and outputs compared to the average conditions across the Unites States. Increases in yield had a trivial impact on EROI, while co-product credits had a large impact on EROI. Based on our results from the spatial analysis and the location of biorefineries across the United States, we conclude that the net energy supplied to society by ethanol is only 0.8% of that supplied from gasoline. Recent work indicates that only energy sources extracted at EROIs of 3:1 or greater have the requisite net energy to sustain the infrastructure of the transportation system of the United States. In light of this work, we conclude that production of corn ethanol within the United States is unsustainable and requires energy subsidies from the larger oil economy.

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1 Introduction

Over the past decade, there has been considerable debate on corn ethanol, most focused on whether it is a net energy yielder. The argument is generally that "if the Energy Return on Investment (EROI) of corn ethanol is positive then it should be pursued." On one side are Pimentel (2003) and Patzek (2004) who claim that corn ethanol has an EROI below one energy unit returned per energy unit invested, and on the other side are a number of studies claiming that the EROI is positive, reported variously as between 1.08 and 1.45 (Wang et al. 1997, 2007; Wang 2001; Shapouri et al. 2002; Graboski 2004; Shapouri et al. 2004; Oliveira et al. 2005; Farrell et al. 2006). Even with numerous publications on this issue, disagreement remains as to whether corn ethanol is a net energy yielder.

We believe that focus within the literature on whether or not corn ethanol yields a positive net energy gain has diverted attention from other fundamental issues. The following is a brief description of some of these issues and how we addressed them in this research.

First, none of the major studies of the EROI of corn ethanol account for statistical error within their analysis. Error is associated with all measurements, and we should expect there to be error associated with EROI as well. Yet each of Farrell et al. (2006), Wang et al. (2007), Patzek (2004), Pimentel (2003), and Shapouri et al. (2002) fail to report even general error statistics associated with their calculation of EROI. Considering that the range of published values for the EROI of corn ethanol is so small (from 0.8 to 1.5), one would expect that even a relatively small amount of error could be meaningful. In response to these concerns, we performed an error analysis for the calculation of the EROI of corn ethanol.

Second, most analyses to date, including those referenced previously, use optimal (i.e. Iowa) values for corn yield, fertilizer, and irrigation, despite the fact that each of these have large geographical (as well as other) variation. Because of this, they fail to represent the variable nature of corn production across space, and by extension, the subsequent variability in the EROI of corn ethanol. Our spatial analysis addressed this issue by examining the impacts of the natural geographic variability of corn inputs and yields on the EROI of corn ethanol production within the United States.

Third, the assumption about increasing corn yields on the EROI of corn ethanol has resulted in much confusion. For example, Wang et al. (2007) report that yield levels could reach 11,000 kg/ha (180 Bu/Ac) by 2015, which is roughly 25% higher than the average 2005 level. Yet they do not indicate how this will impact the EROI of corn ethanol or what increases in fertilizer, pesticides, etc. will be required to reach these elevated yield levels. Although it is clear that increasing corn yields will increase the gross output of corn per unit area, its effect on the EROI of the entire corn ethanol process is less clear because the corn itself becomes just one of many intermediate inputs. The effect of corn yields on EROI depends upon its fraction of the total energy input to corn ethanol production.

Fourth, the debate over whether the co-products of ethanol production, e.g. Distiller's Dry Grains, deserve an energy credit warrants exploration. On one side, Patzek (2004) believes that the co-products must be returned to the field to replenish soil humus. On the other side, Wang et al. (1997, 2007), Shapouri et al. (2002), and Farrell et al. (2006) consider the co-product a valuable output of the corn ethanol production process and assign it an energy credit. Unlike yield, the energy content of the co-products is added directly to the energy content of the ethanol in the calculation of EROI. As a result, energy credits for co-products can have a large impact on the EROI of corn ethanol. To address the concerns about the impacts of both yield increases and co-product credits on EROI, we performed a sensitivity analysis to gauge how EROI will change given changes in either input.

Fifth, Mulder and Hagens (2008), Mearns (2008) and Hall et al. (2009) discuss some of the more comprehensive implications of net energy analysis, including (1) using EROI to relate gross and net energy, (2) the concept of “the minimum EROI for a sustainable society,” and (3) “The Net Energy Cliff”. Below we discuss how both of these concepts relate to our EROI analysis.

1.1 Objectives

The objectives of this paper are to: (1) assess the error associated within the calculation of the EROI of corn ethanol, (2) calculate the EROI of corn ethanol for most corn-producing counties across the United States, (3) perform a sensitivity analysis to estimate how changes in both yield and co-product credits impact the EROI of corn ethanol, (4) calculate how much net energy was produced from biorefineries in 2009, and (5) assess whether the production of corn ethanol meets the minimum EROI for the transportation system of the United States.

1.2 EROI definitions and concepts

Hall et al. (2009) and Murphy and Hall (2010) summarize the present state of the definition, theory, and application of EROI research. The most important concepts are summarized below and can be found in greater detail in those publications.

Energy Return on Investment measures how much energy is gained after accounting for the energy required to produce a unit of the energy in question, or the ratio of energy out to energy in (Cleveland et al. 1984; Hall et al. 1981, 1986; Kaufmann and Cleveland 2007; Murphy and Hall 2010). The numerator and denominator are measured in the same units so that the ratio derived is dimensionless, e.g. 3:1, usually expressed as “three to one”. Since the second number in the ratio is usually one, EROI can be reported as simply the first number (i.e. an EROI of “three” and “three to one” are the same). A ratio greater than 1:1 implies that there is a net energy gain from the fuel invested, while a ratio below 1:1 indicates that it takes more energy to produce the fuel than is obtained from using it. EROI is calculated from the following straightforward equation (Cleveland et al. 1984; Hall et al. 2009; Murphy and Hall 2010):

$$\mathrm{EROI} = \frac{\mathrm{Energy}_{\mathrm{out}}}{\mathrm{Energy}_{\mathrm{in}}} \tag{1}$$

where $\mathrm{Energy}_{\mathrm{out}}$ is the energy produced and $\mathrm{Energy}_{\mathrm{in}}$ is the energy required to produce that energy. It is interesting to analyze how EROI changes over time and space. Time-series measurements of the EROI for oil and gas extraction within the United States show an irregular, yet generally decreasing trend over the past 50 years. The EROI for coal decreased from 80:1 in 1950s to 30:1 in the 1970s, but apparently has increased subsequently to 80:1 or more over the past few decades as huge strip mining operations became dominant (Cleveland et al. 1984; Cleveland 2005).

In this study, we examine how the EROI of corn ethanol varies across the conterminous United States. This is a new endeavor, except for the work of Persson et al. (2009), who examined how the net energy of corn ethanol varied across the southeastern United States, a marginal area for corn growth.

1.3 Mass–energy balance and EROI

The value of EROI can also be derived by accounting for the laws of conservation of mass/energy within a system. The conservation laws state that mass and energy cannot be created or destroyed, which is a useful concept when examining a system with numerous inputs and outputs, such as the production of corn ethanol. Determining which inputs and outputs to consider in an EROI analysis depends entirely on the designation of the system boundary. The boundary provides a starting point (energy/mass units enter the system) and an exit point (energy/mass units exit the system). Using these entry and exit points, mass/energy balance equations can be used to account for all mass and energy that enter the system. The equation can be written simply as the sum of inputs per unit area and time must equal the sum of outputs per unit area and time (Patzek 2007). For complex systems, such as the production of corn ethanol, mass/energy balance equations aid in tracking inputs (e.g. corn kernel) from the field to multiple outputs (e.g. ethanol, greenhouse gas emissions and co-products).

