New Perspectives on the Energy Return on (Energy) Investment (EROI) of Corn Ethanol: Part 1 of 2

Posted by David Murphy on July 26, 2010 - 10:30am in The Oil Drum: Net Energy

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The following is the first of two posts based on a recent paper published under the same title in the journal Environment, Development, and Sustainability. The paper is divided into five sections, and to keep each post succinct, we have divided the paper into two posts. The first post will present the first two sections of the research and the second post will present the last three sections and the conclusions of the research.

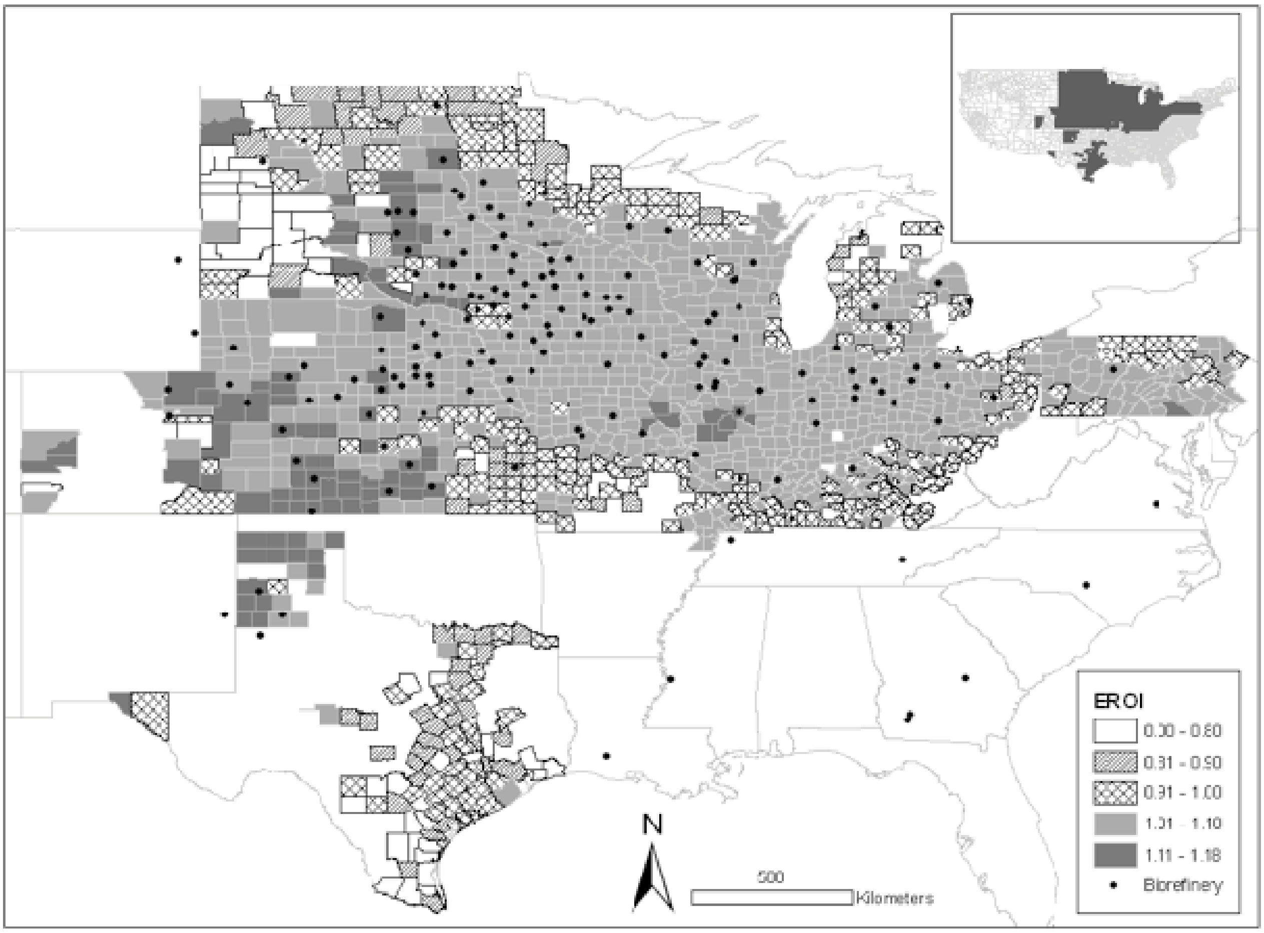


Fig. 2. Map of the EROI of corn ethanol production for counties within states that produced at least 1% of the corn harvest in 2005, and biorefinery locations.

