Biofuels and sustainable development:
Perspectives on the farm and around the globe

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Chapter 1 is a review article for which I was sole author. The three core research chapters in thesis were not done in isolation. My collaborators, along with publication status for each chapter, are indicated below:

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Chapter 4. Opportunities for reducing the global land footprint of pasture

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Dedication

To my wife Barbara, for enduring a long and difficult five years, and never giving up on me. Her love is what sustains me.

Abstract

The idea that biofuels can be sustainable has long been controversial. This research considers three land-related aspects of biofuels sustainability:

1. The effect of local farm management practices on the sustainability of land used to produce corn grain as a biorefinery feedstock.
2. The relative sustainability of land used for producing corn and sugarcane as a function of latitude.
3. The land use implications for biofuels of global pasture-based livestock production systems.

Local corn farm management choices can make the difference between net negative and net positive carbon footprints for grain delivered to biorefineries. Carbon footprints reported here are based on full life cycle assessments of each farm, including modeled soil emissions of greenhouse gases. For a cohort of farmers surveyed in southwest Minnesota, avoiding excess fertilizer use, adopting no till practices and replacing commercial fertilizer with animal manure leads to negative carbon footprints of up to -117 gCO_2eq per ha.

Globally, the choice of land managed for corn or sugarcane versus land maintained to support natural ecosystems is highly dependent on latitude. On average sugarcane produces three times more energy per unit area than does maize. Latitudes closer to the equator have higher net primary productivity (NPP), so there is a greater trade-off between biofuel production and ecosystem productivity in the equatorial zones.

Sugarcane is still twice as productive on average compared to maize in the amount of biofuel energy produced per unit of NPP.

Global pasture systems could reduce their land footprint by several-fold simply by closing the gap between poor performing and high performing pasture systems across climatically-similar parts of the world. Because pasture's global land footprint is so large, closing the performance gap could make vast amounts of land available for biomass feedstocks, with no new land clearing.

Table of Contents

List of Tables

List of Figures

Chapter 1. Biofuels and the conundrum of sustainability

Summary

Sustainable energy is *the* problem of the 21st century. If the biofuels industry wants to be part of the solution, it must accept a degree of scrutiny unprecedented in the development of a new industry. That is because sustainability deals explicitly with the role of biofuels in ensuring the well being of our planet, our economy, and our society both today and in the future. Life cycle assessment (LCA) has been the standard framework for assessing sustainability of biofuels. These assessments show that corn ethanol has a marginally lower fossil energy and greenhouse gas footprint compared to petroleum fuel. Sugarcane ethanol and some forms of biodiesel offer substantially lower footprints. New biofuels may offer low footprints. The science of LCA is being stretched to its limits as policy makers consider direct and indirect effects of biofuels on global land and water resources, global ecosystems, air quality, public health and social justice.

Introduction

Coming to terms with biofuels

For policy makers, one of the biggest problems they face in dealing with biofuels is the bewildering number of feedstock and conversion technology combinations that they must consider, as shown in Figure 1. To put this problem in perspective, consider the fact that California regulators have already analyzed twelve different scenarios reflecting the single pathway of growing and converting corn to fuel ethanol as part of the ongoing regulatory effort in support of California's Low Carbon Fuel Standard. And their analyses are by no means comprehensive (CARB 2009).

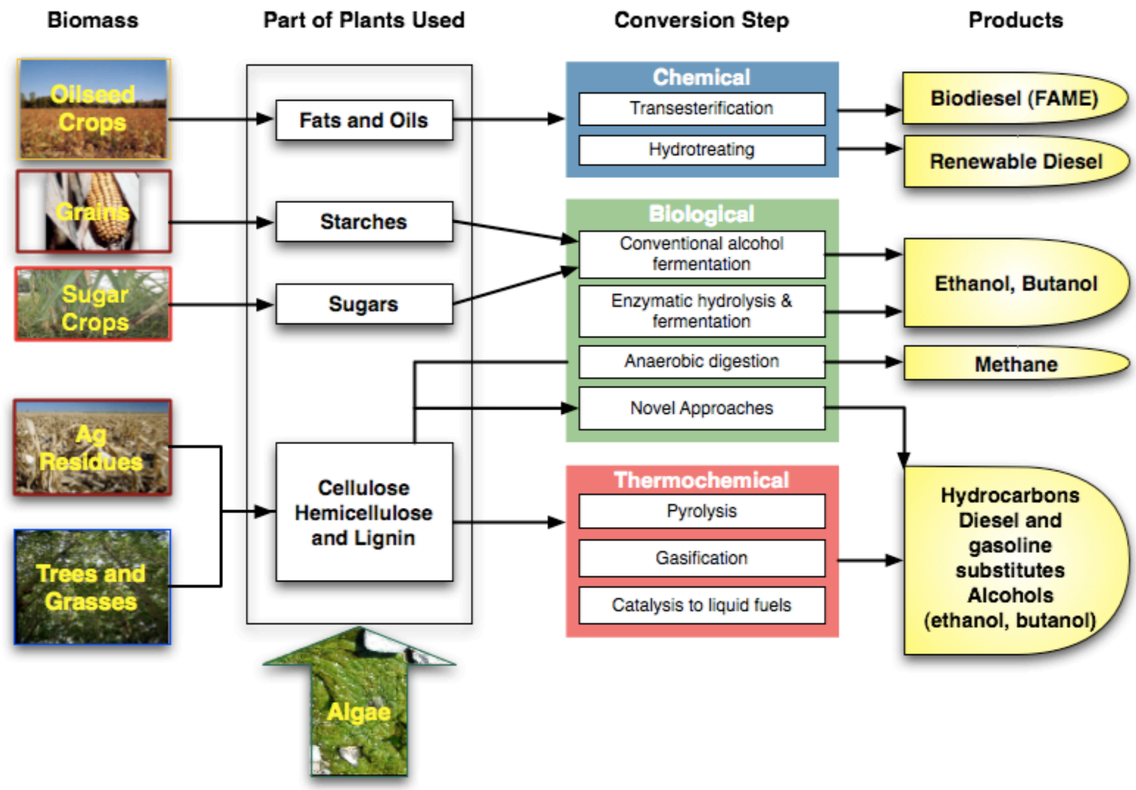


Figure 1. Biofuels—Permutations on a theme

The conundrum of sustainability

Beyond the complexity of characterizing the technology is the tougher question of how to define sustainability. As a concept, sustainability has a long and checkered history. Its roots go back to the controversial writings of Thomas Malthus, who dared to suggest (albeit prematurely with regard to both technology and human reproductive behavior) that the planet had reached the limit of its ability to support human population and the needs of society (Malthus 1999). In the 1970s, the Malthusian perspective returned with public concern about the environment and population growth. Its essence was captured in the system dynamics modeling work at MIT that led to the controversial "Limits to Growth" report to the Club of Rome (1975; Meadows et al 1972). Today, the Malthusian question continues to influence the debate over the sustainability of biofuels and society in general, leading to often-acrimonious debate in both the public sector and the technical community.

In this review, I focus on the rapidly changing nature of dialogue about and the analysis of the sustainability of biofuels, particularly over the past five years. I provide some context on my own views of how a clearer definition for sustainability can better frame the ongoing efforts to measure the sustainability of biofuels. Unfortunately, one of the greatest challenges facing analysts in the nascent field of sustainability is the pace with which policy makers are moving forward with laws to promote sustainability. The field is struggling to keep up with these demands.

Current progress toward an understanding of sustainability

Establishing definitions and metrics for sustainable biofuels

The term sustainability came into vogue in the late 1980s. After several years of study, the United Nations wrote that "[s]ustainable development meets the needs of the present without compromising the needs of future generations." (WCED 1987). This oft-cited definition is what I call the "Kumbaya" definition of sustainability. After all, who could possibly disagree with its stated goal? The problems in defining sustainability arise when one tries to delve more deeply into its meaning.

In framing the analysis of the sustainability of biofuels, it is useful to turn to a more contemporary Malthusian, E. O. Wilson, who wrote that "[t]he common aim must be to expand resources and improve quality of life for as many people as heedless population growth forces upon Earth, and do it with minimum prosthetic dependence. That, in essence, is the ethic of sustainable development" (Wilson 1998). Leaving aside the question of population growth, this definition can be used to parse the work of defining and assessing sustainable fuels:

- *Minimum prosthetic dependence*: This obscure phrase places a premium on systems thinking. Only with a holistic approach can we avoid the never ending cycle of solving problems with new technology solutions from which new problems arise that need new technology solutions. In recent years, researchers have recognized the importance of holistic thinking. The introduction of MTBE in gasoline has been studied as a classic case of solving one problem (reducing vehicle carbon monoxide emissions) while causing a new problem (persistent contamination of water systems with MTBE). Recent studies of the MTBE debacle have highlighted the need for a broad life cycle approach to evaluating technology solutions that focuses on both the benefits and the trade-offs of the technology (Davis, & Thomas 2006; Williams et al 2003).

- *Expanding Resources*: A sustainable energy future requires us to 1) focus on leveraging and reducing our use of nonrenewable resources such as fossil energy, and 2) redirect our energy supply toward renewable resources. The latter was an early focus of the life cycle modeling done on biofuels over the past few decades. In the past two years, analysts and policy makers have woken up to the realities of other critical resource limitations—particularly land and water.

- *The Earth*: A focus on the Earth re-emphasizes the need for systems and life cycle analysis. It also identifies the need to understand the burdens we place on air, water, land and ecosystems upon which we rely for critical ecoservices.
- *Quality of life*: Perhaps the least understood of the aspects of biofuels as a sustainable energy source is the social impacts it brings with it.
- *Ethic of sustainable development*: Recognizing the ethical nature of sustainability (also reflected in the notion of promoting quality of life) helps us to recognize the importance of conducting our assessment of sustainability in a process that promotes open and transparent dialogue.

Minimum prosthetic dependence: Progress on systems thinking and life cycle assessment

The increased emphasis on life cycle assessment as the tool of choice has been nothing short of astounding, as illustrated by the rise in the number of peer-reviewed studies from 1999 to 2009. As Figure 2 indicates, the number of journal articles that have focused on the combined topics of biofuels and sustainability has jumped dramatically. The annual number of life cycle publications on ethanol alone tripled from 2006 to 2008.

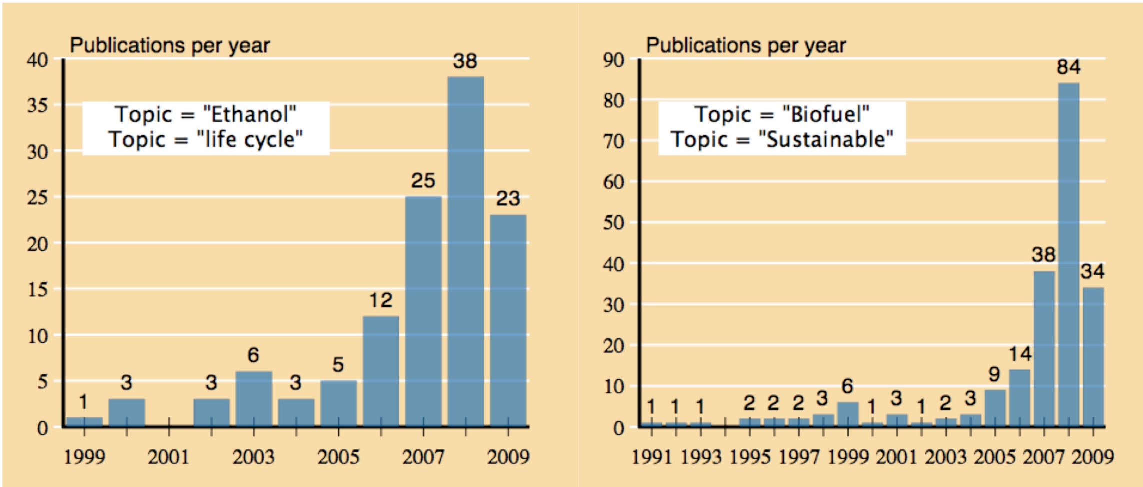


Figure 2. The growth of sustainability studies and life cycle assessment for biofuels (Citation analyses from ISI Web of Science database www.isiknowledge.com conducted on April 27, 2009)

Just as important as the growth in the number of such studies is the ambitious expansion of their scope. In the 1990s, life cycle studies focused on what are now referred to as "attributional LCAs" as opposed to "consequential LCAs" (Ekvall, & Weidema 2004; Schmidt 2008). The difference in the two concepts is illustrated in Figure 3. The five boxes along the bottom represent the stages of a biofuels life cycle for which direct life cycle impacts can be measured. What is included in those direct impacts depends on how the system boundaries for the life cycle have been drawn. Typically, for example, emissions and resource demands for the biomass production stage involve more than just "in the field" elements, but also include impacts from production of fuels, fertilizer and other chemicals used on the farm. In a consequential LCA, however, the system boundaries are extended even further to include emission and resource impacts that occur indirectly as a result of the ripple effects of introducing biofuels in the global economy.