Patzek (2007) uses a mass/energy conservation approach to assess the energy balance of the corn ethanol process, explicitly defining the boundaries of analysis. Much of the literature does not use this mass/energy conservation approach, which has resulted in the use of different boundaries of analysis when calculating the EROI of corn ethanol. Mulder and Hagens (2008) echoed this issue, indicating that of the four ethanol studies they examined, three used different boundaries when performing their EROI analysis. In this analysis, we adopt the boundaries used by Patzek (2004) so that our results agree with the principles of conservation of mass/energy.

1.4 Natural gradients of corn and corn ethanol production

As the economist David Ricardo pointed out long ago, farmers tend to raise crops where those crops grow best (Ricardo 1821). This “best first” principle is a well-established principle in economics and resource science; humans will tend to use the best resources first, and then subsequently lower-quality resources. For example, in the early 1900s, the United States was mining copper ore that was about 4 percent copper on average. By 1969, the average yield had dropped to about 0.5 percent copper, because the best resources had been mined first (Lovering 1969).

Ricardo’s principle, derived for agriculture, applies to American farmers. There is a definite hierarchy of corn productivity by state. For example, in 2005, an average of 173 bushels per acre (10859 kg/ha) were harvested in Iowa, while an average of only 113 bushels per acre (7,093 kg/ha) were harvested in Texas. This is consistent also with the general principal of gradient analysis in ecology, which states that individual plant species grow best near the middle of their gradient space; that is near the center of their range in environmental conditions such as temperature and soil moisture (Whittaker 1956; Hall et al. 1992).

The climatic conditions in Iowa are clearly at the “center of corn’s gradient space” and, at least until recent years, most corn raised for alcohol came from this area. What is less well understood, and what we quantify in this research, is that corn production is also less energy intensive (both per kilogram and per hectare) at or near the center of corn's gradient space, and as a result, the EROI of the corn ethanol process varies across space. This is increasingly important as more ethanol plants are constructed in less optimal areas for corn growth, i.e. outside the states of Iowa, Minnesota, Nebraska, and Illinois.

1.5 Newer concepts within EROI literature

Recent work by Mulder and Hagens (2008), Mearns (2008), and Hall et al. (2009) have brought three new concepts to the discourse on EROI, respectively: (1) how much gross energy must be extracted to deliver one unit of net energy to society, (2) the Net Energy Cliff, and (3) the minimum EROI for fuels to sustain current society. We discuss each of these in turn with respect to corn ethanol.

Mulder and Hagens (2008) proposed a way to express EROI that provides a different perspective on the energy returns from corn ethanol. While EROI is the ratio of outputs to inputs for an energy process, they focus on "net energy," which is the energy gained from an activity beyond that which is needed to maintain that activity (Odum 1973). One unit of net energy is synonymous with one unit of "surplus energy" or "profit energy" and can be considered the useful energy delivered to society, i.e. net energy dictates how many roads, hospitals, schools, etc., can be built. Mulder and Hagens (2008) proposed a method to quantify the total amount of energy (gross energy) required to deliver one unit of net energy from a particular process. The equation is given as:

$$\text{Gross amount of energy required} = \text{EROI}/(\text{EROI} - 1) \tag{2}$$

The equation can be applied in the following way. Gagnon et al. (2009) estimated that the EROI of global oil and gas production for the world is 18:1. To deliver one unit of net energy to society from oil would require the extraction of 1.06 units of energy in total; 1.0 units of net energy and 0.06 units of energy to be reinvested to sustain the energy extraction process. Likewise, when using an energy source with an EROI of 2:1, 2.0 units of energy must be produced at the well head to deliver 1 unit of net energy to society, as half of the energy produced at the well head (or it is energy equivalent) must be reinvested to get one more additional unit of the energy out. Note that it is mathematically and logically impossible for fuels with an EROI of less than one to deliver any net energy at all. By rearranging Eq. 2, it is possible to compute how much net energy is produced given the gross volume of energy and an EROI for the production process. The equation is

$$\text{Net energy} = \text{Gross energy} * \left[\frac{\text{EROI} - 1}{\text{EROI}}\right] \tag{3}$$

Mearns (2008) has taken this analysis a step further by noting there is a declining exponential relation between gross and net energy. The relation between net and gross energy is called "The Net Energy Cliff" (Fig. 1).

Work by Mulder et al. (2010) illuminates another issue with the use of low EROI fuels; the consumption of non-energy inputs. They found that the production of ethanol from corn consumes four orders of magnitude more water (both direct and indirect) than the production of diesel fuel from conventional petroleum.

Hall et al. (2009) analyzed the energy requirements of the transportation industry within the United States. They analyzed costs, from the extraction of oil through the distribution of that oil, and even the energy required to maintain roads and bridges. Using these energy costs, they calculated that fuels must have EROIs of at least 3:1 to pay for all the energy

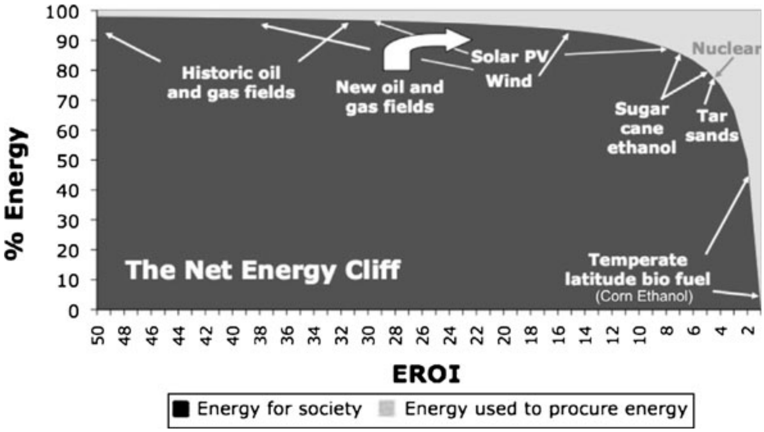

Fig. 1 The net energy cliff, showing how as EROI approaches 1:1, the percent of the fuel delivered to society as net energy drops rapidly. Various technologies are located along this line (Adapted from Mearns 2008)

costs associated with the transportation system. Fuels that have EROIs below 3:1 act as an energy sink on the transportation system, as they provide insufficient energy for the whole transportation system. In this analysis, we will compare our calculation of the EROI of corn ethanol with the minimum EROI for the transportation system of the United States as calculated in Hall et al. (2009).

2 Methods

We performed four major analyses in this research. The first was a meta-error analysis, in which we quantified the error associated with the calculation of EROI of corn ethanol based on various estimates of the energy inputs and outputs found in the literature. The second was a spatial analysis of the EROI of corn ethanol. The third was a sensitivity analysis; wherein we assess the degree to which corn yields and co-product credits impact the EROI of corn ethanol. Fourth, we combined the results of our EROI analysis with the data of biorefinery production to assess how much net energy was delivered to society by ethanol in 2009. We discuss the details of each analysis in turn.

2.1 Meta-error analysis

The main objective of this analysis was to use average values from the literature to calculate and average EROI with an estimation of error. First, we describe how we chose our variables for the average EROI calculation, and then we describe how we propagate the error through the calculation of EROI.

2.1.1 Variables for meta-analysis

We calculated an average value for most agricultural phase inputs based on the values reported in five main studies on corn ethanol: Wang et al. (1997), Shapouri et al. (2002), Pimentel (2003), Patzek (2004), and Farrell et al. (2006) (Tables 1, 2). Some of the studies did not include the indirect energy used to develop hybrid corn seeds or to construct farm machinery. For example, Wang et al. (1997), Shapouri et al. (2002), and Pimentel (2003) omit the energy used to develop and produce hybrid corn seeds, and both Wang et al. (1997) and Shapouri et al. (2002) omit the energy used to construct machinery. According to Patzek (2004) the energy used to construct hybrid corn seeds is much greater than that required for standard corn grains, but since three of the five studies omitted values for this variable, taking an average across all studies seemed inappropriate. The same logic applies to the energy used to construct farm machinery. As a result, for these two variables only, we used the value reported by Patzek (2004).