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; Wang 2001; Shapouri et al. 2002; Graboski 2004; Shapouri 2004; Oliveira et al. 2005; Farrell et al. 2006; Wang et al. 2007). 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 more 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 above, 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 U.S.

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. This analysis was based on the five main studies in corn ethanol: Wang et al. (1997), Shapouri et al. (2002), Pimentel (2003), Patzek (2004), and Farrell et al. (2006). The second was a spatial analysis of the EROI of corn ethanol. It is these two items that are discussed in Part 1.

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. These items are discussed in Part 2, which is a separate post.

Results

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 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).

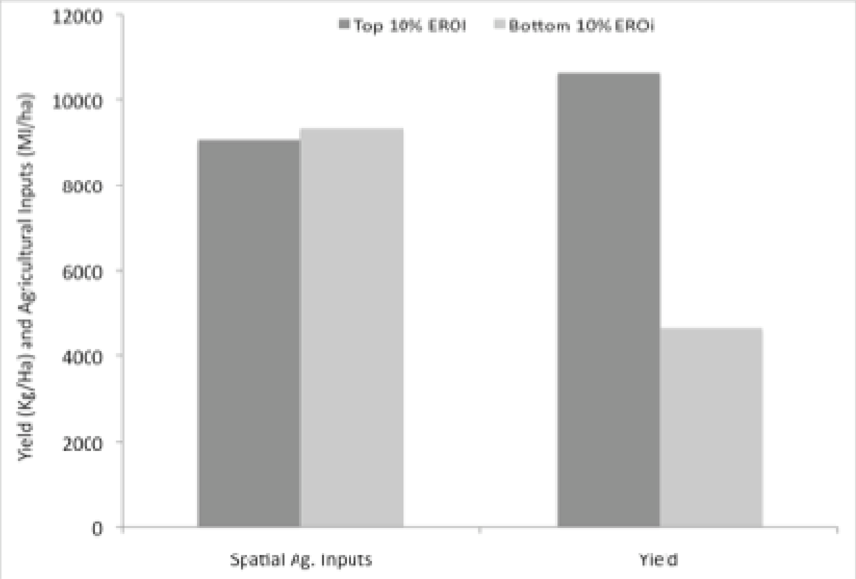


Fig. 4. Average values for spatial agricultural inputs and corn yield for counties with EROI values within the top and bottom 10% of all counties.