This changes the entire nature of life cycle assessment to one which must be able to model global economic interactions. While it has long been recognized that the competition of biofuels for land used for food and fiber was important, no attempt to quantify this effect had been made until 2008 (Fargione et al 2008; Searchinger et al 2008) .

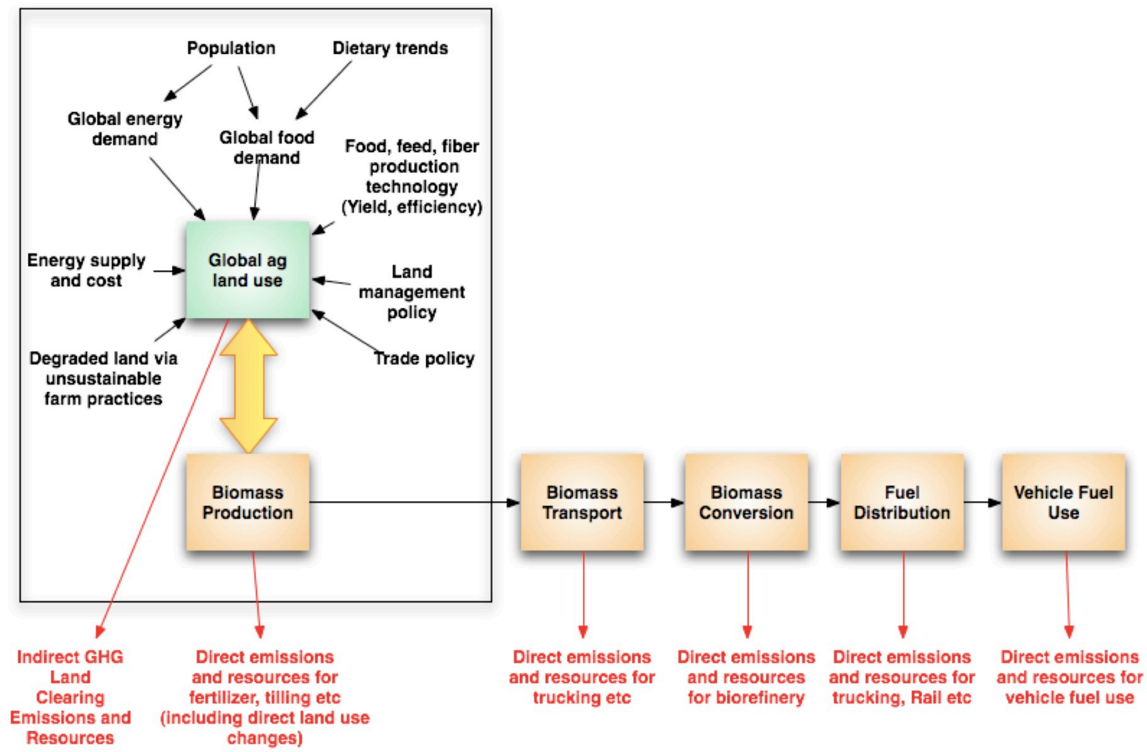


Figure 3. The shift from "attributional" to "consequential" life cycle assessment

From a greenhouse gas perspective, what these studies revealed was the potential for large unintended releases of carbon from new land clearing that occurs as a result of increased demand for biofuels. Their findings, and those of other modelers (CARB 2009;

Gibbs et al 2008; Taheripour et al 2009; Hertel et al 2008) , have generated an intense debate (Johnson 2009; Sperling, & Yeh 2009; Kim et al 2009; Peters et al 2009; Sawyer 2008; Sylvester-Bradley 2008; Gnansounou et al 2008b) .

In the meantime, life cycle modelers continue to refine our understanding of the direct (consequential) life cycle impacts of ethanol, biodiesel and the huge variety of feedstock and fuel combinations reflected in Figure 1 (Spatari et al 2005; Wu et al 2006; Malça, & Freire 2006; Botha, & Von Blottnitz 2006; Kim, & Dale 2006; Hill et al 2006; Fleming et al 2006; Adler et al 2007; Wang et al 2007; Wang et al 2008; von Blottnitz, & Curran 2007; Grant, & Beer 2008; Gabrielle, & Gagnaire 2008; Kim, & Dale 2008; Wu et al 2008; Halleux et al 2008; Liska, & Cassman 2008; Gnansounou et al 2008a; Pradhan et al 2008; Huo et al 2009; Laser et al 2009; Kikuchi et al 2009; Panichelli et al 2009; Kim et al 2009; Yu, & Tao 2009; Hill et al 2009; Farrell et al 2006; de Macedo 1998; Sheehan et al 1998; Fu et al 2003; MacLean et al 2004; Huang et al 2009; Wakeley et al 2009) .

Expanding resources: Meeting our energy needs

A majority of the life cycle studies have focused on the question of how effective biofuels are at reducing our dependence on fossil fuel, as measured by the net energy ratio of the fuel (fuel energy out versus fossil energy used to produce the fuel). Within the variability of the published results, I conclude that corn ethanol is marginally better in terms of reducing fossil fuel inputs relative to gasoline. One comprehensive comparison of the various studies suggests that overall fossil energy savings may only be 5 to 26%.

This study also found that petroleum reductions for corn ethanol were very high (Farrell et al 2006). From the public policy perspective, this confirms an old adage—be careful what you ask for, because you might get it. To a certain extent, corn ethanol is unfairly maligned in the press for its disappointing carbon reduction potential. But that industry started in response to a public mandate to reduce petroleum. It does that quite well, but now finds itself in trouble because it hasn't kept up with the moving target of public demands.

Sugarcane ethanol, by contrast, has fossil energy savings of 90% or greater (Seabra et al 2011; de Macedo 1998; Wang et al 2008). Life cycle assessments of biodiesel show high fossil energy savings as well (Sheehan et al 1998; Hill et al 2006; Pradhan et al 2011; Pradhan et al 2008) . Savings from new technologies using cellulosic biomass could also be substantial (Spatari et al 2005; Wu et al 2006; Botha, & Von Blottnitz 2006; Fleming et al 2006; Adler et al 2007; Kikuchi et al 2009; Fu et al 2003; MacLean et al 2004; Huang et al 2009; Wakeley et al 2009) . It is important to note that these energy savings are based on projected performances for technology that are not commercially proven.

Looking at the normalized fossil energy efficiency of these fuels using traditional life cycle assessments misses another critical part of the sustainability equation—how much total impact can these feedstock/conversion pathways have? While it appears that cellulosic ethanol technology could provide substantially more fuel than most of the existing commercial biofuels options, not nearly enough information is available to adequately address the global potential of these as-yet commercial fuels to provide a truly sustainable supply of transportation fuels.

The Earth—the role of biomass in reducing society's burdens on the planet

The dozens of "attributional" life cycle assessments of biofuels and their impact on climate change come to conclusions that align with the findings they report for fossil energy savings. To the degree that biofuels can reduce fossil energy demand, they can also reduce greenhouse gas emissions. However, more research is needed to improve our understanding of biofuels' non-fossil direct CO_2 greenhouse gas emissions. N_2O emissions from agriculture could, for example, significantly change the picture for direct greenhouse gas emissions of biofuels (Crutzen et al 2008; Smeets et al 2009).

Climate change has become, unfortunately, the single focus of our attention with respect to stewardship of the planet Earth. The recent focus on indirect land use change is an encouraging sign that we are beginning to broaden our horizons, even if, so far, we have simply translated land use pressures of biofuels into climate change effects. Land and water resources on the planet face increasing pressures from a growing population and global economy. The two resources go hand in hand. Our most valuable agricultural lands are the ones with access to "green" (renewable) rainfall. To the extent that dryer climates rely increasingly on irrigation, we are putting pressure on our "blue" (fossil) groundwater supplies. We have barely begun to do our homework on the impacts of biofuels on water. Water issues are highly regional. Biofuels will, for example, be limited by acute water supply problems in the rapidly growing economies of China and India

(McCornick et al 2008; De Fraiture et al 2008; Muller et al 2008; Mubako, & Lant 2008) . The limitations of land and water resources point to the need for a more integrated perspective on management of our natural resources—in conjunction with conservation efforts—to find a balance between societal needs for food, feed, fiber and fuel and the ability of our natural resources to meet them.

The other remaining problem for biofuels and water that is poorly understood is the impact of increased biofuels production on water quality, mainly with regard to nutrient leaching and eutrophication from farming operations (Dominguez-Faus et al 2009; Powers 2007; Donner, & Kucharik 2008). Life cycle studies to date do not adequately account for these effects. As with water supply issues, water quality impacts are regional in nature, making them difficult to capture in traditional LCAs.

Ecosystem health and biodiversity is another aspect of biofuels that remains largely unstudied. Whether in the form of GMO crops or "naturally" bred energy crops, fast growing, water tolerant energy crops could, according to some researchers, prove to be noxious invasive species. There is some reason for concern given the history of well-intended plant introductions that have gone awry. Here the debate has not necessarily been rational, with a high degree of mistrust between biofuels advocates and "invasion biologists" (Raghu et al 2006; Barney, & Ditomaso 2008; Pyke et al 2008; Simberloff 2008) .

But ecosystem health and biodiversity extend well beyond the question of biomass crops as potential invasive species. They include, for example, the encroachment of managed, monoculture-based, agriculture onto the remaining pool of unmanaged and natural ecosystems that support much of the world's biodiversity. So, in the end, the greenhouse gas debate centered on the indirect land use impacts of biofuels is simultaneously a debate about land use more broadly and the choices we make between ecosystem services such as food and energy production and biodiversity.

Quality of life and the ethic of sustainable development: dialogue

Social and technical issues as a rule don't mix. Or at least that is how many scientists and engineers see it. They feel that their work becomes "tainted" when influenced by political and ethical considerations. But sustainability issues are commingled technical and ethical questions. We need processes that allow us to work in this daunting realm of scientific and social enquiry. Life cycle modelers have long recognized this problem. Their solution—engage all stakeholders in the upfront design of technical studies so that: 1) the studies remain open and transparent, and 2) they address the real concerns of all members of society. My own experience with life cycle studies is that such an approach helps to clear the air with respect to what are scientific versus ethical uncertainties (Sheehan et al 2003). Precious little effort has been made to abide by the ISO standards for stakeholder involvement and transparency in life cycle assessment (ISO 1997; ISO 1998), and yet it is the only cure for the current dysfunctional debate of dualing experts about our sustainable energy future. In the words of the 20th century philosopher and educator, Mortimer Adler, "Let us engage in the serious business of conducting our discussion rationally and logically to discover the truth about points on which we differ" (Adler, & Van Doren 1988).

An overview of the research presented in this thesis

The review of the research on the sustainability of biofuels presented in this chapter illustrates the complexity and controversy that surround it. I conclude from this review that the central (but not the only) issue for sustainable production of biofuels is their relation to the broader societal and global choices we make about land use. In this thesis, I focus on a limited number of case studies that touch on some of the key issues identified in this chapter. This research considers three land-related aspects of biofuels sustainability:

1. The effect of local farm management practices on the sustainability of land used to produce corn grain as a biorefinery feedstock.
2. The relative sustainability of land used for producing corn and sugarcane biorefinery feedstocks, and for supporting net primary productivity in natural ecosystems as a function of latitude.
3. The land use implications for biofuels of global pasture-based livestock production systems.

Chapter 2. Managing land for low-carbon corn: a Minnesota case study

Corn is the dominant source of sugars for fuel ethanol production in the United States. New regulations promoting low carbon biofuels have established that corn based fuels offer relatively small benefits in terms of reducing net emissions of greenhouse gases viz-à-viz petroleum based fuels, especially in comparison to advanced cellulosic biofuels (USEPA. 2010; Sheehan 2009). This conclusion is based on life cycle assessments of US national average or regional Midwest average corn farm data.

In this study, we look beyond the average corn farm to consider individual farm level estimates of life cycle greenhouse gas emissions. We surveyed farmers in southwest Minnesota who are potential suppliers to a new isobutanol biofuel refinery located in Luverne, MN, and then used this detailed farm level data to estimate farm to farm variation in life cycle greenhouse gas emissions per kg of harveseted corn grain. The motivation for this analysis is to establish the potential for reducing the carbon footprint of corn delivered to the biorefinery based on *existing* management practices observed among the farms.

In effect, this study offers a glimpse at what might be called the "carbon footprint gap" among a specific cohort of farmers. Based on this data, we identify scenarios under which the gap between poor performing (i.e., high greenhouse gas emitting) farms and high performing (i.e., low greenhouse gas emitting) farms might be closed, resulting in overall reductions in emissions per kg of corn delivered to the isobutanol facility.

Carbon footprints are calculated based on a life cycle inventory of each farm that includes life cycle contributions of all farm inputs as well as modeled estimates of soil greenhouse gas emissions.