The five major studies report values that are similar for the following non-farm variables: biorefinery yield, ethanol energy content, and the cost of the biorefinery phase (note: "cost" in this study refers to energy cost, unless otherwise noted, Table 1). We used the average across all studies for each of these variables. There is little agreement among these studies in regards to the energy credits for co-products. The values range from 0.0 (Patzek 2004) to 5.89 MJ/L (Shapouri et al. 2002). We decided to use the average across all studies (3.46 MJ/L) for our calculation of average EROI. We deemed this appropriate because we estimated the effect of using different values for co-products credits within the sensitivity analysis.

2.1.2 *Propagation of error*

We used a simple, conservative method to propagate standard error through the calculation of EROI to derive a 95% confidence interval. Our Table 2 is a modified version of Table 18 provided by Patzek (2004), and we used it to calculate the average EROI across all five studies, called $\mathrm{EROI_{LIT}}$. For this section, we calculate the average $\mathrm{EROI_{LIT}}$ according to the following equation so that the values in the equation match those listed in Table 3

$$\mathrm{EROI_{LIT}} = \frac{\left(\frac{\text{Corn yield (GJ/Ha)} \cdot 1000\ \text{(MJ/GJ)}}{\text{Ethanol yield (L/Ha)}}\right) + \text{Coproduct credits (MJ/L)}}{\left(\frac{\text{Agricultural phase (MJ/Ha)}}{\text{Ethanol yield (L/Ha)}}\right) + \text{Biorefinery phase (MJ/L)}} \tag{4}$$

Table 1 Parameter values required for analysis, with references

Unit	Value	Source
Corn	25.40 (kg/Bushel)	Farrell et al. (2006)
Corn energy content	16.20 (MJ/kg)	Patzek (2004)
Biorefinery efficiency for corn ethanol	0.40 (L EtOH/kg Corn)	Farrell et al. (2006)
Ethanol energy content	21.46 (MJ/L)	Farrell et al. (2006)
Gasoline energy content	34.56 (MJ/L)	Patzek (2004)
Energy content of a barrel of oil equivalent	6115.00 (MJ/boe)	Farrell et al. (2006)
Fertilizer		Patzek (2004)
Nitrogen	54.43 (MJ/kg)	
Phosphorus	6.80 (MJ/kg)	
Potassium	6.80 (MJ/kg)	
Lime	1.75 (MJ/kg)	Patzek (2004)
Irrigation	131 (MJ/cm-Ha)	Patzek (2004)

kg kilogram, *L* liter, *MJ* megajoule, *boe* barrels of oil equivalent, *EtOH* ethanol, *cm* centimeter

Table 2 Non-spatial energy inputs consumed during the agricultural phase of the corn ethanol process

Input (MJ/Ha)	Wang et al. (1997)	Shapouri et al. (2002)	Pimentel (2003)	Patzek (2004)	Farrell et al. (2006)	Average	SE	Value used in Our Study
Lime	469.2	469.2	929.7	582.8	472.5	584.7	89.0	584.7
Herbicide	53.5	59.0	63.3	289.9	74.8	108.1	45.6	108.1
Insecticide	728.5	1,234.5	886.2	662.9	985.1	899.5	101.2	899.5
Seed[a]	0.0	0.0	0.0	2,935.9	228.0	632.8	577.5	2,935.9
Transportation	210.0	410.0	1,120.0	750.0	934.0	684.8	166.8	684.8
Gasoline	1,064.3	1,268.3	2,333.9	1,008.6	1,277.5	1,390.5	241.9	1,390.5
Diesel	3,000.8	3,899.2	3,979.0	3,097.6	2,719.4	3,339.2	253.0	3,339.2
Natural gas	417.0	182.0	0.0	246.0	670.1	303.0	113.5	303.0
LPG	778.1	1,575.6	0.0	1,128.7	765.3	849.5	258.7	849.5
Electricity	86.8	747.4	143.6	687.6	820.0	497.1	157.6	497.1
Labor	390.0	1,100.0	1,050.0	1,100.0	574.0	842.8	150.4	842.8
Machinery and infrastructure[a]	0.0	0.0	6,050.0	6,050.0	393.6	2,498.7	1,451.6	6,050.0
Total	7,198.0	10,945.2	16,555.7	18,539.9	9,914.3	12,630.6	2,122.0	18,485.0

Spatial inputs, including fertilizer and irrigation, are included in Table 4

[a] Inputs for which the average of the five studies was not used

Table 3 Quantity of energy used and produced in the ethanol process reported in various publications (adapted from Patzek 2004)

	Agricultural phase (MJ/Ha)	Corn yield (GJ/ha)	Biorefinery phase (MJ/L)	Co-product credits (MJ/L)	Ethanol yield (L/ha)
Wang et al. (1997)	15,692.39	55.32	14.39	5.38	2,603.00
Shapouri et al. (2002)	17,962.62	52.79	14.89	5.89	2,484.00
Pimentel (2003)	27,652.57	57.51	16.07	1.88	2,706.00
Patzek (2004)	27,844.52	57.51	16.19	0.00	2,706.00
Farrell et al. (2006)	19,434.73	73.42	15.24	4.13	3,463.39
Our value	21,717.37	59.31	15.36	3.46	2,792.48

We also include the value used in our study

There are many mathematical steps involved when calculating $\mathrm{EROI}_{\mathrm{LIT}}$, yet only two mathematical functions: addition and division. As the calculation of $\mathrm{EROI}_{\mathrm{LIT}}$ proceeds, the error is propagated according to one of two equations, depending upon the mathematical function being performed. If addition was performed, then the following equation was used to propagate the error:

$$\mathrm{SE}^* = \sqrt{\sum_{i=1}^{n} (\mathrm{SE}_i)^2} \tag{5}$$

where SE* is the standard error of the solution, SE is the standard error of each input being aggregated, and "*i*" is one of "*n*" inputs being aggregated in this portion of the error propagation. If division was performed, then the following equation was used to propagate the error:

$$\mathrm{SE}^* = x^* \sqrt{\sum_{i=1}^{n} \left(\frac{\mathrm{SE}_i}{x_i} \right)^2} \tag{6}$$

where SE* is the standard error of the solution, x^* is the value of the solution, x_i is the average value for input "i" of "n" inputs, and SE_i is the standard error of input "i" of "n" inputs. We multiplied the final standard error by 1.96 to attain a 95% confidence interval for the average $\mathrm{EROI}_{\mathrm{LIT}}$.

Using this technique of error propagation assumes that the input factors are independent and that all variables are normally distributed. We think these assumptions are acceptable because there is no a priori reason to assume that the errors among the input variables are correlated or that the variables have a non-normal distribution.

2.2 Spatial analysis

We performed a spatial analysis of the energy gains and costs of corn ethanol for the entire United States using spatially variable data for corn yield, fertilizer, and irrigation. Yield data was available at the county-level, while fertilizer and irrigation data were available at the state-level (USDA 2009). Yield, fertilizer, and irrigation data were converted to energy units using conversion ratios provided in Table 1, and assuming an application rate of 20 cm of water per hectare for irrigation (Patzek 2004). The energy value for corn, fertilizer, and irrigation were multiplied by the per county yield (for corn) or per state usage (for fertilizer and irrigation) to attain the total energy input for each item. All data are for 2005. The spatial data for yield, fertilizer, and irrigation were merged with a county and state boundary map attained from the United States Census Bureau using the ArcGIS software program and Federal Information Processing Standards codes (USCB 2007; ESRI 2007). This merge allowed us to view all data spatially. The values used in this study for non-spatial variables were the average of the values listed in five other studies except for seeds and machinery (Tables 1 and 2).