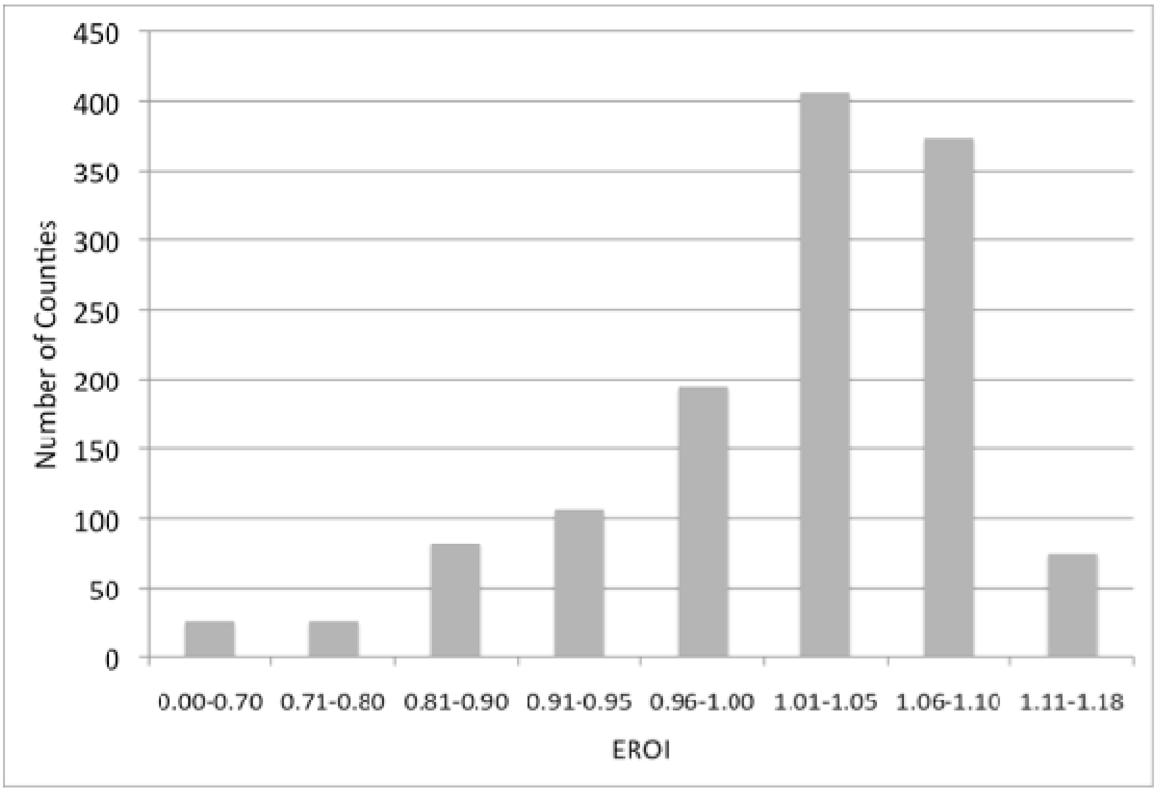
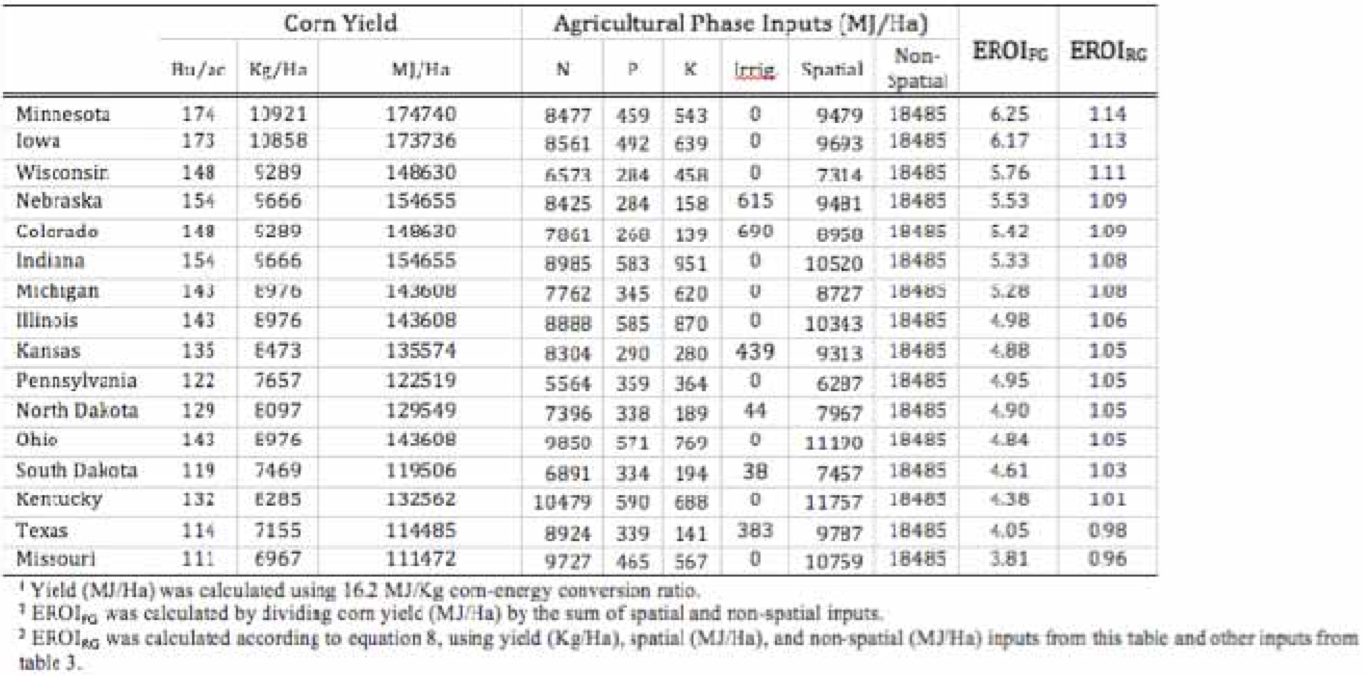