Background

Isobutanol is a second generation fermentation-based biofuel that offers significant advantages over ethanol with respect to fuel market infrastructure and vehicle compatibility (Chen et al 2011; Connor, & Liao 2009). It is a fuel that can be blended to higher levels than ethanol without requiring special handling in the fuel distribution system or special modification to existing conventional gasoline fueled cars and trucks. Finally, because its volumetric energy density is higher than that of ethanol, it can deliver more miles per gallon and greater miles per tank of fuel than ethanol. Isobutanol also has value as an intermediate feedstock for production of other chemicals and fuels, including jet fuel.

Gevo is a Colorado-based biofuels start-up company that has built its first commercial demonstration facility for conversion of corn to isobutanol (USEPA 2011). The facility is located in Luverne, Minnesota. Gevo has retrofitted an existing corn ethanol plant to accommodate its isobutanol technology, and will take advantage of an existing 400 to 500-farm supply chain associated with the current plant.

Gevo has funded this research in order to understand how it can work with its existing Minnesota corn suppliers to reduce the environmental footprint of its feedstock and deliver a compatible and cost effective alternative fuel (isobutanol) that might better compete for market share in the low carbon fuel market.

Goals and objectives of the research

The University of Minnesota's Institute on the Environment was contracted by Gevo, Inc. to characterize the environmental footprint of the corn supply for Gevo's Luverne, MN isobutanol facility. Key objectives are to:

- Establish a baseline characterization of life cycle impacts of current corn production based on a sampling of the suppliers currently associated with the Laverne ethanol facility.
- Evaluate possible changes to farm practices that will reduce carbon emissions and other environmental impacts of the corn feedstock delivered to the isobutanol plant
- Evaluate additional improvements to the isobutanol process that will further reduce the carbon emissions and overall environmental footprint of corn based isobutanol
- Determine key measures of the environmental footprint via stakeholder and supplier discussions
- Collect detailed farm management data for Gevo's potential corn suppliers
- Use data on farm management and other data to estimate the current environmental footprint of Gevo's corn suppliers

A survey was constructed to collect data on all aspects of farm operations that could influence the carbon footprint of potential corn suppliers for the Gevo facility. It was sent out by Gevo to all suppliers who have in recent years provided feedstock to the ethanol facility acquired by Gevo. The surveys were mailed to the 343 suppliers on the plant's active corn procurement list.

The survey includes five sections (see appendix):

1. Red section: soil, acreage, yield and location information
2. Blue section: nutrient management (fertilizer and manure use)
3. Orange section: pest management (herbicide and pesticide use)
4. Green section: tillage practices and residue management
5. Purple section: energy use

Overview of farmers and their operations

Who we heard from

Figure 4 shows the distribution of farmers who were requested to fill out the survey. As the map shows, 291 of the farms were within a close radius of the Luverne facility, with a handful of farms located in South Dakota and Iowa.

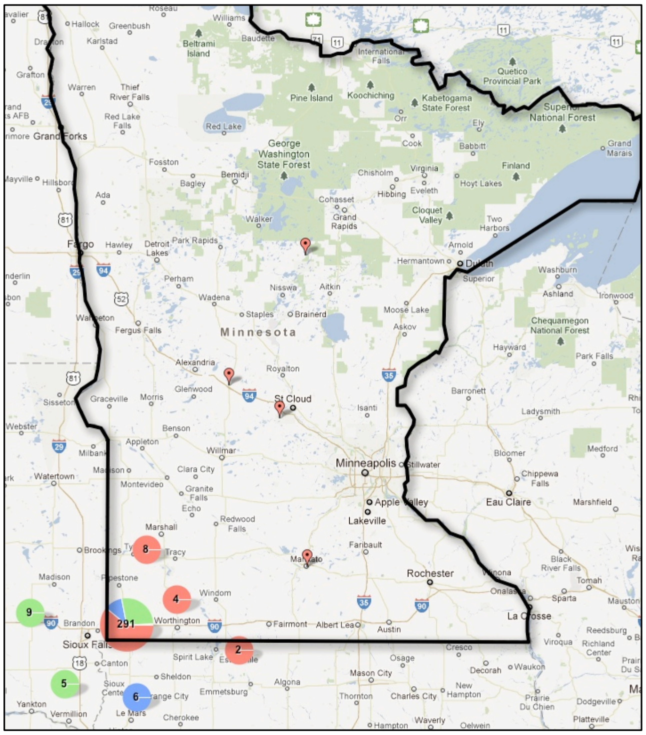


Figure 4. Geographic distribution of Gevo survey mailing list

Fifty one farmers responded to the survey. After a careful process of QC, we winnowed down these responses to a set of 43 farms that had provided reliable data on all or most of the questions asked.[1] This represents only a 13% response rate. While we had hoped for a response rate closer to 20 to 25%, we felt that even this relatively small dataset provided an opportunity to delve more deeply into the individual farm level variations in environmental performance as a function of key management practices. Figure 5 provides two close-in views of the southwest corner of Minnesota and surrounding states that highlight total farms surveyed versus actual farm operations that

[1]The number of responses that were useable for a given question could be considerably lower.. For example, the number of data points for which sufficient data was available to do soil emissions calculations was around 32.

provided data. About half of the respondents come from directly around the Luverne facility. This makes sense. These farmers are the most likely ones to participate in supply agreements with the isobutanol plant. Figure 6 provides information on county locations of the respondents.

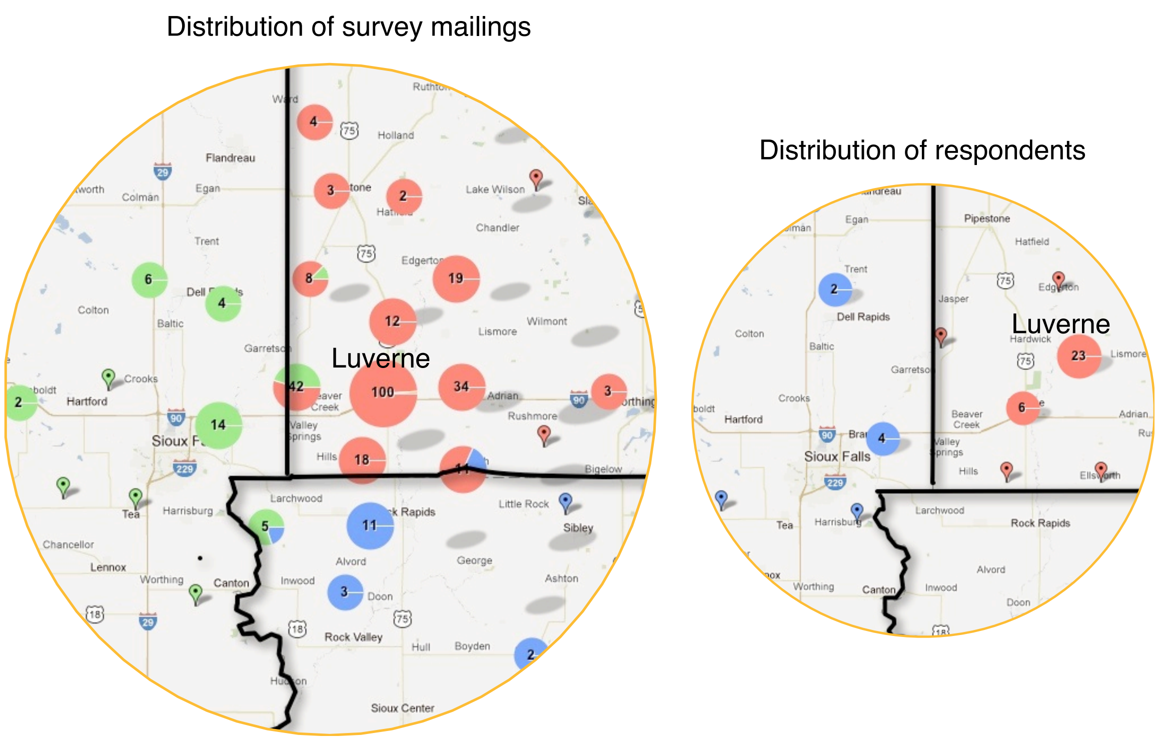


Figure 5. Close up view of geographic distribution for farms surveyed and farms with useable responses

To get another perspective on the representativeness of our survey sample size, we looked at how total annual corn production among the respondents compares with Rock county production and with the annual supply needs of the Gevo facility (see Figure 7). Annual production and feedstock supply levels are reported in millions of bushels per year, and production is reported (from the survey and from USDA) for years 2008, 2009 and 2010. The amount of corn produced by our respondents in 2010 is equivalent to about half of the total annual demand for the Gevo plant.

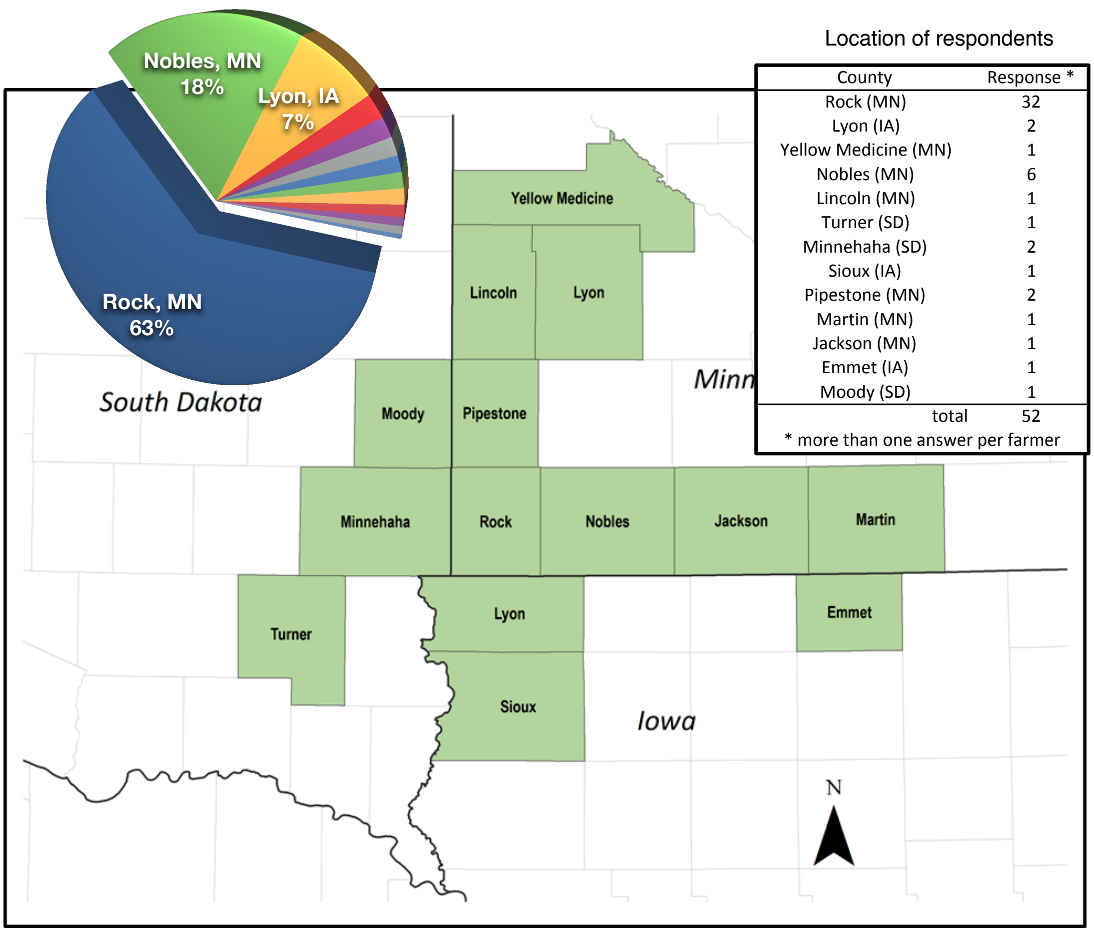


Figure 6. State and county distribution of survey respondents

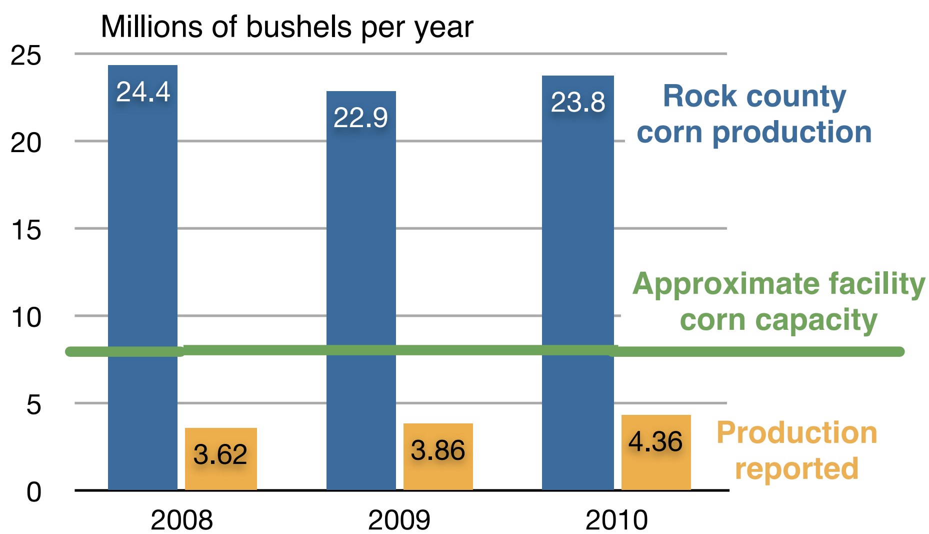
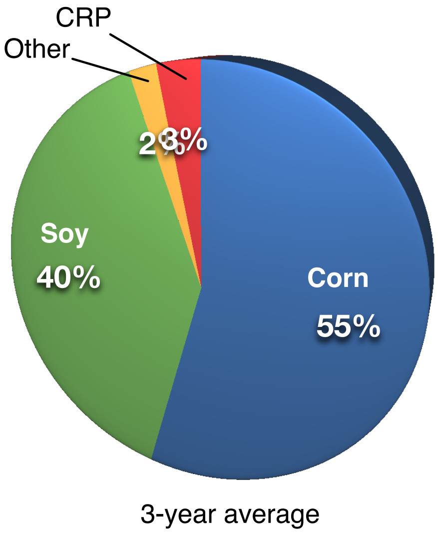


Figure 7. Farm survey response relative to local production and facility demand.