We calculated two different EROI values based on the boundary of analysis: farm gate and refinery gate. Farm gate EROI ($\mathrm{EROI}_{\mathrm{FG}}$) is the EROI of corn farming with the final product being the corn itself (Eq. 7), while the refinery gate EROI ($\mathrm{EROI}_{\mathrm{RG}}$) is the EROI of corn ethanol production with the final products being ethanol and co-products.

$$\mathrm{EROI}_{\mathrm{FG}} = \frac{\text{Corn yield (MJ/Ha)}}{\text{Agricultural phase inputs (MJ/Ha)}} \tag{7}$$

$$\mathrm{EROI}_{\mathrm{RG}} = \frac{\text{Ethanol} + \text{Coproduct credits (MJ/L)}}{\left(\frac{\text{Spatial+Nonspatial inputs (MJ/Ha)}}{\text{Yield (Kg/Ha)} \cdot \text{Biorefinery yield } (\mathrm{L_{etoh}/Kg_{corn}})} \right) + \text{Biorefinery input(MJ/L)}} \tag{8}$$

We calculated the EROI per county for corn ethanol production within the United States using Eq. 8, then created a map of EROI values for every county within the states that produced at least 1% of the 2005 corn harvest.

2.3 Sensitivity analysis

2.3.1 Yield

To address the impact of possible future higher yields on the EROI of corn ethanol, we calculated EROIs for various scenarios using yield levels that were up to three times greater than the average yield in 2005. We do not expect that average corn yields will reach a level three times greater than the 2005 average; rather we include them to serve as a theoretical maximum to show the trend in EROI given changes in yield. Although increasing yields would certainly require increases in the use of at least some fertilizers, lime, and/or irrigation, for simplicity's sake, we increased yield levels only, keeping other numbers in the EROI calculation constant.

2.3.2 Co-product credits

To assess how sensitive the calculation of EROI is to changes in co-product credits, we performed three calculations. We first calculated the EROI_{LIT} based on the average co-product credits calculated across all five studies (3.46 MJ/L). Then, we calculated the EROI without co-product credits, called the "Patzek Case." Lastly, we calculated the EROI using a co-product credit of 5.89, called the "Shapouri Case."

2.4 Gross versus net energy analysis

We used Eq. 3 to estimate how much of the current ethanol production is "gross" and how much is "net" energy. To do this, we overlaid a map of 180 biorefineries onto the map of EROI (RFA 2009). Of the 180 biorefineries that we overlaid on the map, a number of them were excluded from our analysis for one of three reasons: (1) they were in a county for which we had no data, (2) they were ethanol facilities under construction and not producing ethanol in 2009, or (3) corn was not the sole feedstock. Our final list included 127 biorefineries that produced 31.6 billion liters of ethanol in 2009—approximately 93% of total US ethanol production. The merged biorefinery and corn production data (including EROI_{RG}) are included in Appendix 1. We assumed that the EROI_{RG} for the county in which the biorefinery is located is an accurate measure of the EROI_{RG} for corn ethanol produced from that biorefinery. Then, we input the EROI_{RG} and production data for each biorefinery into Eq. 3 to figure out how much net energy is produced from our current ethanol infrastructure. For perspective, we used the biorefinery data to compare gross and net energy production from both corn ethanol and gasoline.

3 Results and discussion

The main results from our study were as follows. (1) The average EROI_{LIT} calculated using the literature values for inputs was 1.07 ± 0.2. (2) The average EROI_{RG} value calculated across all counties in the spatial analysis was 1.01. (3) The net energy produced from ethanol in 2009 was only 0.8% of that produced from gasoline in the US. (4) Increasing yields have a trivial impact on EROI, while co-product credits have a strong influence on EROI. Details of these results follow.

The results from our meta-error analysis indicated that the average EROI for corn ethanol was 1.07 with a standard error of 0.1. The 95% confidence interval was 1.07 ± 0.2. This result is interpreted as follows: there is a 95% chance that the true value of the EROI of corn ethanol is contained within 0.2 of 1.07. Alternatively, this calculation means that we are unable to assert whether the true value of the EROI of corn ethanol is greater than one.

EROI values calculated in the spatial analysis ranged from 0.36 in less optimal corn-growing areas, for example southern Texas, to 1.18 in optimal areas, for example Nebraska (Fig. 2). If we apply the same confidence calculated in the meta-error analysis to the results of the county EROI analysis, we find that none of the counties had an EROI that was high enough (> 1.20) to conclude that corn ethanol was produced at an energy profit. The average EROI value across all counties was 1.01, which was 0.06 less than the average calculated across the literature. This supports the idea that the literature used optimal values for corn ethanol inputs and outputs and as such has underestimated costs, overestimated benefits, or both. The distribution of EROI values followed a normal distribution skewed slightly left (Fig. 3). The vast majority of counties had EROIs that fell within either the 1.01–1.05 or 1.06–1.10 category.

Our spatial analysis indicated diminishing returns to EROI as distance from the Corn Belt increased. Counties with high EROI values were located in Nebraska and other Corn Belt states, while the lower EROI values were located in counties toward the northwest or southeast of the area analyzed, essentially northwestern South and North Dakota, and southeastern Texas, respectively (Fig. 2). As expected, the counties with EROI values within the top 10% had a combination of higher yields and lower agricultural inputs, while

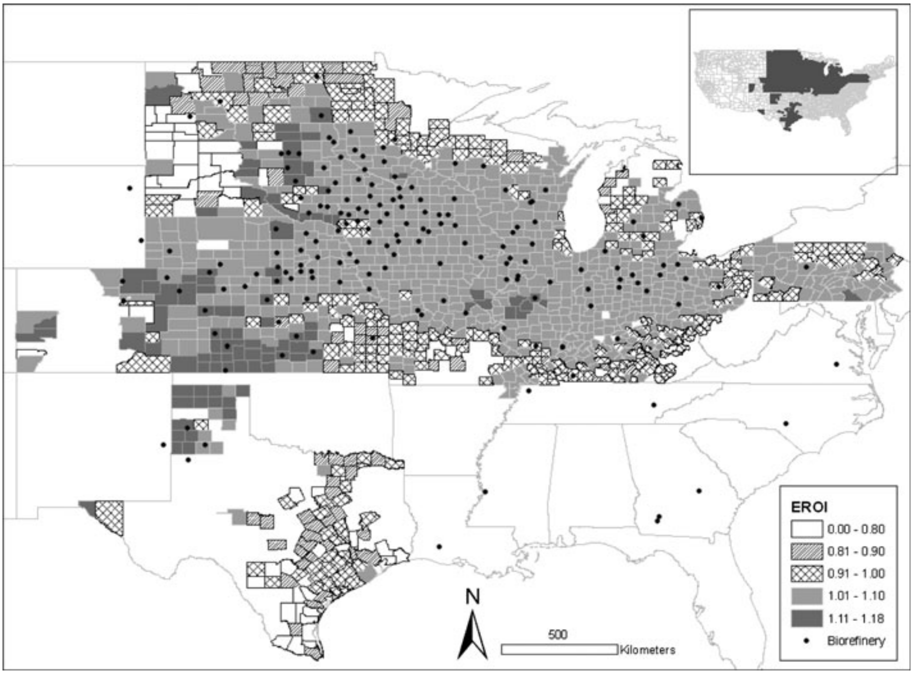

Fig. 2 Map of the EROI of corn ethanol production for counties within states that produced at least 1% of the corn harvest in 2005, and biorefinery locations

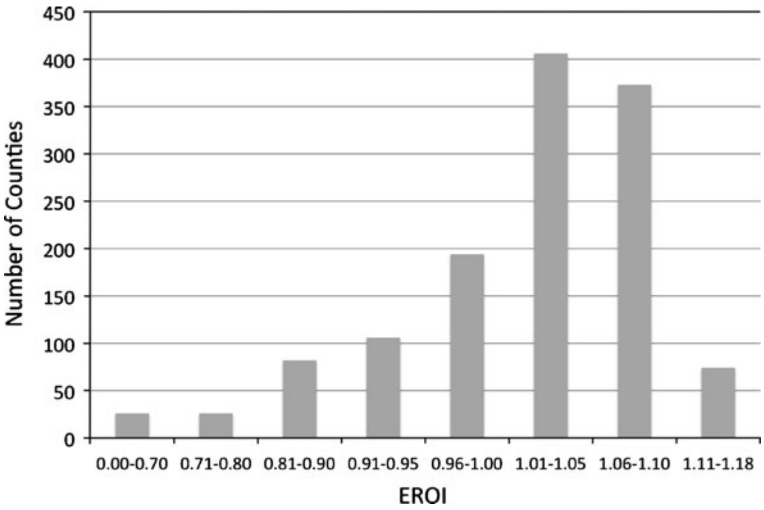

Fig. 3 Histogram of number of counties vs. EROI

the counties within the lowest 10% of EROIs had lower yields and higher agricultural inputs on average (Fig. 4). We can conclude that even with a precision of ±0.2, 48 counties have EROIs below 1, as the EROI calculated for each of these counties was <0.80 (Fig. 3).