Fig. 3. Histogram of number of counties vs. EROI.

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. $EROI_{FG}$ (EROI "Farm Gate") ranged from 3.81 to 6.25, while $EROI_{RG}$ (EROI "Refinery Gate") 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).



	Corn Yield			Agricultural Phase Inputs (MJ/Ha)						$EROI_{FG}$	$EROI_{RG}$
	Bu/ac	Kg/Ha	MJ/Ha	N	P	K	Irrig.	Spatial	Non-Spatial		
Minnesota	174	10921	174740	8477	459	543	0	9479	18485	6.25	1.14
Iowa	173	10858	173736	8561	492	639	0	9693	18485	6.17	1.13
Wisconsin	148	9289	148630	6573	284	458	0	7314	18485	5.76	1.11
Nebraska	154	9666	154655	8425	284	158	615	9481	18485	5.53	1.09
Colorado	148	9289	148630	7861	260	139	690	8950	18485	5.42	1.09
Indiana	154	9666	154655	8985	583	951	0	10520	18485	5.33	1.08
Michigan	143	8976	143608	7762	345	620	0	8727	18485	5.28	1.08
Illinois	143	8976	143608	8888	585	870	0	10343	18485	4.98	1.06
Kansas	135	8473	135574	8304	290	280	439	9313	18485	4.88	1.05
Pennsylvania	122	7657	122519	5564	359	364	0	6287	18485	4.95	1.05
North Dakota	129	8097	129549	7396	338	189	44	7967	18485	4.90	1.05
Ohio	143	8976	143608	9850	571	769	0	11190	18485	4.84	1.05
South Dakota	119	7469	119506	6891	334	194	38	7457	18485	4.61	1.03
Kentucky	132	8285	132562	10479	590	688	0	11757	18485	4.38	1.01
Texas	114	7155	114485	8924	339	141	383	9787	18485	4.05	0.98
Missouri	111	6967	111472	9727	465	567	0	10759	18485	3.81	0.96

[1] Yield (MJ/Ha) was calculated using 16.2 MJ/Kg corn-energy conversion ratio.

[2] $EROI_{FG}$ was calculated by dividing corn yield (MJ/Ha) by the sum of spatial and non-spatial inputs.

[3] $EROI_{RG}$ was calculated according to equation 8, using yield (Kg/Ha), spatial (MJ/Ha), and non-spatial (MJ/Ha) inputs from this table and other inputs from table 3.

Table 4. 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 EROIRG.