Farm size distribution among survey respondents

The average farm is 918 acres (371 ha) in size. These farmers are predominantly corn and soybean producers, with 55% planted in corn, 40% in soy and 2% in other uses. Only 3% of their land is in the Conservation Reserve Program (see Figure 8). Figure 9 shows the distribution of total farm acres as reported in each of the three years (2008 through 2010). Both the median and average statistics for this population are much larger than those for the US as a whole. The average of 918 acres (371 ha) for this group of farmers is more than twice the US average of 441 acres (179 ha). The median farm size for this group is 580 acres (215 ha), which is more than six times the median size for the US.



Farm size in acres

	2008	2009	2010	Average
Total	887	902	961	917
Corn	473	501	526	500
Soy	365	354	386	368
Other	21	19	18	19
CRP	29	29	31	30

Farm size in hectares

	2008	2009	2010	Average
Total	359	365	389	371
Corn	192	203	213	202
Soy	148	143	156	149
Other	8	8	7	8
CRP	12	12	12	12

Figure 8. Farm size and crop distribution of survey respondents

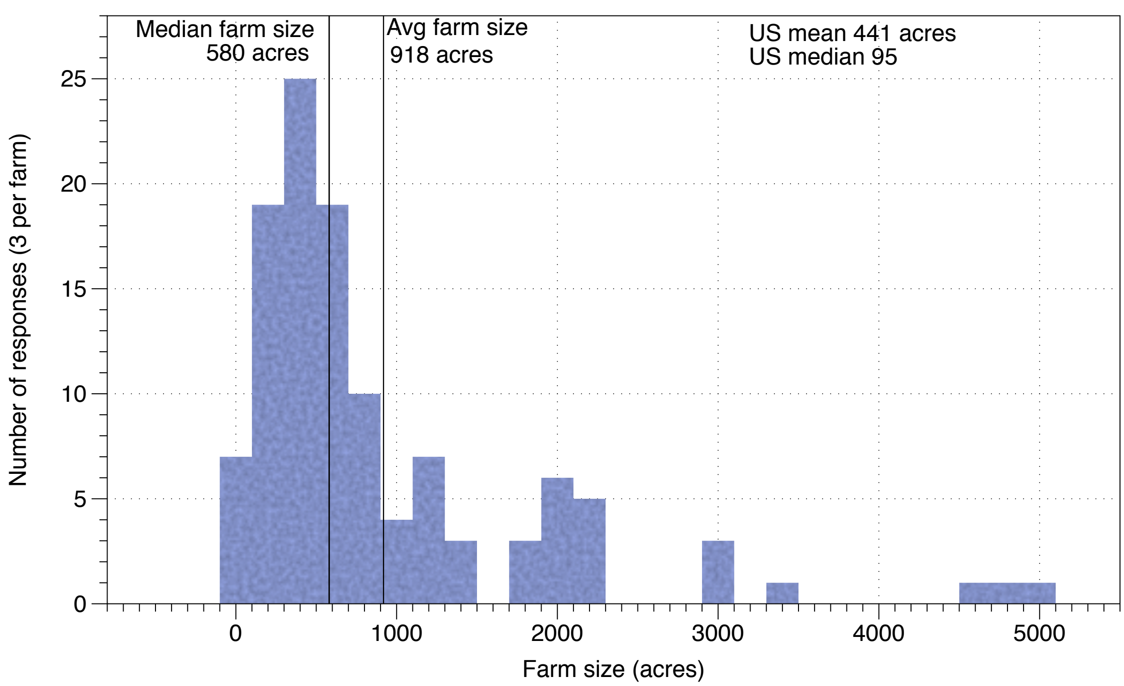


Figure 9. Distribution of farm sizes among survey respondents

Aggregating individual farm data

Aggregation of the farm data for the purposes of estimating the current overall characteristics of the supply available to Gevo was done using the following approach. It applies to all major parameters discussed in this section of the report. For Parameter P_j reported for i = 1 to n farms, the aggregate, area-weighted average value is:

Equation 1. Aggregating individual farm data

$$\overline{P_j} = \frac{\sum_{i=1}^{n} A_i P_j}{\sum_{i=1}^{n} A_i}$$

When calculating a single estimate for all years, we sum across all farms and across all years. Thus, for example, 38 farms with three years of responses (each of which can and often does have a different set of values) will have 38 x 3 = 114 values of area and parameter values that will go into the average calculated above. Average values for a single year are calculated based on a sum across all farms in each year.

Average corn grain yields for our survey respondents

As Figure 10 shows, the Gevo facility draws from a region that performs substantially above US national averages for corn grain yields. Minnesota farmers in general achieve higher yields than the US, and Rock County farmers in the immediate vicinity of the plant do even better. Responding farmers in this survey averaged over 190 bushels per acre in the three years for which yields were reported, again slightly better their colleagues in Rock County. The three-year average yield reported in the survey was 23% higher than the yield for the US in the same time period.

As a check on the reasonableness of these yields, we looked at the average survey results and recent local yields in in the historical context of yields for Rock County, the state of Minnesota and the US (see Figure 11). Yields locally and in the state have been appreciably higher than the US average for most of the past ten years—reflecting a reversal of the situation found in most years since 1960 that appears to have started in the mid 1990s.

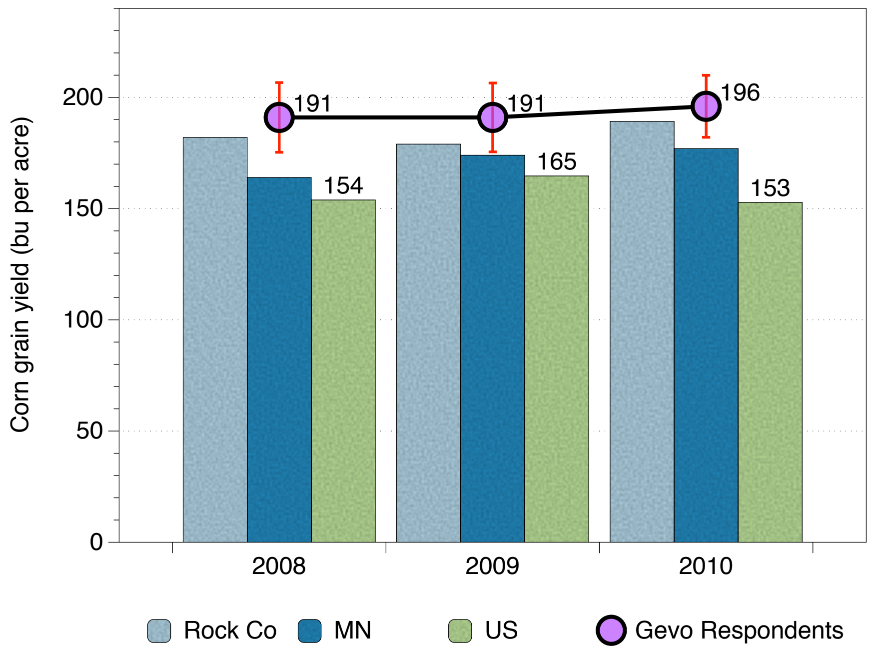


Figure 10. Comparison of corn grain yields reported among respondents versus local, state and US averages for 2008, 2009 and 2010

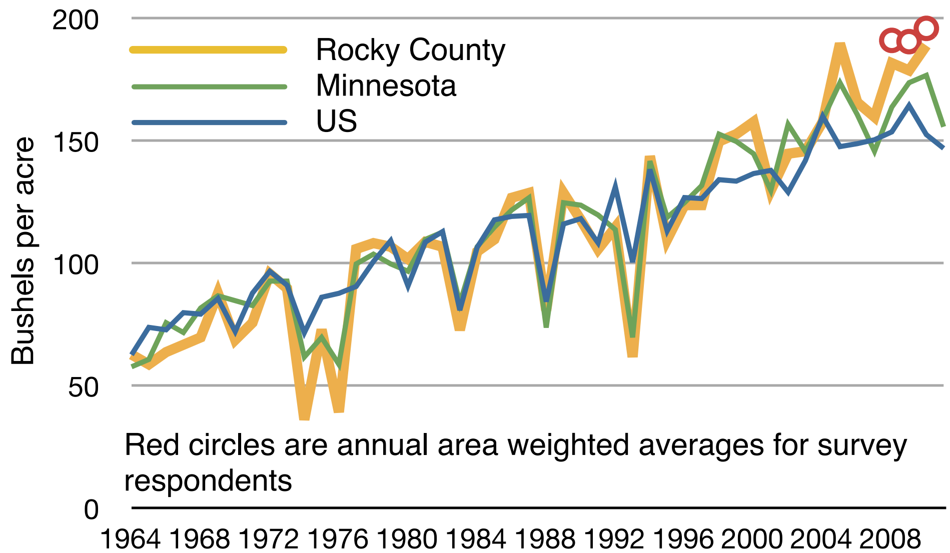


Figure 11. Survey respondents' yields in historical context for Rock County, Minnesota and the US

Average nitrogen fertilizer use among survey respondents

Fertilizer use, in particular application of industrial nitrogen fertilizer, is one of the largest contributors to greenhouse gas emissions and fossil energy use in corn production. Thus, it is important to understand how much nitrogen is used among Gevo's potential corn suppliers. Table 1 and Figure 12 summarize the overall and annual synthetic nitrogen fertilizer use reported by the survey respondents. The type and amount of fertilizer used vary some from year to year. Average rates are calculated on an area-weighted basis. Overall, urea represents around half of the nitrogen fertilizer applied, and ammonia about another one-third of total applied.

Table 1. Area-weighted nitrogen fertilizer usage among survey respondents in lb N per acre

Fertilizer	2008	2009	2010	Avg
Ammonia, anhydrous	68.59	65.20	41.52	57.17
Ammonium polyphosphate	0.70	0.52	0.57	0.59
Ammonium thiosulfate	0.00	0.00	0.15	0.06
Diammonium phosphate	14.77	13.04	12.95	13.51
Monoammonium phosphate	4.17	3.52	4.79	4.19
Urea	78.71	77.67	101.92	87.21
Ammonium sulfate	1.44	1.76	1.75	1.66
Total synthetic N lb N per ac	168.37	161.71	163.65	164.40

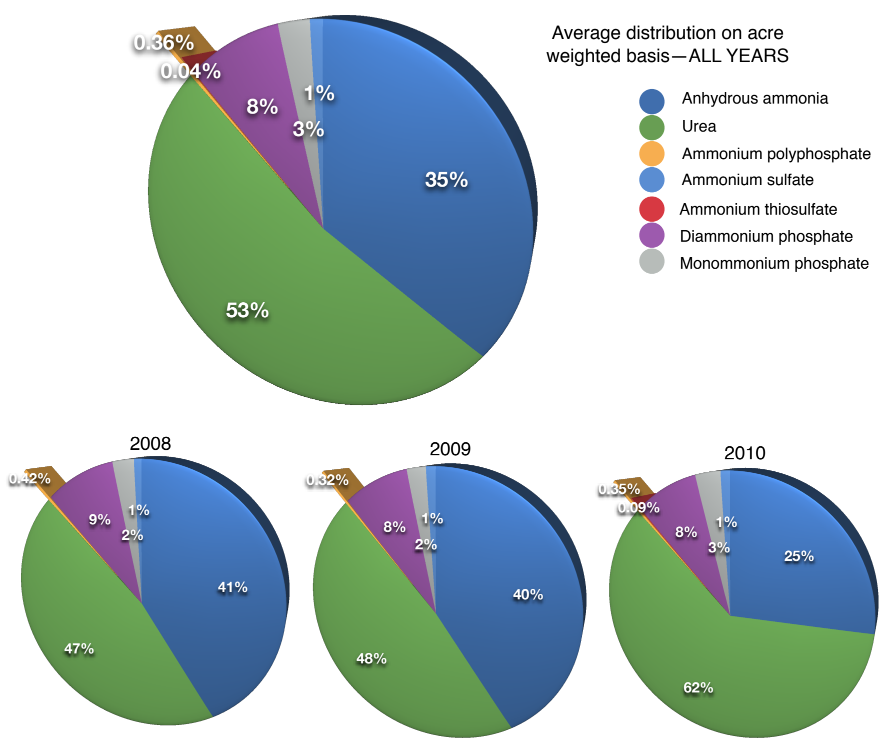


Figure 12. Area-weighted nitrogen fertilizer usage among survey respondents

Figure 13 compares total nitrogen application rates among the survey respondents with historical US and state nitrogen fertilizer use data. Although some data for 2006 through 2009 for nitrogen application rates are not available from USDA for the US and for the state of Minnesota (and no data is available on county level nitrogen use), the historical trends up to 2005 and the latest numbers for 2010 suggest that nitrogen application rates for our respondents are measurably higher than state and national rates. In 2010, the area weighted nitrogen application rate among our respondents was 163 lb of N per acre, 17% higher than the US average of 140 lb of N per acre and 31% higher than the state average of 125 lb N per acre.