An analysis at the state-level indicated a similar geographic pattern, as the Corn Belt states, i.e. Nebraska, Minnesota, Iowa, Illinois, had EROI values in the upper half of the states analyzed and states further from the optimal corn-growing lands were located in the bottom half,.e.g. Kentucky, Texas, Missouri. $EROI_{FG}$ ranged from 3.81 to 6.25, while

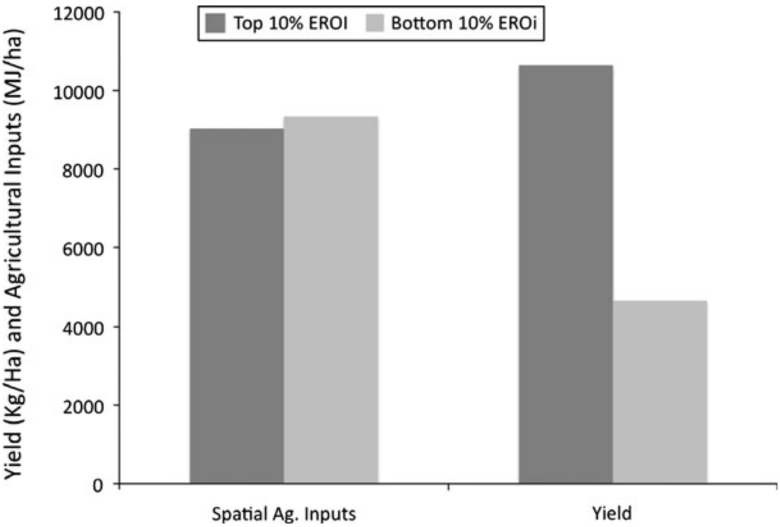

Fig. 4 Average values for spatial agricultural inputs and corn yield for counties with EROI values within the top and bottom 10% of all counties

Table 4 Summary statistics of the costs and gains of the agricultural phase of corn ethanol production for states that produced at least 1% of the 2005 corn harvest in the United States, ranked by decreasing $\mathrm{EROI}_{\mathrm{RG}}$

	Corn yield			Agricultural phase inputs (MJ/Ha)						$\mathrm{EROI}_{\mathrm{FG}}$	$\mathrm{EROI}_{\mathrm{RG}}$
	Bu/ac	kg/Ha	MJ/Ha	N	P	K	Irrig.	Spatial	Non-spatial		
Minnesota	174	10,921	174,740	8,477	459	543	0	9,479	18,485	6.25	1.14
Iowa	173	10,858	173,736	8,561	492	639	0	9,693	18,485	6.17	1.13
Wisconsin	148	9,289	148,630	6,573	284	458	0	7,314	18,485	5.76	1.11
Nebraska	154	9,666	154,655	8,425	284	158	615	9,481	18,485	5.53	1.09
Colorado	148	9,289	148,630	7,861	268	139	690	8,958	18,485	5.42	1.09
Indiana	154	9,666	154,655	8,985	583	951	0	10,520	18,485	5.33	1.08
Michigan	143	8,976	143,608	7,762	345	620	0	8,727	18,485	5.28	1.08
Illinois	143	8,976	143,608	8,888	585	870	0	10,343	18,485	4.98	1.06
Kansas	135	8,473	135,574	8,304	290	280	439	9,313	18,485	4.88	1.05
Pennsylvania	122	7,657	122,519	5,564	359	364	0	6,287	18,485	4.95	1.05
North Dakota	129	8,097	129,549	7,396	338	189	44	7,967	18,485	4.90	1.05
Ohio	143	8,976	143,608	9,850	571	769	0	11,190	18,485	4.84	1.05
South Dakota	119	7,469	119,506	6,891	334	194	38	7,457	18,485	4.61	1.03
Kentucky	132	8,285	132,562	10,479	590	688	0	11,757	18,485	4.38	1.01
Texas	114	7,155	114,485	8,924	339	141	383	9,787	18,485	4.05	0.98
Missouri	111	6,967	111,472	9,727	465	567	0	10,759	18,485	3.81	0.96

Yield (MJ/Ha) was calculated using 16.2 MJ/kg corn energy conversion ratio

$\mathrm{EROI}_{\mathrm{FG}}$ was calculated by dividing corn yield (MJ/Ha) by the sum of spatial and non-spatial inputs

$\mathrm{EROI}_{\mathrm{RG}}$ was calculated according to Eq. 8, using yield (kg/Ha), spatial (MJ/Ha), and non-spatial (MJ/Ha) inputs from this table and other inputs from Table 3

$EROI_{RG}$ ranged from 0.96 to 1.14 (Table 4). Since much of the costs of the agricultural phase of corn production were constant across all states in this study (i.e. non-spatial), the range in $EROI_{FG}$ reflects the corn yields and fertilizer inputs in different environments rather than differences in the energy cost of planting and harvesting an acre of corn. On the other hand, the small range in $EROI_{RG}$ indicated that the off-farm costs dwarfed the energy costs on-farm. We calculated that 65% of the costs of producing ethanol from corn originated in the biorefinery phase (Fig. 5).

According to Eq. 2, to deliver one liter of ethanol as net energy at an EROI of 1.18 (max found in the spatial analysis), 7.5 liter of ethanol must be produced; 1 liter as net energy and 6.5 liter (or its energy equivalent) to be reinvested to produce more ethanol. If we assume that the average we calculated across all counties (1.01) was the actual value for EROI, then producing ethanol is virtually a zero sum game; i.e. energy produced equals energy consumed.

Applying Eq. 2 to our spatial analysis reveals other interesting results. Eight liters of ethanol must be produced to deliver one unit of net energy in Minnesota, using an EROI of 1.14. Another way, only 13% of the ethanol produced in Minnesota is net energy because the energy equivalent of 87% of the ethanol produced must be reinvested to produce more ethanol. The energy reinvested is in many forms, including, but not limited to, the fossil energy required to generate corn, fertilizer, lime, gasoline, natural gas, diesel, etc. For states with an EROI below 1.0 (Texas and Missouri), the production of ethanol is acting as a drain on the energy system, requiring more energy to produce ethanol than the energy contained in the ethanol product.

