Introduction

Conventional Corn Ethanol

The use of corn ethanol as a transportation fuel has generated a great deal of controversy [1, 2]. Although ethanol offers the possibility of a low-carbon liquid transportation fuel derived from domestic resources [3, 4], legitimate concerns have been raised about the energy and environmental intensity of the production processes used [2, 5]. The primary environmental concerns pertain to the agricultural methods employed in feedstock production1, however these are essentially criticisms of conventional agriculture, not of ethanol itself.

Recent research suggests that crop production in the US causes between 2002 $5-16 billion annually ($30-96 per hectare) in damages to human and environmental health, through damage to air, water, and soil resources, and by reducing biodiversity [6]. Corn (Zea mays L.) is the largest crop in the US by acreage [7], and receives the most fertilizer and pesticide per unit area of all major crops [8]. A substantial fraction of the total harm caused by US agriculture is therefore attributable to corn production.

Corn is also the predominant ethanol feedstock, accounting for well over 90% of current domestic ethanol capacity [9]. While recent studies have considered reduced tillage methods to improve the life-cycle benefits of corn ethanol [10, 11], none has considered producing corn using agroecological principles.

As a high-input crop, corn is not the ideal biofuel feedstock. Commercial technology currently utilizes only the easily fermentable starch fraction for ethanol production. Perennial crops such as switchgrass (Panicum virgatum L.) offer greater energetic and environmental benefits, but the enzymes required to convert recalcitrant lignocellulosic materials to fermentable sugars have remained too costly for commercial-scale production [12]. This may change soon, however, as two enzyme companies recently announced thirty-fold cost reductions for the requisite enzymes, and another firm is currently raising funds for a commercial-scale cellulosic ethanol facility in western Canada [13].

Subsidies at both the federal and state level, as well as concerns about energy security, have spurred major investment in US corn ethanol production facilities. Domestic ethanol capacity has doubled capacity in the past four years to more than 4 billion gallons per year, with another 1.2 billion gallons per year of capacity under construction. [9]. This trend will likely continue in order to meet the renewable fuels standard of the Energy Policy Act of 2005, which requires increasing levels of renewable fuels in the domestic transport fuel supply through 2012 [14].

Given this large capital investment in corn ethanol production facilities, corn will continue to be produced as an ethanol feedstock well past 2012. Although breakthroughs

1 The conversion of biomass to ethanol in the biorefinery also impacts the environment, producing CO₂ and high-BOD effluent water. Technical solutions to these problems are feasible, and in the case of process water, and even may be economic. These topics, however, are beyond the scope of this paper.
in lignocellulosic conversion will allow corn stover to be utilized as well—doubling the biomass yield per unit area—the environmental impacts of corn production remain a serious concern.

**Alternative Performance Indicators and Agronomic Practices**

At this time, no comprehensive set of indicators exists to compare ethanol production systems with alternative agricultural and fuel options. In addition to greenhouse gas emissions and energetics, ethanol has potential positive and negative agroecosystem impacts including soil erosion, soil quality, water quality, biodiversity, farmer income and equity, urban air quality, federal budgets, and more. Ideally, each of these considerations would be incorporated into a calculable metric, with acceptable and desirable value ranges determined through a public process involving all stakeholders.

Despite the lack of a comprehensive approach, several recent studies have expanded the life cycle analysis of corn-based ethanol to consider a broader array of environmental concerns. Sheehan, et al. consider the energy, climate, air quality, and soil erosion impacts of no-till corn production resulting from various levels of corn stover removal [11]. They use USDA-defined “tolerable” soil loss limits as a constraint on stover removal to explore the tradeoff between increasing soil carbon by leaving residues in the field, and avoiding fossil carbon emissions by displacing gasoline use with ethanol.

Kim and Dale have modeled the global warming, eutrophication, and acidification potentials from four biofuel production systems using no-till cultivation, including a corn-soybean rotation and three continuous corn systems with varying degrees of stover removal [10]. In these systems, the corn kernels and stover (where collected) are used to produce ethanol, and the soybeans are used to produce biodiesel.

As we begin to measure the broader ecological and social impacts of ethanol production and use, it is appropriate to consider as well a broader array of agricultural practices. There are a number of agroecologically preferred production methods that could be or currently are being practiced in the US. In 1996, almost 60% of US corn was grown in rotation with legumes, reaching 82% in the corn belt [15]. Nearly 16 million acres of corn were grown under no-till cultivation in 2004 [16], amounting to 21.5% of all corn planted that year. However only 0.13% of all corn grown in 2003 was produced organically [17]. Organic production may involve a number of different practices adapted to specific sites and resources, such as long rotations, intercropping, cover-cropping, green manures, compost application, biological pest control, and more. While the common two-year rotation between corn and soy somewhat reduces the need for synthetic fertilizers and pesticides, these systems still rely primarily on industrial agrochemical inputs as the primary fertilization and pest control schemes. The same is true of no-till methods, which greatly improve soil carbon and reduce erosion, but as commonly practiced, remain dependent on herbicides for weed management [18].