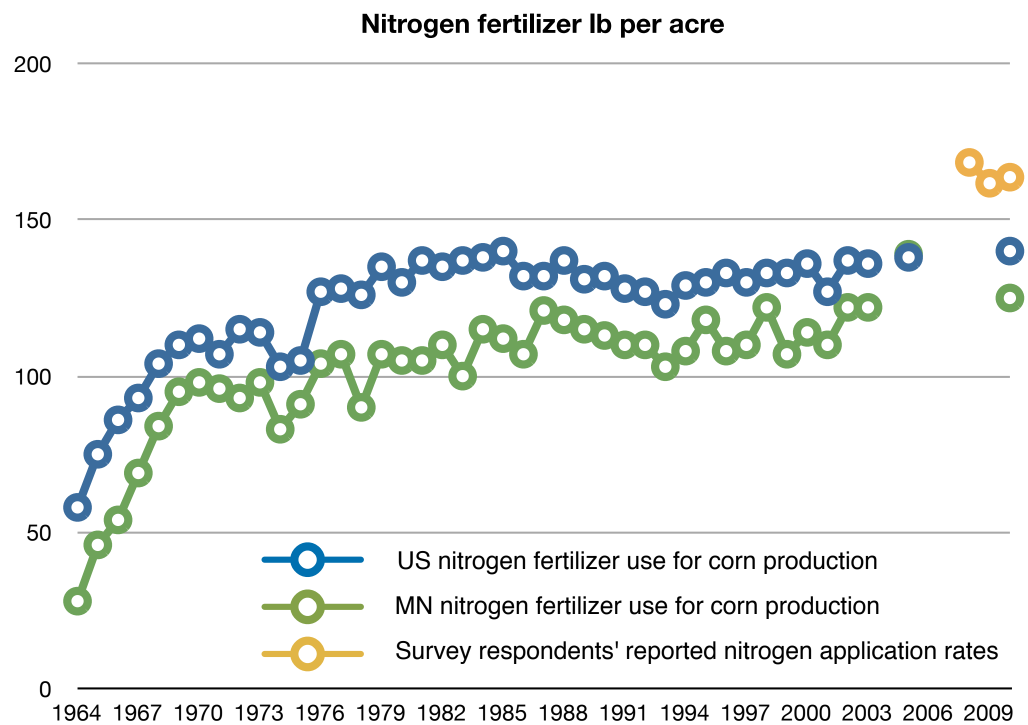


Figure 13. Industrial nitrogen fertilizer application rates for survey respondents and historical nitrogen rates for Minnesota and US corn farmers

This does not tell the whole story. Normalizing the nitrogen fertilizer application rates relative to grain yield offers a more useful way of comparing the Gevo survey respondents' use with state and national level fertilizer use. As Figure 14 shows, the comparison of nitrogen fertilizer applied per bushel of corn grain harvested looks very different. The higher yields observed among the survey respondents make up for the higher nitrogen fertilizer use, leading to per bushel rates that are slightly lower than the US average, but somewhat higher than the state average for Minnesota in 2010.

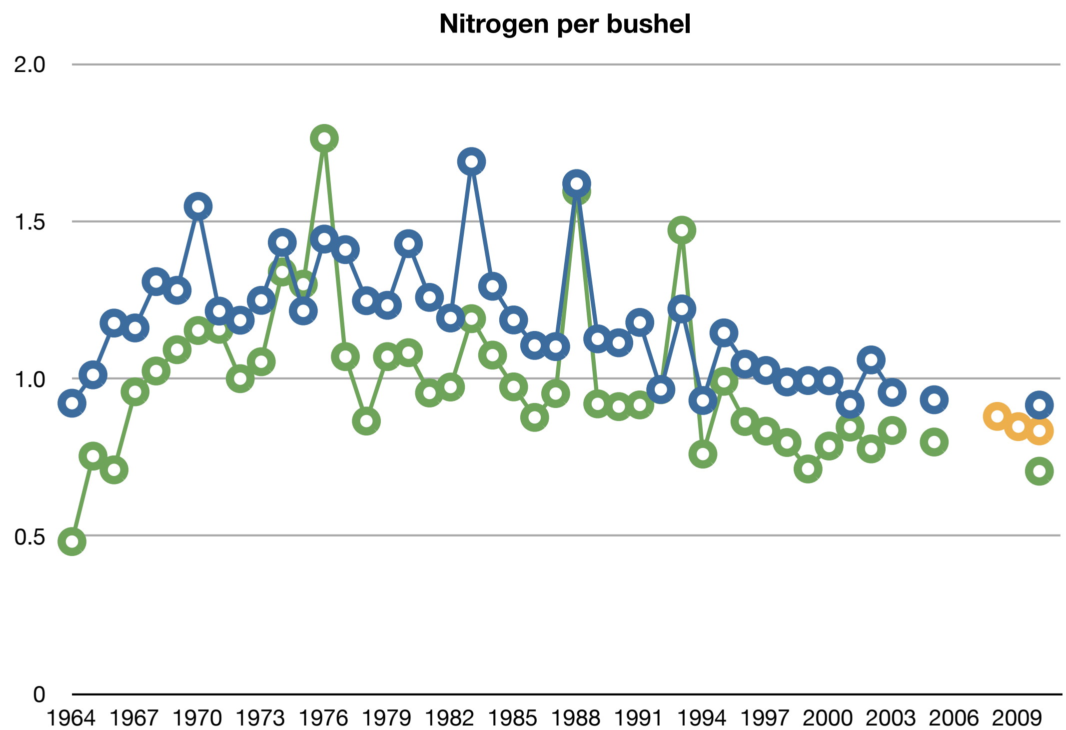


Figure 14. Ntrogen fertilizer use per bushel among survey respondents compared with historical values for MN and US corn farmers

Average phosphate fertilizer use among survey respondents

Phosphate fertilizer application rates are summarized in Figure 15 and Table 2. Average rates are calculated on an area-weighted basis. According to our survey responses, between 50 and 60 lb per acre of industrial phosphate fertilizer (reported as P_2O_5) were applied on corn acres in the years 2008 to 2010. Diammonium phosphate is the most common form applied (60% of total phosphate applied on average). Monoammonium phosphate accounts for another 35%, and the remaining few percent reflect the ammonium polyphosphate included in starter formulations at planting. We do not have comparable data on historical phosphate fertilizer usage for the US and the state of Minnesota.

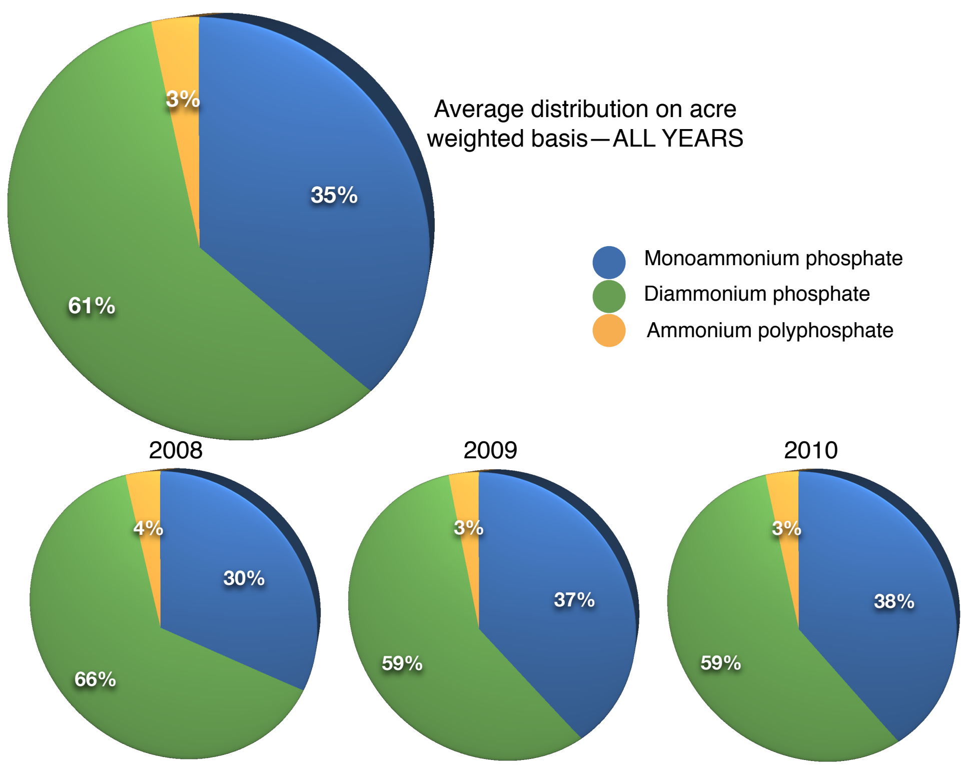


Figure 15. Area-weighted distribution of phosphate use for survey respondents

Table 2. Area-weighted distribution of phosphate use for survey respondents

All years	2008	2009	2010	Avg
Monoammonium phosphate	19.75	18.26	19.16	21.53
Diammonium phosphate	34.42	40.02	30.52	33.46
Ammonium polyphosphate	1.92	2.22	1.62	1.97
Total industrial phosphate	56.09	60.50	51.31	56.96

Average potash fertilizer use among survey respondents

Potash is a source of potassium for plant growth. Potash application rates are summarized in Table 3. Rates are reported in lb of K_2O per acre. As with the previous fertilizer estimates, results are calculated on an area weighted basis. Average usage is 43 lb K_2O per acre for all years, with values ranging from 40 to almost 48 lb K_2O per acre.

Table 3. Area-weighted potash fertilizer use

Fertilizer	All years	2008	2009	2010
Potash lb K2O per acre	40.26	38.42	37.97	43.88

Manure application rates and their contribution to nutrient management

While the bulk of the acres farmed in the period of 2008 to 2010 received nutrients in the form of industrial fertilizers, there was a significant portion of acres that were treated with animal manure. We estimate that 22% of all corn acres farmed across all three years had some form of manure applied. But manure application practices are far from homogeneous. The histogram in Figure 16 shows that around 78% of the time, farmers relied strictly on industrial fertilizers (corresponding to zero percent manured acres per corn acres). The remaining 22% of corn acres saw manure applied to at least a portion of their cropland. A handful of farmers—approximately 10% of the survey population—applied manure on at least as many acres as they report having planted for corn. Note that the percent of manured corn acres is greater than 100% on a few farms. For those cases, we assume that this reflects manure use on some non corn acres (most likely soy).