The EROI values for counties with biorefineries ranged from 0.64 in Stark, North Dakota, to 1.18 in Phillips, Kansas. Our analysis of 127 biorefineries indicated that of 31.6 billion liters of ethanol produced in the United States, only 1.6 billion liters were net energy (roughly 5%). As a point of comparison, of the 136 billion liters of gasoline consumed in 2009, roughly 122 billion liters (90%) were net energy, assuming that the 136

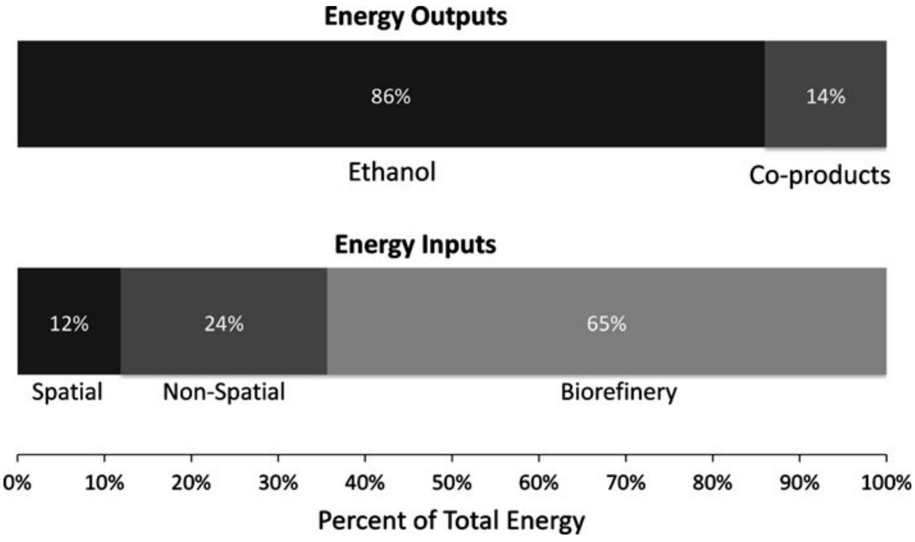

Fig. 5 Relative mix of inputs (spatial agricultural inputs, non-spatial agricultural inputs, biorefinery phase) and outputs (ethanol and co-products) of corn ethanol production

billion liters were produced at an EROI of 10 (Cleveland 2005). Adjusting for the lower energy content of ethanol (21.46 MJ/L etoh vs. 34.56 MJ/L gasoline = 0.62), we calculated that the net energy from ethanol is roughly 0.99 billion "gasoline-equivalent" liters. Dividing the net energy supplied to society from ethanol by that from gasoline, we calculated that the supply of net energy to society from ethanol is only 0.8% of that from gasoline (0.99/122 = 0.8%). Thus comparing simply the gross production of gasoline-equivalent liters of both ethanol and gasoline is misleading, as one would conclude that the US production of ethanol is 14% of gasoline consumption (19.6/136 = 14%).

3.1 Sensitivity analysis

Increasing yield even far beyond the highest levels in 2005 had a trivial impact on the EROI of corn ethanol (Fig. 6). As a result, efficiency gains that occur post-farm gate only (such as the distillation or transportation processes) are able to increase the EROI_{RG} significantly. To that end, recent research by Liska et al. (2008) calculated the EROI of corn ethanol using various methods of distillation that utilized a variety of current technologies. They found that the EROI range for corn ethanol remained low, from 1.29–1.70 (we excluded two hypothetical scenarios that they also assessed). With the absence of technology to boost the efficiency of the distillation process and the trivial impact that increases in yield have on the EROI of corn ethanol, we conclude that there is no reason to expect that the EROI of corn ethanol will increase much beyond current levels in the foreseeable future.

EROI analysis is highly sensitive to co-product credits. When using the "Patzek Case" (energy credit = 0), the mean US EROI of corn ethanol decreases from 1.07 to 0.91, but when using the "Shapouri Case" (energy credit = 5.89), the EROI increases from 1.07 to 1.17. Thus, the co-product credit alone can determine whether the EROI is less than or

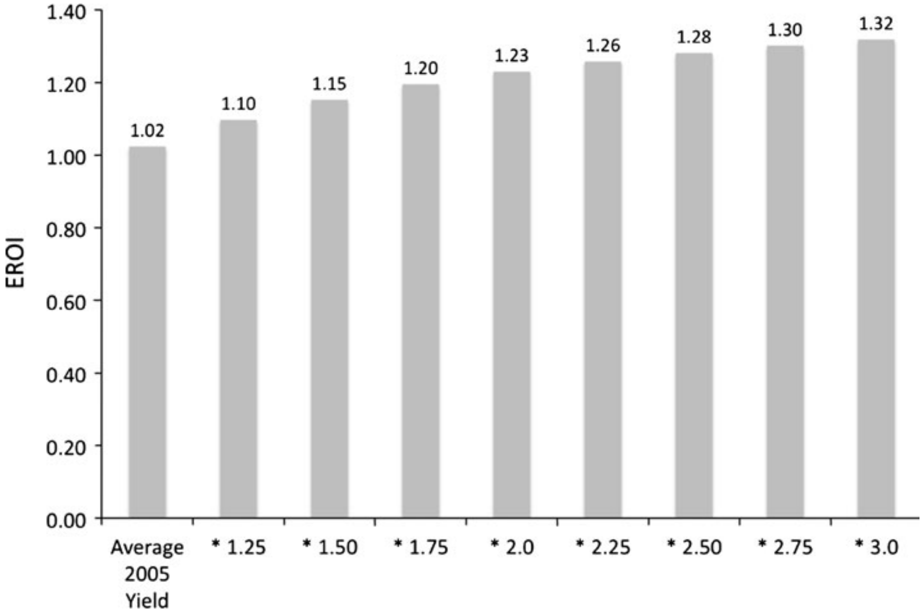

Fig. 6 EROI as a function of increasing yield. Average 2005 yield (8,795 kg/Ha) was multiplied by the values listed across the X-axis for each respective calculation

greater than one. This contradicts Shapouri et al. (2002) who claimed that the EROI is greater than one before accounting for co-product credits. Using an alternative weighting mechanism, such as price, may ameliorate some of the sensitivity of the EROI statistic to co-product credits.

Fundamentally, the disagreement over the value of co-product credits hinges on one's attitude toward the science of nutrient cycling and erosion. Those who believe that corn yields are maintained without spreading the nutrients contained in the co-products back onto the field will generally assign a co-product credit in the EROI calculation. Those who believe that the science is unclear will generally assign a conservative co-product credit or even omit the credit altogether. We believe that until a clear consensus emerges, the precautionary principle should apply, and one should be very cautious in assigning coproduct credits.

4 Conclusion

The debate over the EROI of corn ethanol has been concerned mostly with whether it is a net energy yielder. As such, the dialogue has veered away from many of the larger implications of EROI analyses. Our results indicate that the EROI of corn ethanol is statistically inseparable from one energy unit returned per energy unit invested, and it is likely that much of our ethanol production is acting as an energy sink, requiring more energy for production than that contained in the ethanol product. This conclusion was confirmed in our spatial analysis, where the average $\mathrm{EROI}_{\mathrm{RG}}$ was 0.06 lower than the average calculated from the literature.

Increasing yields is oft-touted as a way to increase the EROI of corn ethanol, but our analysis indicates that the gains in EROI are small even when the average yield from 2005 was tripled. Co-product credits, on the other hand, have a large influence on the EROI from corn ethanol. There is no consensus within the literature regarding an appropriate co-product value, and until one emerges (one way or another), we should err on the side of caution when applying credits to co-products. Finally, the analysis of ethanol production from biorefineries supports our conclusion from the spatial analysis: the EROI is too low in too many locations to make an impact on our gasoline consumption. Our best estimate is that the net energy provided from ethanol accounts for only 0.8% of the net energy provided by gasoline.

The evidence provided in this research is clear: we do not know the exact EROI of ethanol, but even if we are remotely close (± 0.2), we are still, in the best case scenario, gaining an insignificant amount of net energy. Furthermore, Hall et al. (2009) estimated that only fuels with an EROI greater than 3:1 provide the requisite net energy to provide a fuel source and to maintain the infrastructure associated with the current U.S. transportation system. Fuels that have an EROI below 3:1 require subsidies from other energy sources to pay for all of the infrastructure associated with the transportation system of the US. The EROI of corn ethanol that we calculated is lower than the 3:1 threshold, indicating that corn ethanol requires large subsidies from the general fossil fuel economy, and as a result, drains energy from the US transportation system.