Every study we have seen examining the energetic and environmental aspects of fuel ethanol presupposes conventional agriculture. While a few studies consider reduced tillage or cover crops, none considers alternatives to industrial pesticide and fertilizer—
two factors contributing heavily to the external environmental costs of agriculture. Thus the published literature has focused on the most common alternatives to conventional agriculture, while ignoring other practices offering even greater agroecological benefits.

**Methodological Difficulties in Comparing Yields across Systems**

A primary reason why agroecological methods are not employed is the expectation of reduced yield in the target crop due to lower N fertilization levels and greater anticipated pest pressure.\(^2\) Another factor is the tendency in agroecological systems toward longer rotations: conventional corn is typically grown in annual rotation with soybeans\(^3\), whereas organic practices may use 3- and 4-year rotations such as corn-soybean-oats/alfalfa and corn-soybean-oats/alfalfa-alfalfa, greatly reducing the average annual corn yield.

The question of yield reduction is difficult to answer in any general way. Although many studies have compared organic and conventional production practices, both systems include a range of tillage and pest management practices. Moreover, differences in geography, temperature, precipitation, soil type, rotation constituents, rotation lengths, land use history, farmer knowledge, and the biodiversity of the surrounding area make it very difficult to generalize or even to compare studies.

Numerous studies have compared conventional agricultural methods with a range of alternatives. These include no-till, cover cropping, low input, organic, or biodynamic till [19-21]. The comparisons have explored several dimensions, including yield, energy, biodiversity, soil changes, greenhouse gas (GHG) fluxes, and profitability [22-29].

Organic yields can be nearly as high, or even higher than conventional, depending on crops, weather, and specific practices. Delate et al. found no loss of yield during the transition from conventional to organic production, and reports increased yields post-transition [26]. Reganold reports similar yields in conventional and organic apple production systems [29]. Other studies found that organic practices reduced yield, although the magnitude of the loss varied by crop [19, 30, 31].

Pimentel reports on a 22-years study by the Rodale Institute showing similar corn and soybean yields between organic and conventional systems [27]. This study, however, exemplifies the difficulty of comparing yield between dissimilar rotations: the conventional system employed a five-year corn-soybean rotations (C-C-S-C-S), whereas the organic animal-based system used a rotation including corn, soybean, corn silage, wheat, and red clover-alfalfa hay, as well as a rye cover crop.\(^4\) So while corn yields were similar between the two systems, the conventional system produced far more corn on an annual basis.

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\(^2\) The other factors are increased complexity and knowledge intensity, which are not addressed herein.

\(^3\) Five-year corn-corn-soybean-corn-soybean rotations are also used, but this pattern varies little from the simple corn-soybean rotation.

\(^4\) The paper does not provide the precise details of the rotation.
This same phenomenon is seen in Delate’s NK-LTAR study comparing conventional corn-soy with organic corn-soybean-oats/alfalfa and corn-soybean-oats/alfalfa-alfalfa rotations. The longer organic rotation with an extra year of alfalfa results in corn yields comparable to the conventional system—but corn is produced half as frequently [26, 28].

Crops used as green manure, or to feed animals that produce manure, effectively “subsidize” the cash crops. A whole-system perspective would provide a more robust comparison between these systems. Kim and Dale take precisely this approach in comparing tillage systems for corn ethanol production, simulating net petroleum use and GHG emissions over 40 years of production under each cropping system [10].

Studies of corn ethanol net energy value (NEV) typically utilize data that is averaged across the US or across the major corn producing states for yield, fertilizer and pesticide rates, primary energy consumption, and so on. As such, these studies characterize recent “average” agronomic and ethanol production processes. However, the lack of data on a large set of organic corn farms and the site-specific nature of fertility and pest management schemes in organic agriculture do not permit such an analysis. Alternatively, it is possible to compare particular organic and conventional practices within experimentally matched plots. This type of analysis attempts to show that an organic production system exists which can outperform the conventional practice on key indicators within a specific ecological and social context. The degree to which such an analysis can be generalized is a matter of discussion. Furthermore, even these comparisons have been questioned as possibly biased, comparing highly optimized organic plots against “off-the-shelf” conventional technology [32].

Despite the difficulties in directly comparing conventional and alternative systems, the potential for equivalent yields under more ecologically sound agronomic methods indicates that organically produced corn ethanol clearly deserves further study.