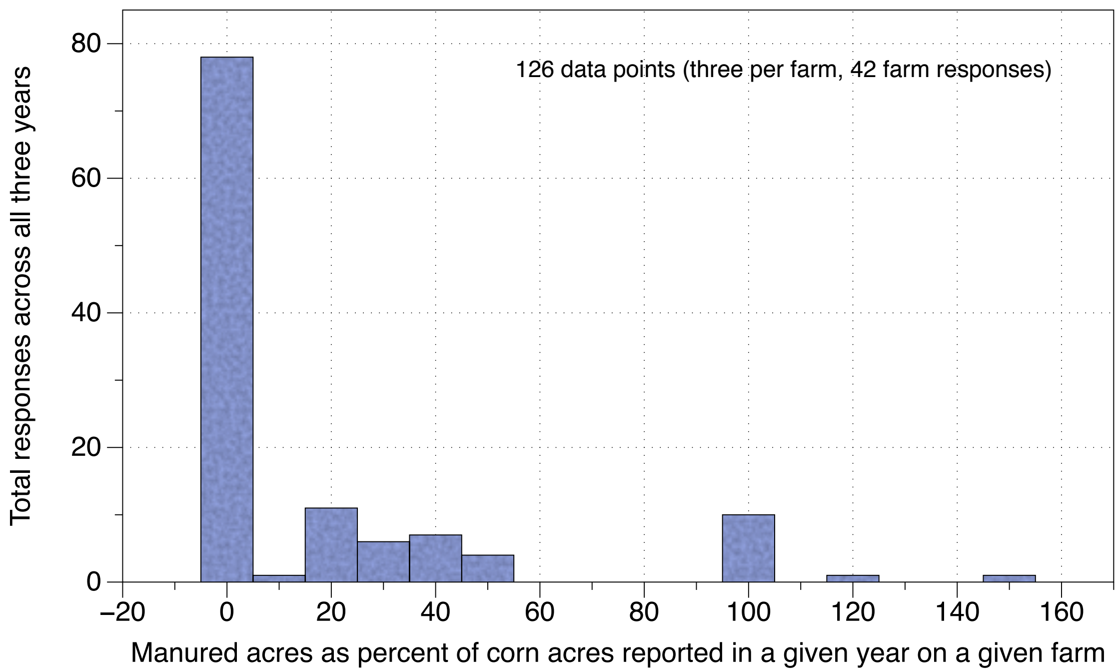


Figure 16. Distribution of extent of manured acres relative to corn acres reported annually

Greenhouse gas emissions associated with manure use are ignored in our estimate of life cycle fossil carbon emissions because we do not have complete information on the life cycle impacts associated with the handling and delivery of the manures to the farm. We do, however, estimate the nutrient contributions made by the use of manure. For nitrogen, this is particularly important. Soil emissions of N_2O (a potent greenhouse gas) is influenced by the total amount of nitrogen that is added to the field from both industrial fertilizer and manure.[2] Assumptions for nitrogen, phosphate and potassium content of the different manure types are shown in Table 4. Estimates for nutrient composition are based on data from the University of Minesota Extension (Blanchet, & Schmitt 2007).

Table 4. Adjusted rate of application and assumed nutrient content for manure as fertilizer

Manure type	Units per acre	Adjusted rate of application	Nitrogen (lb N per unit applied)	Phosphate (lb P_2O_5 per unit applied)	Potassium (lb K_2O per unit applied)
Beef	tons/acre	1.58	7	4	7
Chicken	tons/acre	0.08	60	46	31
Dairy (dry)	tons/acre	0.02	10	3	6
Dairy (liquid)	gal/acre	84.26	0.031	0.015	0.019
Swine (liquid)	gal/acre	594.27	0.03	0.025	0.024

Nitrogen balance for survey respondents

Using the area weighted average values for industrial fertilizer and manure inputs, we have estimated the overall nitrogen uptake ratio of the farms included in the survey responses. We calculate the uptake ratio as the ratio of total nitrogen taken up in the crop's above ground biomass to the total nitrogen applied in the field. Nutrient uptake in the plant is estimated based on literature values for each nutrient component (N, P and K) in each of the major components of the corn plant (Belyea et al 2004; Domalski et al 1986; Peplinski et al 1989; Sawyer, & Mallarino 2007; NRC 1982; Latshaw, & Miller 1924; Greaves, & Hirst 1929; Johnson et al 1994; Heckman et al 2001; Halvorson, & Johnson 2009) . and published data on the relative proportion of cob to grain (Halvorson, & Johnson 2009). All non-cob residue is taken as the difference between

[2]We discuss in a subsequent section the methodology for calculating soil emissions of nitrogen oxides due to application of industrial nitrogen fertilizer and manure.

total stover and cob harvested. Total stover yield is based on a harvest index of 0.5. Estimates for corn plant composition are shown in Table 5

Table 5. Average values and standard deviations for nutrient composition of corn crop components

Component	Grain	Std dev	Cob	Std dev	Stover	Std dev
wt pct N	1.437	0.027	0.368	0.064	0.59	0.156
wt pct P	0.187	0.052	0.032	0.01	0.063	0.045
wt pct K	0.263	0.058	0.589	0.27	0.74	0.683
wt pct S	0.095	0.013	0.016	0.008	0.052	0.037

The results for nitrogen are summarized in Table 6. The overall efficiency for uptake of nitrogen is 88%. This is an important parameter for characterizing the local corn suppliers' performance, as excess nitrogen (nitrogen not utilized by the crop) is likely to show up as nitrogen emissions from the soil that can contribute substantially to greenhouse gas emissions. The absolute value of this estimate is fraught with error (particularly when it comes to estimating the nitrogen content of the non grain components of the corn plant). But it does turn out to be a very good comparative indicator for individual farm performance (which will be discussed in subsequent sections).

Soil emissions of greenhouse gases

Greenhouse gas emissions from crop land soil on each farm were estimated by researchers at Colorado State University using their DailyDayCent model, the latest version of the DayCent model (Del Gross et al 2000; Parton et al 1998). DayCent is a general biogeochemical model that simulates daily fluxes of carbon and nitrogen among the atmosphere, vegetation, and soil. The model simulates plant growth, decomposition and soil organic matter dynamics, mineral nitrogen transformation and soil water and temperature dynamics for cropland, grassland, forest and savanna ecosystems. DayCent is used by a number of research groups world-wide and is used for the US national GHG inventory (Del Grosso et al 2010; USEPA 2012) .

Table 6. Nitrogen balance for survey respondents

Component	Nitrogen
INPUTS	
Urea (kg N per ha)	97.92
Ammonia (kg N per ha)	64.19
Monoammonium phosphate (kg N per ha)	4.71
Diammonium phosphate (kg N per ha)	15.17
Ammonium polyphosphate (kg N per ha)	0.67
Ammonium sulfate (kg N per ha)	1.87
Ammonium thiosulfate (kg N per ha)	0.07
Total nitrogen fertilizer (kg N per ha)	184.51
Manure N (kg N per ha)	40.71
Total applied N (kg N per ha)	225.22
OUTPUTS	
N uptake cob (kg N per ha)	5.95
N uptake grain (kg N per ha)	148.07
N uptake stover (kg N per ha)	44.37
Total uptake (kg N per ha)	198.39
N Uptake efficiency	0.88

Survey data for thirty-eight farm systems were used to construct DailyDayCent model input files for the simulation of each system. Survey data indicated the dominance of corn and soybeans throughout the survey region so initial simulations were confined to corn-soybean rotations. Two versions of the rotation were simulated (corn-soybean, soybean-corn) so yields for both corn and soybean could be obtained for each year of the simulation.

Corn nitrogen fertilizer rates reported by each respondent for the three year period were used as model inputs. If more than one value was reported, then the average rate was used as model input. No nitrogen fertilizer applications were reported for soybeans so no fertilizer was applied in the soybean years in the simulations. Soil types and series reported in the farm surveys were used whenever possible to pull texture data from county soils survey reports. When soil types reported in the surveys were vaguely described or were of a type not found in the county soil surveys, a comparable soil series was used. Where no data on parcel soil was available the dominant soil in the county was used. All soils were simulated as non-hydric (low moisture) soils.[3]

Tillage practices reported by respondents for the survey years (2008-2010) were used to construct typical practices for each system. These practices were converted to model input. Reported tillage included intensive tilled systems, moderate tilled systems, and light tillage systems. If tillage data was missing for any system then the most common practices in the survey were used. For more detail see the next section.

Some survey respondents reported the use of manure additions on a portion of their acreages. Average manure N application rates were determined and applied to all acres. Manure carbon:nitrogen ratios were estimated by manure source. Simulated manure applications were scheduled in all cases as single applications following soybean harvest.

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[3]This is an assumption that applies to well drained land.

Individual simulation runs were conducted for each farm-by-soil type combination to capture the effects of specific farm management on each soil type reported by the farmer. The soil-percentage value reported by the farmer were then used as weighting factors in order to aggregate outputs from different soil types into an overall per-farm output. In order to capture the differences between corn-soy and soy-corn rotational "phases", the above procedure was carried out twice for each farm: once with corn planting on even years and once with corn planting on odd years. Reported values were obtained by averaging these two "phased" outputs.

Weather files obtained from NOAA's North American Regional Reanalysis (NARR) weather database, which has gridded daily weather data, were based on county centroids. Initial analysis of these data for the study area showed some bias compared to data from other sources, including a data set from the University of Minnesota, and therefore the precipitation values in these NARR weather files were adjusted to more closely match reported historical records. This adjustment improved average simulated yields in comparison to those reported by the National Agricultural Statistics Service (see Figure 17). Simulated yields also showed very good agreement with survey results for the years of 2008-2010.

The soil emissions are based on the average of 12 years' of area-weighted averages for simulated N_2O and soil organic carbon (SOC) fluxes at each farm for the period of 1999 - 2010. These results are summarized across all the farms in Table 7. The simulated N_2O fluxes, as with the soil carbon, are representative of stable management systems under the assumption that reported survey management practices had been essentially the same for a thirty year period. Under this assumption, the N_2O flux on each farm varied mainly as a function of yearly weather conditions that directly impact N_2O emission processes, via soil moisture and aeration and soil temperature, as well as through indirect effects of weather on plant uptake, N volatilization and N leaching.

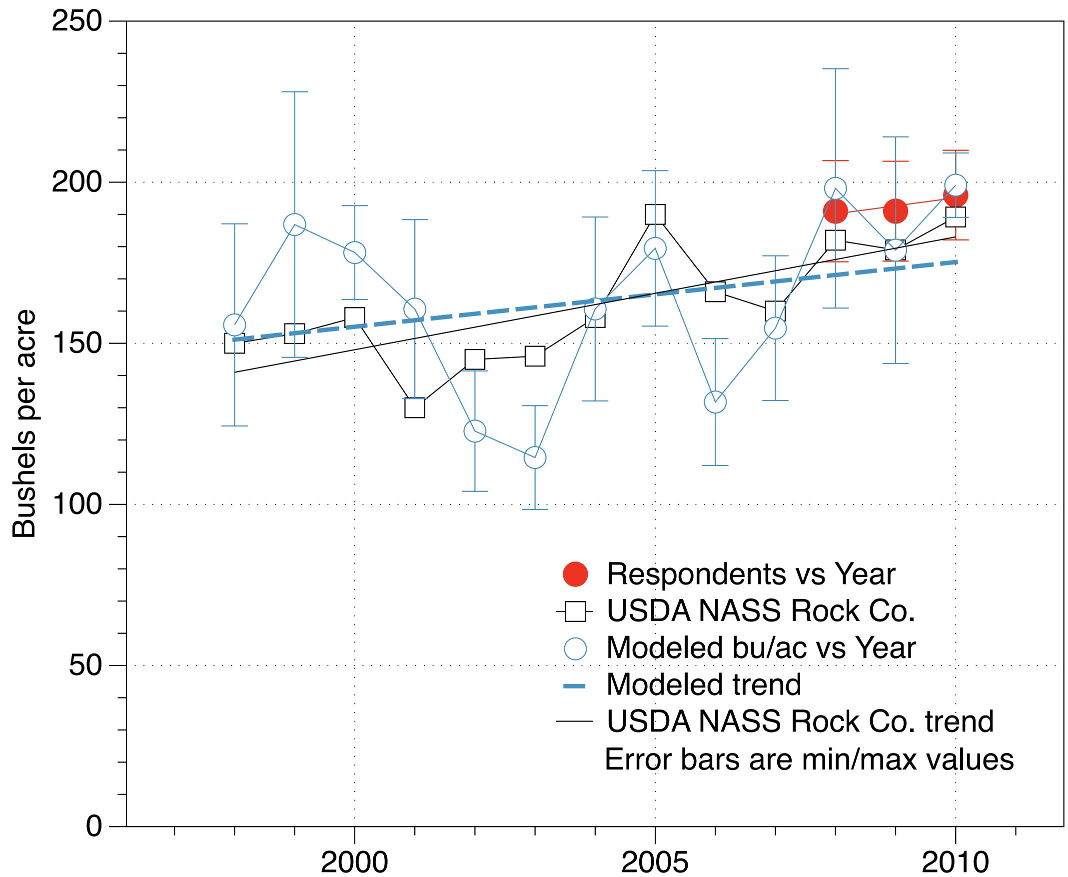

Figure 17. Comparison of modeled and reported yield data from 1998 to 2010

Table 7. Model average emissions associated with corn-soybean simulations for the surveyed farms

Soil emission	Average	StDev
Direct N2O g N2O per sq m yr	0.303	0.097
Indirect N2O g N2O per sq m yr	0.028	0.015
Total N2O g N2O per sq m yr	0.331	0.108
CO2 SOC g per sq m yr	-58	44
CO2 Soil N2O eq g per sq m yr	99	32
CO2 Soil total eq g per sq m yr	40	62

For conversion of N_2O-N (the measure for nitrous oxide reported by the model) to CO_2 equivalents, a molar ratio of 28 g N per 44 g of N_2O, is used along with a global warming potential (GWP) of 298 (corresponding to a 100 year time horizon) for N_2O, which is the value used by EPA in the US national greenhouse gas inventory. Net greenhouse gas emissions from the soil are about 40 gCO_2 eq per sq m per year, with substantial farm to farm variability as reflected in the standard deviations.