Acknowledgments The authors would like to thank the Santa Barbara foundation for financial support. We would also like to thank 3 anonymous reviewers for many helpful comments.

Appendix 1

See Table 5.

Table 5 Production per biorefinery along with the yield and production cost data for the county in which the biorefinery is located

Biorefinery data				County data					EROI	Net energy
County	State	Operator	EtOH Production 10^6 liters	Yield (kg/Ha)	N (MJ/Ha)	P (MJ/Ha)	K (MJ/Ha)	Irrig. (MJ/Ha)		
Stark	ND	Red trail energy, LLC	189	2,886	7,396	338	189	44	0.64	−106
Anderson	KS	East kansas agri-energy, LLC	132	5,772	8,304	290	280	439	0.89	−16
Christian	KY	Commonwealth agri-energy, LLC	125	6,650	10,479	590	688	0	0.91	−12
Ida	IA	Quad-county corn processors	114	6,901	8,561	492	639	0	0.95	−5
Davison	SD	POET Biorefining—Mitchell	257	6,587	6,891	334	194	38	0.97	−8
Saint Clair	MI	Marysville ethanol, LLC	189	6,964	7,762	345	620	0	0.97	−6
Morrison	MN	Central MN ethanol coop	81	7,340	8,477	459	543	0	0.98	−2
Calhoun	MI	The Andersons albion ethanol LLC	208	7,152	7,762	345	620	0	0.98	−4
Cherokee	IA	Little Sioux corn processors, LP	348	7,529	8,561	492	639	0	0.99	−4
Plymouth	IA	Plymouth ethanol, LLC	189	7,529	8,561	492	639	0	0.99	−2
McLean	ND	Blue flint ethanol	189	7,152	7,396	338	189	44	0.99	−2
Saint	IN	New energy corp.	386	8,093	8,985	583	951	0	1.00	1
Holt	MO	Golden triangle energy, LLC	76	8,344	9,727	465	567	0	1.01	1
Edmunds	SD	Glacial lakes energy, LLC—Mina	405	7,529	6,891	334	194	38	1.02	7
Crawford	IA	Amazing energy, LLC	208	8,219	8,561	492	639	0	1.02	4
Wabash	IN	POET Biorefining—North Manchester	257	8,532	8,985	583	951	0	1.02	6
Ford	IL	One earth energy	379	8,532	8,888	585	870	0	1.02	9
Madison	NE	Louis Dreyfus commodities	170	8,281	8,425	284	158	615	1.02	4
Otter Tail	MN	Otter tail Ag enterprises	218	8,281	8,477	459	543	0	1.02	5
Turner	SD	POET Biorefining—Chancellor	416	7,780	6,891	334	194	38	1.03	12
Turner	SD	NuGen energy	416	7,780	6,891	334	194	38	1.03	12
Seneca	OH	POET Biorefining—Fostoria	257	8,909	9,850	571	769	0	1.03	7

Table 5 continued

Biorefinery data				County data					EROI	Net energy
County	State	Operator	EtOH Production 10^6 liters	Yield (kg/Ha)	N (MJ/Ha)	P (MJ/Ha)	K (MJ/Ha)	Irrig. (MJ/Ha)		
Clearfield	PA	Bional clearfield	416	7,466	5,564	359	364	0	1.03	13
Roberts	SD	North country ethanol, LLC	76	7,842	6,891	334	194	38	1.03	2
Marion	OH	POET Biorefining—Marion	257	8,972	9,850	571	769	0	1.03	8
Greene	IA	POET Biorefining—Coon rapids	204	8,532	8,561	492	639	0	1.03	6
Page	IA	Green plains renewable energy	208	8,532	8,561	492	639	0	1.03	7
Buena Vista	IA	Valero renewable fuels	416	8,532	8,561	492	639	0	1.03	13
Guthrie	IA	Hawkeye renewables, LLC	416	8,532	8,561	492	639	0	1.03	13
Furnas	NE	Mid America agri products/Horizon	170	8,470	8,425	284	158	615	1.03	5
Valley	NE	Green plains renewable energy	189	8,470	8,425	284	158	615	1.03	6
Wells	IN	Green plains renewable energy	416	8,846	8,985	583	951	0	1.04	14
Hitchcock	NE	Trenton agri products, LLC	151	8,532	8,425	284	158	615	1.04	5
Winnebago	WI	Utica energy, LLC	182	7,905	6,573	284	458	0	1.04	6
Ionia	MI	Carbon green bioenergy	189	8,344	7,762	345	620	0	1.04	7
Tuscola	MI	POET Biorefining—Caro	201	8,407	7,762	345	620	0	1.04	8
Pottawattamie	IA	Southwest Iowa renewable energy, LLC	416	8,721	8,561	492	639	0	1.04	16
Merrick	NE	Green plains renewable energy	379	8,658	8,425	284	158	615	1.04	15
Macon	MO	POET Biorefining—Macon	174	9,097	9,727	465	567	0	1.04	7
Audrain	MO	POET Biorefining—laddonia	189	9,097	9,727	465	567	0	1.04	8
Juneau	WI	Castle rock renewable fuels, LLC	189	8,030	6,573	284	458	0	1.04	8
Adams	IA	POET Biorefining—Corning	246	8,783	8,561	492	639	0	1.04	10
Dunn	WI	Western wisconsin energy, LLC	151	8,093	6,573	284	458	0	1.05	7
Buchanan	IA	Hawkeye renewables, LLC	416	8,846	8,561	492	639	0	1.05	18

Table 5 continued

Biorefinery data				County data					EROI	Net energy
County	State	Operator	EtOH Production 10^6 liters	Yield (kg/Ha)	N (MJ/Ha)	P (MJ/Ha)	K (MJ/Ha)	Irrig. (MJ/Ha)		
Butler	IA	Hawkeye renewables, LLC	416	8,846	8,561	492	639	0	1.05	18
Stephenson	IL	Adkins energy, LLC	151	9,097	8,888	585	870	0	1.05	7
Jasper	IN	Iroquois Bio-energy company, LLC	151	9,160	8,985	583	951	0	1.05	7
Gage	NE	E Energy Adams, LLC	189	8,846	8,425	284	158	615	1.05	9
Saline	MO	Mid-Missouri energy, Inc.	189	9,285	9,727	465	567	0	1.05	9
Jay	IN	POET Biorefining—Portland	257	9,222	8,985	583	951	0	1.05	12
Mahaska	IA	Cargill, Inc.	132	8,972	8,561	492	639	0	1.05	6
Floyd	IA	Valero renewable fuels	416	8,972	8,561	492	639	0	1.05	20
Henry	IL	Patriot renewable fuels, LLC	379	9,222	8,888	585	870	0	1.05	19
Henry	IL	Big river resources Galva, LLC	379	9,222	8,888	585	870	0	1.05	19
Chickasaw	IA	Homeland energy	379	9,034	8,561	492	639	0	1.05	19
Jackson	MN	Heron lake Bioenergy, LLC	189	8,972	8,477	459	543	0	1.05	10
Yellow medicine	MN	Granite falls energy, LLC	197	8,972	8,477	459	543	0	1.05	10
Green	WI	Badger state ethanol, LLC	182	8,281	6,573	284	458	0	1.05	9
Putnam	OH	POET Biorefining—Leipsic	257	9,536	9,850	571	769	0	1.05	13
Carroll	MO	Show Me ethanol	208	9,411	9,727	465	567	0	1.05	11
Fulton	IL	Riverland biofuels	140	9,348	8,888	585	870	0	1.06	8
Republic	KS	Nesika energy, LLC	38	9,034	8,304	290	280	439	1.06	2
Muscatine	IA	Grain processing corp.	76	9,160	8,561	492	639	0	1.06	4
Chippewa	WI	ACE ethanol, LLC	155	8,407	6,573	284	458	0	1.06	9
Hardin	IA	Pine lake corn processors, LLC	117	9,222	8,561	492	639	0	1.06	7
Hardin	IA	Hawkeye renewables, LLC	341	9,222	8,561	492	639	0	1.06	19