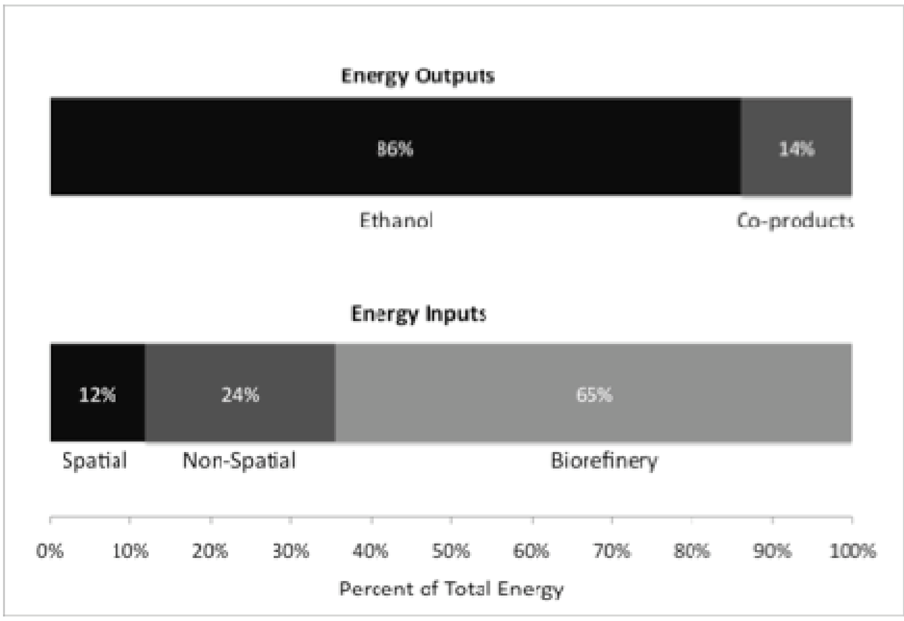


Fig. 5. Relative mix of inputs (spatial agricultural inputs, non-spatial agricultural inputs, biorefinery phase) and outputs (ethanol and co-products) of corn ethanol production.

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.

Equation 2. Gross amount of energy required to deliver one unit of net energy = EROI/(EROI-1)

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 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%).

New Perspectives on the Energy Return on (Energy) Investment (EROI) of Corn Ethanol: Part 2 of 2

Posted by David Murphy on August 9, 2010 - 10:30am in The Oil Drum: Net Energy

The following is the second of two posts based on a recent paper published under the same title in the journal Environment, Development, and Sustainability. I was the lead author for the article. The other two authors were Charles Hall and Bobby Powers. Part 1 of this series can be found at this link.

In the analysis underlying our paper "New Perspectives on the Energy Return on (Energy) Investment (EROI) of Corn Ethanol," we performed four major analyses relating to the EROI of corn ethanol. 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 spacial analysis of the EROI of corn ethanol. These two items were discussed in Part 1 of this series.

In this part, we will discuss a two additional research areas from the paper. These two additional research areas are:

A sensitivity analysis, in which we assess the extent to which corn yields and co-product credits impact the EROI of corn ethanol.

An assessment of how much net energy was delivered to society by ethanol in 2009.

We have also included our more general conclusions.

Sensitivity Analysis: Corn Yields

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.

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.

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 $EROI_{RG}$ (EROI "Refinery Gate") 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.