Tilling practices

Planting and tilling events were reported as DailyDayCent inputs for four events in the corn and soy rotations: 1) corn in the Fall, 2) corn in the spring, 3) soy in the Fall and 4) soy in the spring. The description of tillage practices and equipment provided in the survey responses were used to qualitatively categorize each tillage system per the designations in Table 8.

Table 8. Tilling categories used in DailyDayCent model and score

Reporting category for DailyDayCent model	Score used to evaluate tilling in this report
No till	0
Light	1
Light-Moderate	2
Moderate	3
Heavy-moderate	4
Heavy	5

The scores in the right column are arbitrary. They are used here in this report to come up with an overall indicator of the degree of tilling intensity for each farm. An overall score each farm was calculated as the average of the four scores for each of the four events when tilling and planting occur for each of the crops.

Figure 18 shows the average tillage scores for the survey respondents. Error bars reflect one standard deviation for each score. Not surprisingly, tillage for corn in the fall after harvest is, on average, fairly intensive. The average score of 4.21 puts the farms in the "heavy-moderate" category. Tillage in the spring before corn planting is "light-moderate." Tillage for the soybean rotation in the fall is between "light" and "light-moderate." Tillage in the spring before planting soy (presumably after a corn rotation) is in the "light-moderate" to "moderate" range.

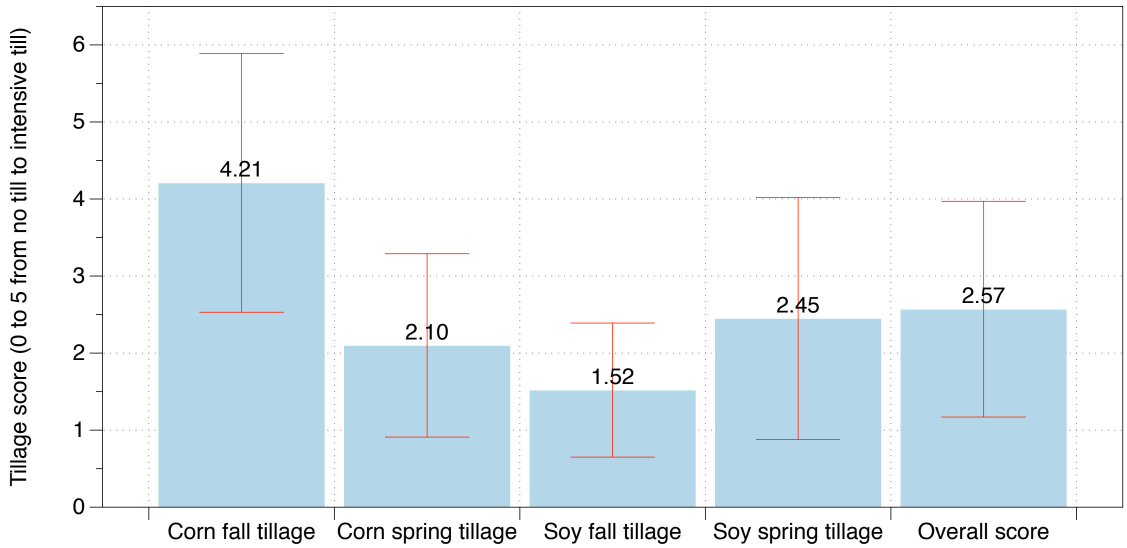

Figure 18. Average tilling intensity for corn and soybean rotations

Seed rates for survey respondents

Farmers in the survey planted 32,907 seed kernels per acre on an area-weighted average basis, corresponding to 18.51 lb per acre (20.78 kg per ha). This seed rate is consistent with the ongoing trend toward denser planting of corn, resulting in a steady increase in the number of kernels planted per acre since 1985 (see Figure 19).

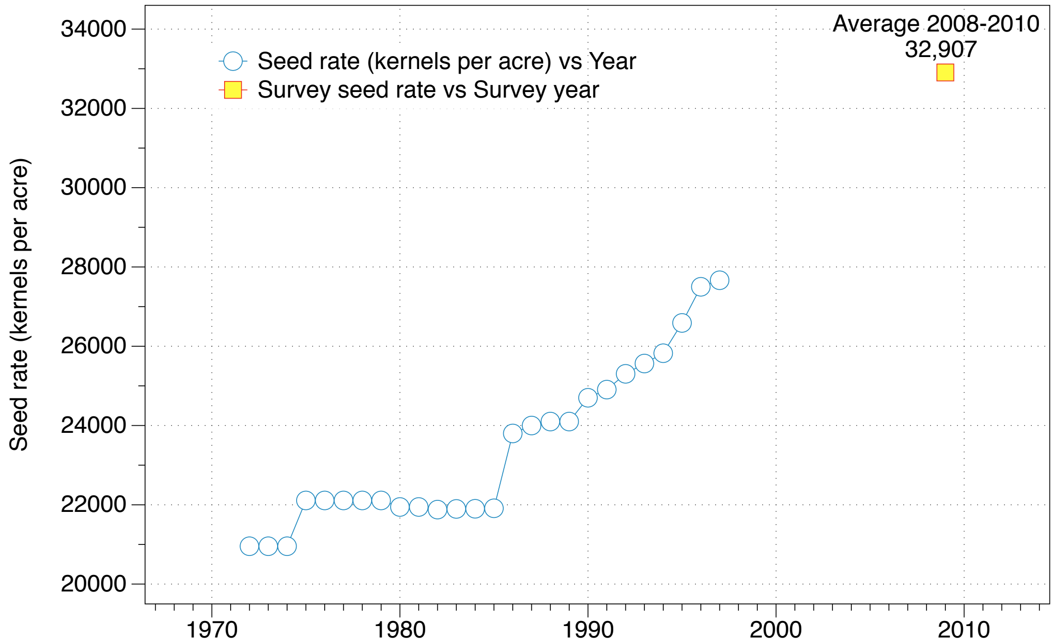

Figure 19. Area-weighted seed rate for survey respondents vs historical seed rates in the US

Fuel consumption for field operations and grain transport

While respondents to the survey provided their own estimates of total fuel consumption, in general we found that these numbers seemed low. Therefore fuel consumption demands were calculated based on other information provided in the survey. In the case of in-field fuel use, we constructed a spreadsheet model of fuel consumption for specific types of equipment and tilling practices to estimate the fuel consumed at each step of planting, tilling, cultivation and harvest as described in the survey responses (see Table 9).

Table 9. Equipment and energy requirements for various tilling, harvesting and planting activities

Operation	Implement Assumed	Diesel (gal/ac)
Min till Planting	16 Row-30 40 ft	0.53
Harvesting	Combine Corn Hd 8 Row-30 20 ft	1.88
Grain Cart	Grain Cart 30 ft	1.44
Lime, urea broadcast, urea dry, urea spreader, urea floater, other dry fert, DAP spinner	Spreading dry fertilizer, bulk cart	0.15
Herbicide - liquid or dry, fungicide - headline	Boom sprayer 50 ft	0.1
Stalk shredding	Stalk shredder 20 ft	0.17
SEEDBED prep	---	---
Ground roller used for soybean	---	---
Anhy tilling, anhy incorporate, anhy knife, anhy bar	Anhydrous ammonia (30-inch spacing)	0.55
Urea strip till	---	---
Corn residue baled and removed.	---	---
Rake corn stalks	Hy Rake (Wheel, 2-16") 30 ft	0.07
Bale corn stalks	Round Baler 1500 lb, 20 ft	0.35
Moving bales off field	Hauling, field plus 1/2 mile = green forage	0.3
Field cultivator	Field cultivator, 47'	0.32
Disk	Tandem Disk H.D. 30 ft fold	0.79
In-line ripper	V-Ripper 30" O.C. 17'	0.99
Row cultivation	16 Row-30, 40 ft	0.44
Soil finisher	Field cultivator, 47'	0.32
Strip-till machine	V-Ripper 30" O.C. 17'	0.99
Manure incorporated/broadcast	Spreading dry fertilizer, bulk cart	0.15
Manure injected with sweeps or knives	Chisel plow 15'	0.6
No till drill	No till drill 30ft	0.81
Harvesting silage	Corn Head for SP Harvstr Base 8 Row, 20 Ft	2.35
Disc-chisel	16.3 foot and 21.3 foot "Chisel plow, front disk"	0.97
Disc-ripper	Comb Disk & V-Ripper 22.5 or 17.5Ft	1.47

For grain transport to either the Gevo facility or to a local collection point, reported distances were used along with descriptions of the type of vehicles used to deliver the grain to estimate fuel required to haul the entire harvest (see Table 10). Fuel requirement for grain transport from each farm in a given year is simply calculated as:

$$\frac{2 \times \text{distance}}{\text{fuel economy}} \times \frac{\text{bushels per acre} \times \text{acres}}{\text{bushels per load}}$$

Table 10. Assumptions for grain transport energy requirements

Transport type	Fuel economy mpg	Capacity (bushels per load)
Semi	8	950
Tractor + wagon	3	1300
Grain truck	8	625
Tractor+wagon/Grain	5.5	962.5
Grain truck/Semi	8	625

Agrochemicals usage—herbicides and pesticides

Table 11 summarizes herbicide and pesticide usage as reported by farms, on an area-weighted basis across all farms and years.

Table 11. Area-weighted average herbicide and pesticide usage

Ag chemical	Application rate (kg per hectare)
Glyphosate kg per ha	0.7878
Glufosinate ammonium kg per ha	0.0108
Sulfonyl urea compounds kg per ha	0.0002
Phenoxy 2 4 D kg per ha	0.0042
Atrazine compounds kg per ha	0.1760
Acetochlor kg per ha	0.5174
Metolachlor kg per ha	0.0282
Dicamba kg per ha	0.0004
Clopyralid kg per ha	0.0088
Pesticides unspecified kg per ha	0.0298
Other herbicides kg per ha	0.0201
Isoxaflutole kg per ha	0.0010
Mesotrione kg per ha	0.0161
Diflufenzopyr kg per ha	0.0001
Flumetsulam kg per ha	0.0028

Lime usage

Figure 20 summarizes lime treatment rates for the US, Minnesota and the Gevo respondents.

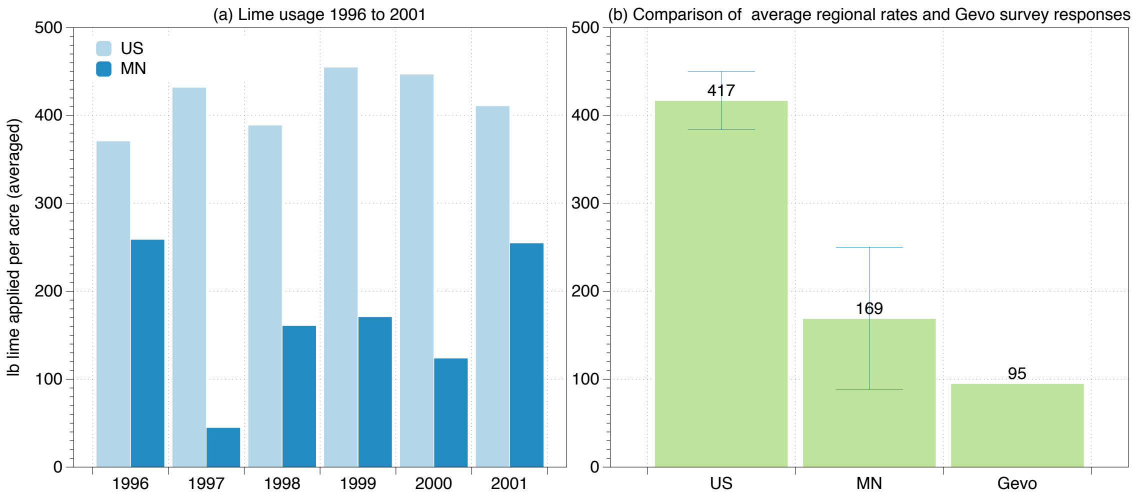

Figure 20. US and Minnesota trends for lime usage from 1996 to 2001

Gevo responses on average are just over half the average rates for Minnesota, at only 95 lb of lime per acre.[4] Given the huge variability from year to year in the state data (see chart on the left in Figure 20), we have little confidence in any of the estimates. This is a contentious issue. In a recent exchange on the life cycle impacts of corn ethanol, Plevin[5] argues that the correct value for average usage in the US Midwest states should be 425 lb per acre—very similar to the six year average shown in the chart on the right in Figure 20. But we note that levels of lime addition in Minnesota are consistently lower than the rest of the major corn producing states. So, it is not out of the question that rates for lime use are genuinely lower in Minnesota.