Table 5 continued

Biorefinery data				County data					EROI	Net energy
County	State	Operator	EtOH Production 10^6 liters	Yield (kg/Ha)	N (MJ/Ha)	P (MJ/Ha)	K (MJ/Ha)	Irrig. (MJ/Ha)		
Greene	IA	Louis dreyfus commodities	379	9,222	8,561	492	639	0	1.06	21
Freeborn	MN	POET Biorefining—Glenville	159	9,160	8,477	459	543	0	1.06	9
Waseca	MN	Guardian energy	416	9,160	8,477	459	543	0	1.06	24
Cerro Gordo	IA	Golden grain energy, LLC	435	9,348	8,561	492	639	0	1.06	27
Dawson	NE	Cornhusker energy Lexington, LLC	151	9,285	8,425	284	158	615	1.07	9
Dakota	NE	Siouxland ethanol, LLC	189	9,285	8,425	284	158	615	1.07	12
Boone	NE	Valero renewable fuels	416	9,285	8,425	284	158	615	1.07	25
Blue Earth	MN	POET Biorefining—Lake crystal	212	9,285	8,477	459	543	0	1.07	13
Grant	IN	Central Indiana ethanol, LLC	151	9,662	8,985	583	951	0	1.07	9
Sioux	IA	Siouxland energy and livestock Coop	227	9,411	8,561	492	639	0	1.07	14
Fillmore	MN	POET Biorefining—Preston	174	9,348	8,477	459	543	0	1.07	11
Ogle	IL	Illinois river energy, LLC	379	9,662	8,888	585	870	0	1.07	24
Rock	WI	United ethanol	197	8,658	6,573	284	458	0	1.07	13
Dickinson	IA	Green plains renewable energy	208	9,473	8,561	492	639	0	1.07	14
O'Brien	IA	Valero renewable fuels	416	9,473	8,561	492	639	0	1.07	27
Morrill	NE	Bridgeport ethanol	204	9,411	8,425	284	158	615	1.07	13
Lincoln	NE	Midwest renewable energy, LLC	95	9,473	8,425	284	158	615	1.07	6
Madison	IN	POET Biorefining—Alexandria	257	9,850	8,985	583	951	0	1.07	17
Faribault	MN	Corn Plus, LLP	167	9,536	8,477	459	543	0	1.07	12
Kandiyohi	MN	Bushmills ethanol, Inc.	189	9,536	8,477	459	543	0	1.07	13
Redwood	MN	Highwater ethanol LLC	208	9,536	8,477	459	543	0	1.07	14
Palo Alto	IA	POET Biorefining—Emmetsburg	208	9,662	8,561	492	639	0	1.08	15

Table 5 continued

Biorefinery data				County data					EROI	Net energy
County	State	Operator	EtOH Production 10^6 liters	Yield (kg/Ha)	N (MJ/Ha)	P (MJ/Ha)	K (MJ/Ha)	Irrig. (MJ/Ha)		
Osceola	IA	POET Biorefining—Ashton	212	9,662	8,561	492	639	0	1.08	15
Putnam	IL	Marquis energy, LLC	379	9,913	8,888	585	870	0	1.08	27
Darke	OH	The Andersons marathon ethanol, LLC	416	10,226	9,850	571	769	0	1.08	30
Wright	IA	Corn, LP	227	9,724	8,561	492	639	0	1.08	17
Lincoln	SD	POET Biorefining—Hudson	212	8,972	6,891	334	194	38	1.08	16
Swift	MN	Chippewa Valley ethanol Co.	170	9,724	8,477	459	543	0	1.08	13
Grant	SD	POET Biorefining—Big stone	299	9,034	6,891	334	194	38	1.08	23
Story	IA	Lincolnway energy, LLC	208	9,850	8,561	492	639	0	1.08	16
Pierce	NE	Husker Ag, LLC	284	9,787	8,425	284	158	615	1.08	22
Martin	MN	BioFuel energy—buffalo lake energy, LLC	435	9,787	8,477	459	543	0	1.08	33
Kossuth	IA	Global ethanol/midwest grain processors	371	9,913	8,561	492	639	0	1.08	29
Washington	NE	Cargill, Inc.	322	9,850	8,425	284	158	615	1.09	25
Hall	NE	BioFuel energy—pioneer trail energy, LLC	435	9,850	8,425	284	158	615	1.09	34
Columbia	WI	Didion ethanol	151	9,097	6,573	284	458	0	1.09	12
Columbia	WI	United WI grain producers, LLC	185	9,097	6,573	284	458	0	1.09	15
Rock	MN	Agri-energy, LLC	79	9,913	8,477	459	543	0	1.09	6
Hale	TX	White energy	416	10,038	8,924	339	141	383	1.09	34
Webster	IA	POET Biorefining—Gowrie	261	10,038	8,561	492	639	0	1.09	21
Logan	CO	Sterling ethanol, LLC	159	9,787	7,861	268	139	690	1.09	13
Fillmore	NE	Advanced bioenergy, LLC	379	10,038	8,425	284	158	615	1.09	32
Adams	NE	AGP	197	10,101	8,425	284	158	615	1.09	17
Codington	SD	Glacial lakes energy, LLC	379	9,411	6,891	334	194	38	1.10	33

Table 5 continued

Biorefinery data				County data					EROI	Net energy
County	State	Operator	EtOH Production 10^6 liters	Yield (kg/Ha)	N (MJ/Ha)	P (MJ/Ha)	K (MJ/Ha)	Irrig. (MJ/Ha)		
Brookings	SD	Valero renewable fuels	454	9,473	6,891	334	194	38	1.10	40
Richland	ND	Hankinson renewable energy, LLC	416	9,662	7,396	338	189	44	1.10	37
Weld	CO	Front range energy, LLC	151	10,101	7,861	268	139	690	1.10	14
Sibley	MN	Heartland corn products	379	10,352	8,477	459	543	0	1.10	35
Holt	NE	NEDAK ethanol	167	10,665	8,425	284	158	615	1.11	17
Kearney	NE	KAAPA ethanol, LLC	151	10,728	8,425	284	158	615	1.11	15
Cass	ND	Tharaldson ethanol	416	10,164	7,396	338	189	44	1.11	43
Beadle	SD	Heartland grain fuels, LP	121	9,975	6,891	334	194	38	1.11	12
Rice	KS	Kansas ethanol, LLC	208	10,916	8,304	290	280	439	1.12	23
Perkins	NE	Mid America Agri products/wheatland	167	11,042	8,425	284	158	615	1.12	18
Spink	SD	Redfield energy, LLC	189	10,603	6,891	334	194	38	1.13	22
Lake	SD	Dakota ethanol, LLC	189	10,665	6,891	334	194	38	1.14	23
Washington	CO	Yuma ethanol	151	11,544	7,861	268	139	690	1.14	19
Seward	KS	Arkalon energy, LLC	416	11,920	8,304	290	280	439	1.15	54
Brown	SD	Heartland grain fuels, LP	189	11,481	6,891	334	194	38	1.16	26
Brown	SD	POET Biorefining—Groton	201	11,481	6,891	334	194	38	1.16	28
Bon Homme	SD	POET Biorefining—Scotland	42	12,046	6,891	334	194	38	1.17	6
Phillips	KS	Prairie Horizon Agri-energy, LLC	151	13,112	8,304	290	280	439	1.18	23

Rows are ranked by increasing EROI

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