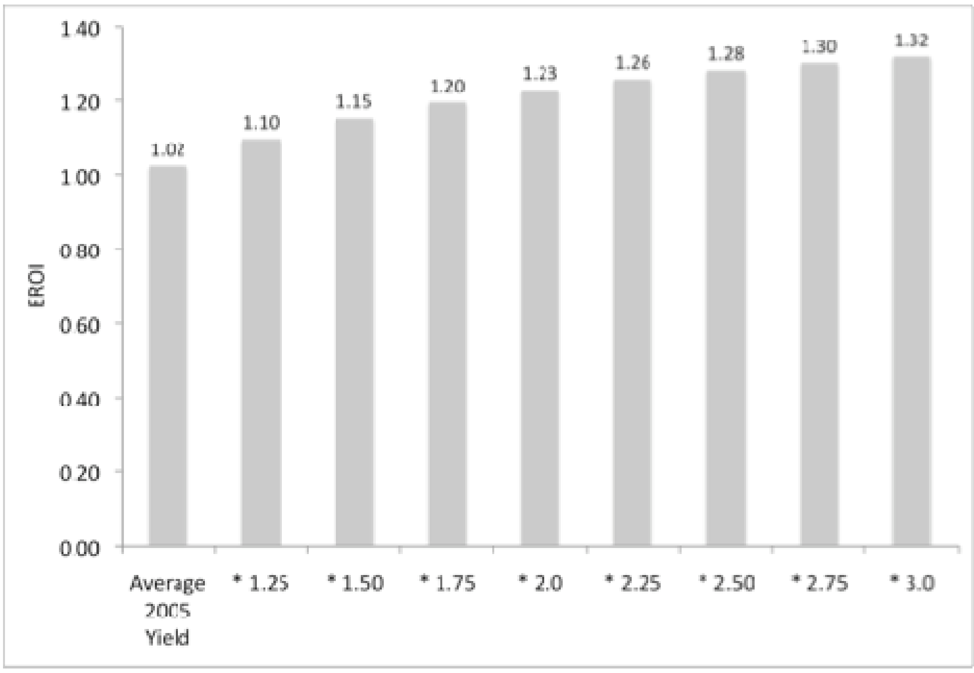


Fig. 6. EROI as a function of increasing yield. Average 2005 yield (8795 Kg/Ha) was multiplied by the values listed across the x-axis for each respective calculation.

Sensitivity Analysis: Co-Product Credits

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), Shapouri et al. (2002), Farrell et al. (2006), and Wang et al. (2007) 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.

To assess how sensitive the calculation of EROI is to changes in co-product credits, we performed three calculations. We first calculated the EROILIT 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."

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 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.

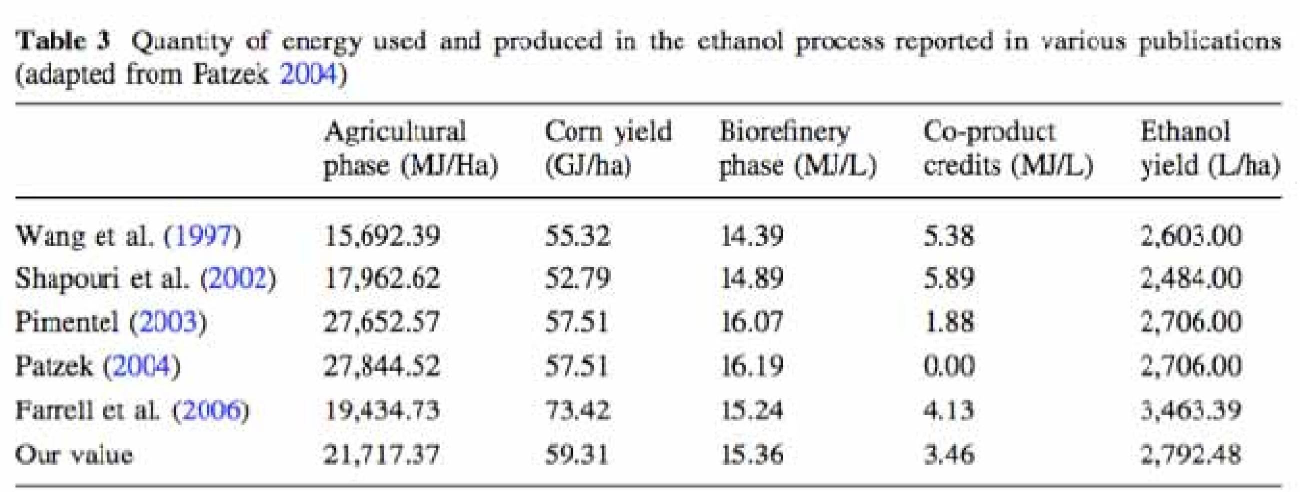


Table 3 Quantity of energy used and produced in the ethanol process reported in various publications (adapted from Patzek 2004)

	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

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

Net Energy Returned to Society by Ethanol

As I wrote in this post, low EROI resources deliver a low amount of net energy to society because much of the energy extracted is required to run the energy extraction process. Comparing the gross energy produced from ethanol to that from gasoline is hence misleading. In the paragraph below we compare the net energy produced from ethanol to that produced from oil each year in the U.S.

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 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%).

Conclusions

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 $EROI_{RG}$ 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.