**Methods**

Our study compares the life cycle net energy value (NEV), petroleum consumption, and greenhouse gas (GHG) emissions for the production of corn ethanol under two agronomic systems: a conventional corn-soybean rotation and an organic corn-soybean-oats rotation utilizing cover crops of rye and alfalfa. The conventional system relies primarily on agrochemical inputs for fertility and pest management, whereas the organic system utilizes composted manure for fertility and mechanical row-cultivation combined with the occasional use of a flame cultivator for pest control. A longer rotation of corn, soybeans and oats presumably contributes to fertility and pest management goals as well. Our analysis relies on published reports from the Neely-Kinyon Long Term Agricultural Research (NK-LTAR) experiment in Iowa, which compares various organic and conventional rotation systems involving corn [26].

To perform this analysis, we use EBAMM (ERG Biofuels Analysis Meta-Model), a simple life cycle ethanol production model developed by the authors with faculty and students of the Energy and Resources Group and Goldman School of Public Policy at UC Berkeley [33]. The model was developed to explore the wide range of net energy values
for corn ethanol reported in the literature, and is easily parameterized to accommodate non-conventional production practices.

Consistent with the literature on ethanol production, our life cycle analysis of corn ethanol considers only those agricultural practices and inputs directly associated with corn production. The rotational context does impact our analysis, however, by changing the yield and external nitrogen demands of corn via pest interactions, nitrogen fixation, soil organic carbon content, and so on. A more holistic approach would consider the entire rotation as a single system producing many coproducts of which corn ethanol is just one. Such an analysis, however, is beyond the scope of the current study.

Unlike the literature on conventional corn ethanol production that uses statistical averages of corn production, we focus on specific production practices at a single site in Iowa. Because our data is drawn from a research site, several on-farm energy inputs typically accounted for in the ethanol literature are not present at Neely-Kinyon. These include electricity and natural gas for farm facilities among others. Where required, we fill these data gaps using the values adopted in the “Ethanol Today” case in EBAMM [33] based on the best-documented parameters available in the published literature. Although the inclusion of these values permits a comparison between the NK systems and the “statistical” systems reported elsewhere, the NK systems represent only one specific site and should be considered indicative only.

Data for agronomic inputs and practices are taken from annual reports of the Neely-Kinyon LTAR experiment [26], which provide detailed accounts of all field operations and input rates, except diesel fuel consumption.\(^5\) We use average data from the years 2000-2004, excluding 1998-1999 to allow for a transition effect and because somewhat different management practices were employed in the first two years. We estimate diesel consumption for field operations and manure transportation using the average monitored values reported by Dalgaard, et al. [31] who compared reported fuel consumption estimates from the literature with monitored usage on private Danish farms.

Embodied energy values for pesticides and commercial fertilizers are taken from the EBAMM “Ethanol Today” case [34]. Embodied energy in swine manure is taken from McLaughlin, et al. [35], who treat manure as wasteproduct rather than a coproduct of swine farming. Thus all of the energy embodied in swine manure is assumed to result from composting activities, transportation, and application in the field, not from swine farming itself.\(^6\)

Although the swine manure used the Neely-Kinyon LTAR study is actually transported 60 miles from the university’s experimental deep-bedded hoop house, organic producers in the region tend to produce manure on-farm [36]. In order to reflect this practice, we

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\(^5\) We finally reached Kathleen Delate on Friday 12/16/05, and received a spreadsheet containing diesel usage data. We regret that time constraints did not permit us to integrate this data into our analysis.

\(^6\) We were unable to find an energy value for turning the compost, so the embodied energy value for manure may be low. However, we assume 5 miles of transport, which would be high if prevailing practices include animal integration.
chose a transport distance of only five miles to reflect a more locally-based manure economy.

Data for post-farm aspects of ethanol production are taken from the “Ethanol Today” case in EBAMM [37].

**Results**

Our results are summarized in Table 1. Gasoline values are included for comparison. Ethanol from the organic system has a higher NEV, indicating that less non-renewable energy is used in its production. However, a significantly larger portion of that energy comes from petroleum. This result can be attributed to increased use of LPG and diesel fuel for weed control operations including mechanical tillage and flame cultivation, as well as significant energy expended transporting manure to the farm. Producing the manure locally (simulated by setting the transport distance to zero) reduces per MJ petroleum use by more than half. The life-cycle greenhouse gas emissions are marginally lower for the organic system, indicating that processes associated with the production and application of agrochemical inputs are more greenhouse intensive than the increased tillage and manure transport in the organic system.

Table 1: Primary Ethanol Metrics for Corn Produced at the Neely-Kinyon LTAR

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Organic (a)</th>
<th>Organic (b)</th>
<th>Gasoline*</th>
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<tbody>
<tr>
<td><strong>Net Energy Value</strong></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>(MJ / L ethanol)</td>
<td>6.3</td>
<td>7.2</td>
<td>8.1</td>
<td>-0.2</td>
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<tr>
<td><strong>Petroleum Use</strong></td>
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<tr>
<td>(MJ petroleum / MJ ethanol)</td>
<td>0.01</td>
<td>0.07</td>
<td>0.03</td>
<td>1.11</td>
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<tr>
<td><strong>GHG Emissions</strong></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>(g CO2e / MJ ethanol)</td>
<td>66</td>
<td>56</td>
<td>53</td>
<td>94</td>
</tr>
</tbody>
</table>

*Gasoline values from EBAMM [37].

**Discussion**

Producing ethanol from organic corn seems to be a promising alternative to conventionally produced ethanol. The organic system that we analyzed yields modest improvements in net energy and greenhouse gas emissions over an experimentally matched conventional control system. However, the organic system is associated with a significantly larger use of petroleum energy. Comparing each of these ethanol fuel systems to conventional gasoline, though, we see that the organic system is still a major improvement from the perspective of achieving a low petroleum fuel supply. Previous studies have found that greenhouse gas emissions associated with corn ethanol are equivalent or only marginally better than gasoline [37]. Thus our finding that both conventional and organic ethanol from the NK-LTAR site offer reductions in greenhouse gas emissions relative to gasoline is significant. Furthermore, the marginal improvement in greenhouse gas emissions under organic practices indicates that corn ethanol at other locations might be improved by switching to organic methods, especially if manure is produced on-site.

We have only considered three indicators commonly reported in the current ethanol literature. The organic system is likely to be associated with greatly improved soil and
water quality, biodiversity impacts, etc. As mentioned above, a more comprehensive set of sustainable agriculture and sustainable fuel indicators would facilitate the evaluation of all of the important tradeoffs inherent in alternative biofuel production methods.

The finding that organic corn ethanol is more petroleum intensive than conventional ethanol—even with manure produced on-site—suggests areas of potential improvement in the organic system. Rather than relying only on flame and mechanical row cultivation for weed control, organic corn production could utilize a spatial polyculture, growing beneficial understory plants such as beans and squash to crowd out potential weeds. Further research is needed to determine how such a system would work in a context-specific way while maintaining high corn yields for ethanol production. Finding methods to minimize petroleum use in organic corn, such as by increasing biodiesel use, would be an important first step. In addition, the transportation of large amounts of manure (even for 5 miles) was a large contribution to the petroleum use of the organic system. Integrating corn production with animal production and minimizing the transportation of manure would further improve petroleum consumption.

The context-specific nature of agroecologically sensitive farming is a barrier to generalizing our results. Because the organic system that we chose to analyze is essentially an input-substitution method, we feel that it could be applied at a larger scale throughout the Midwest. Our research suggests that doing so would likely offer improvements in the life-cycle greenhouse gas emissions of ethanol while still providing a fuel that utilizes much less petroleum than gasoline.

Other important issues must be addressed for the scale-up of organic production. The longer temporal rotation of corn with soybeans and oats would mean a significant shift in the total mix of crops grown in the Midwest. Currently, oat acreage in Iowa is less than 2% of corn acreage [38], but the scale-up of this particular organic system would require roughly equal acres of corn and oats. While some degree of substitutability of different grains is possible (e.g. as animal feed), the yield of oats is lower than that of corn and the nutritional qualities differ as well. Performing such a shift would require a re-evaluation of the various uses of commodity grains and legumes, and public policy would be required to funnel resources into those uses that produce the most societal and ecological benefits.

**Conclusion**

The organic corn production system at the NK-LTAR site could be used to produce ethanol that yields a higher net energy value and produces lower life-cycle greenhouse gas emissions compared to the conventional system employed at the same site. This suggests the possibility of improving net energy value and greenhouse gas emissions of corn ethanol by employing organic methods at a larger scale.

However, the organic system was associated with increased petroleum use, and further research is needed to minimize this impact through less mechanically intensive pest control practices and reduced manure transportation distances. Nonetheless, ethanol produced from the organic system uses much less petroleum per MJ than gasoline, and so
still offers improvements compared to the dominant transportation fuel used in the US. Additional indicators are needed to compare organic and conventional ethanol production in a broader context of ecological and social sustainability.

Finally, scaling-up organic corn production in the Midwest will involve major changes in the mix of crops being produced. Effective public policy will be needed to guide this transition and ensure that all agricultural products, including ethanol, are associated with social and ecological benefits to greatest extent possible.

References

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