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[4]Data from USDA ERS for Illinois, Indiana, Iowa, Missouri, Ohio, Michigan, Minnesota, Nebraska, South Dakota and Wisconsin for the years 1996 to 2001.

[5]Liska & Cassman in *Journal of IndustrIal Ecology* 13 (2009)

However, we also do not have a lot of confidence in the reported lime values from our survey. The reason is that the survey questions related to lime treatment may lead to under-estimation of the actual value. Lime addition is typically not done on all acres, nor is it done every year. Our survey asks for the percent of acres treated with lime in each of the past three years, as well as the amount of lime applied. However, the USDA data reports the average number of years between lime application. For Minnesota, the average time between treatments is consistently around 5 years. With only three years of data, we cannot be sure that we have captured a complete picture of lime usage. As a result, we use the six year average for Minnesota of 169 lb per year.

A closer look at individual farms

Averages are fictions that serve at best to give us a very general sense of how the local corn supply for Gevo's plant stacks up against average corn production statistics at the national, state and county level. And since such averages are typically used in evaluating the carbon foot print of corn production, there is some value in looking at these numbers. But the really interesting information is obscured by such statistical summaries. That is because Gevo's interest goes beyond the possibility that their local supply may have a lower aggregate footprint relative to the national corn production system. Gevo wants to know if there are differences in existing farm practices that might suggest guidelines for improving the total supply pool for their facility. This requires looking at individual differences in farm operations.

Variations in yield

As Figure 21 shows, yields reported from farm to farm show significant variation. Inspection of the distribution suggests that there are at least two major groupings of farms. There is a large number of farms that consistently achieve around 9.5 Mg of corn per hectare per year. But there is a peak including around 30 annual yield data points at 10.5 Mg of corn per hectare per year. Finally, there is small group of data points representing yields between 11 and 12 Mg of corn per hectare per year. We are interested in investigating the causes of these differences, especially since most of the farms are in the same geographic region and thus experience the same climate conditions.

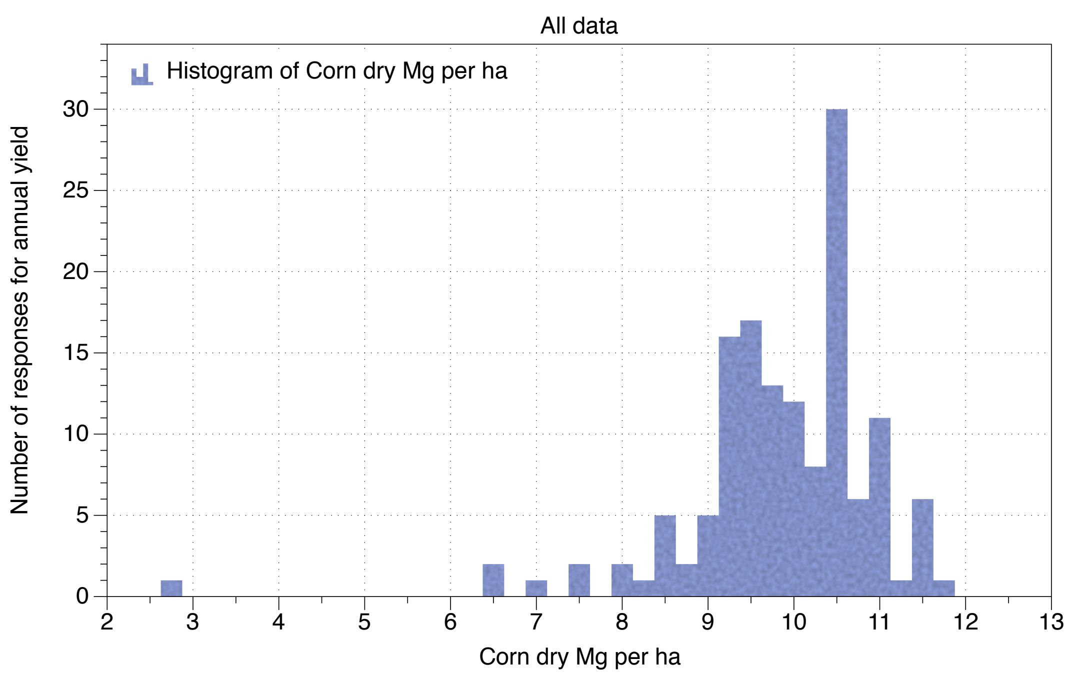
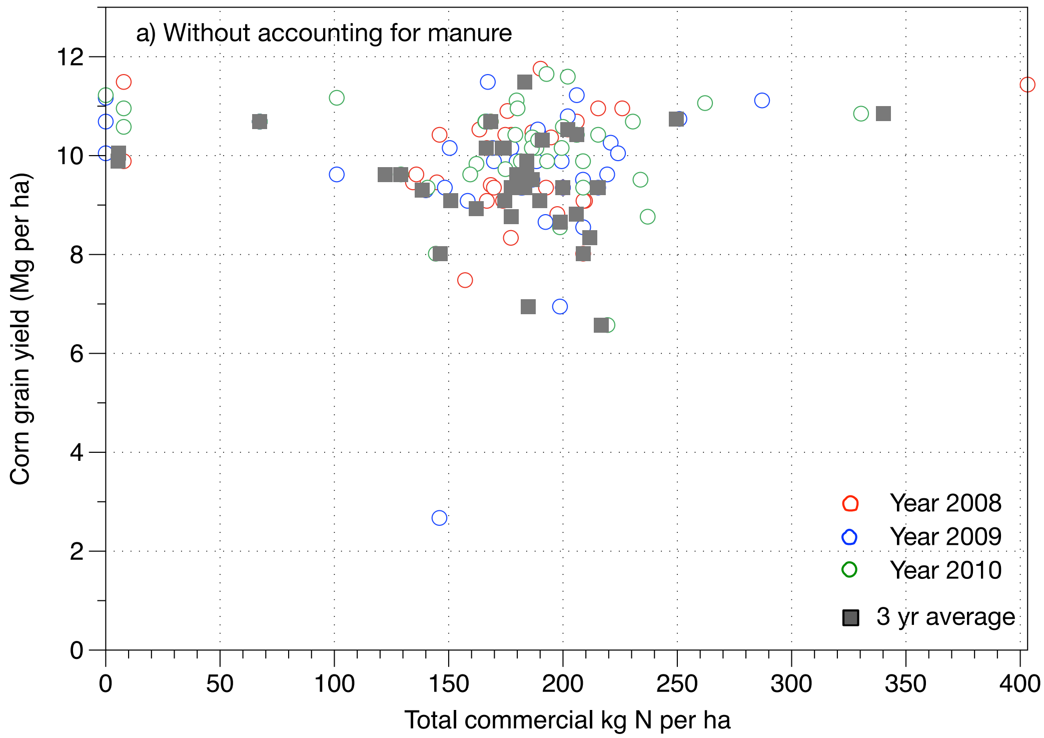


Figure 21. Distribution of corn grain yields (Mg per hectare)

Variation in nitrogen fertilizer use

Our first look at the fertilizer use data was puzzling. More than two thirds of total nitrogen use came from industrial fertilizer, but we found a number of farms that had zero rates of application for these fertilizers, while maintaining high yields (see graph in Figure 22a). A majority of farms show nitrogen fertilizer rates clustered around 150 to 250 kg N per ha, with values tailing off on the low and high side of the grouping (from zero to 400 kg N per ha.



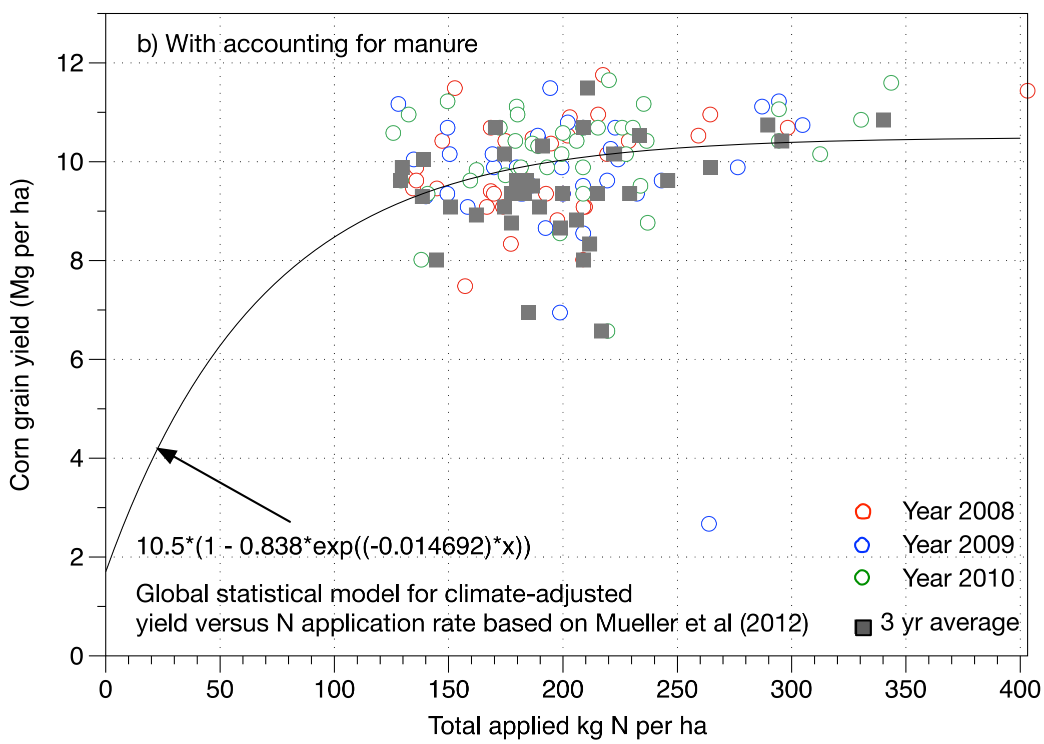


Figure 22. Yield and nitrogen fertilizer use among surveyed farmers

When we looked at total nitrogen application including manure on a farm by farm basis (Figure 22b), most of the farms' annual responses still clustered together in a range of 150 to 250 kg N per ha, with yields spanning 6 to 12 Mg per ha of grain. When corrected for manure use, the minimum level of nitrogen application rate is around 125 kg per ha. Perhaps more interestingly is the spread of farms that used any where between 200 and 350 kg per ha of nitrogen. The data reveal farms achieving consistently high yields of 10 Mg per ha, but with huge differences in how much nitrogen fertilizer they are using—a 3.5 fold difference from highest to lowest. Thus, while the average nitrogen usage did not show any differences between Gevo suppliers and the nation as a whole, the wide spread within this population reveals tremendous potential for finding a sweet spot of high yields at lower nitrogen usage rates. The average numbers hide the fact that some farmers are being extremely efficient in using nitrogen fertilizer, while others are applying large amounts of fertilizer that result in no commensurate yield gain.

We were also able to provide a global context to the respondents' effectiveness in using nitrogen fertilizer. The University of Minnesota's Global Landscapes Initiative (GLI) has developed statistical models of yields around the globe as a function of climate conditions and management practices (including fertilizer use). For each major crop (including corn), they have identified 100 distinct climate zones within which the differences in yield performance can primarily be explained by differences in farm management practices.

Not surprisingly, corn yield responds most strongly to fertilizer use (and, in particular, nitrogen usage). Nathan Mueller has provided us with his statistical analysis of the relationship between yield and fertilizer use for the climate zone that corresponds to the Luverne, MN region (see Mueller et al 2012). Note, this does not mean that the relationship is based only on the geographic region around Luverne. The yield data in this relationship comes from agricultural data for any region around the globe that has the same climate conditions as the Luverne, MN region.

Figure 22b overlays our farmer survey data on the global relationship for nitrogen developed by Nathan Mueller. The match between individual farm data in the Luverne region and the statistical model drawn from broad ranging global data sources is reassuring. With this global model as a guide, we can now hone in on the range of nitrogen application rates that correspond to the most efficient use of fertilizer. In this case, the ideal nitrogen use rate corresponds to the elbow in the response curve where yield is high, and incremental gains in yield due to incremental fertilizer additions are small. This starts somewhere around 180 kg of nitrogen per hectare. Much beyond this, the gain in yield from added fertilizer may not be worth the economic, energy and environmental cost of adding the nitrogen fertilizer to the field. Rates below 180 kg of nitrogen hectare lead to unacceptable yield losses. We plan to look much more closely at those farms that are able to hit this sweet spot.

Another way to look at this sweet spot is in terms the efficiency of nitrogen uptake in the plant. We have analyzed published data on nitrogen content in corn grain, corn cobs and corn stover to come up with ball park figures for total nitrogen uptake ratio as a function of corn grain yield and nitrogen fertilizer application rate. The nitrogen uptake ratio is defined as the estimated amount of nitrogen present in the corn plant at harvest divided by the total amount of nitrogen fertilizer (synthetic and manure) added to the field.[6] Figure 23 shows where the Gevo farmer respondents fall on this curve.

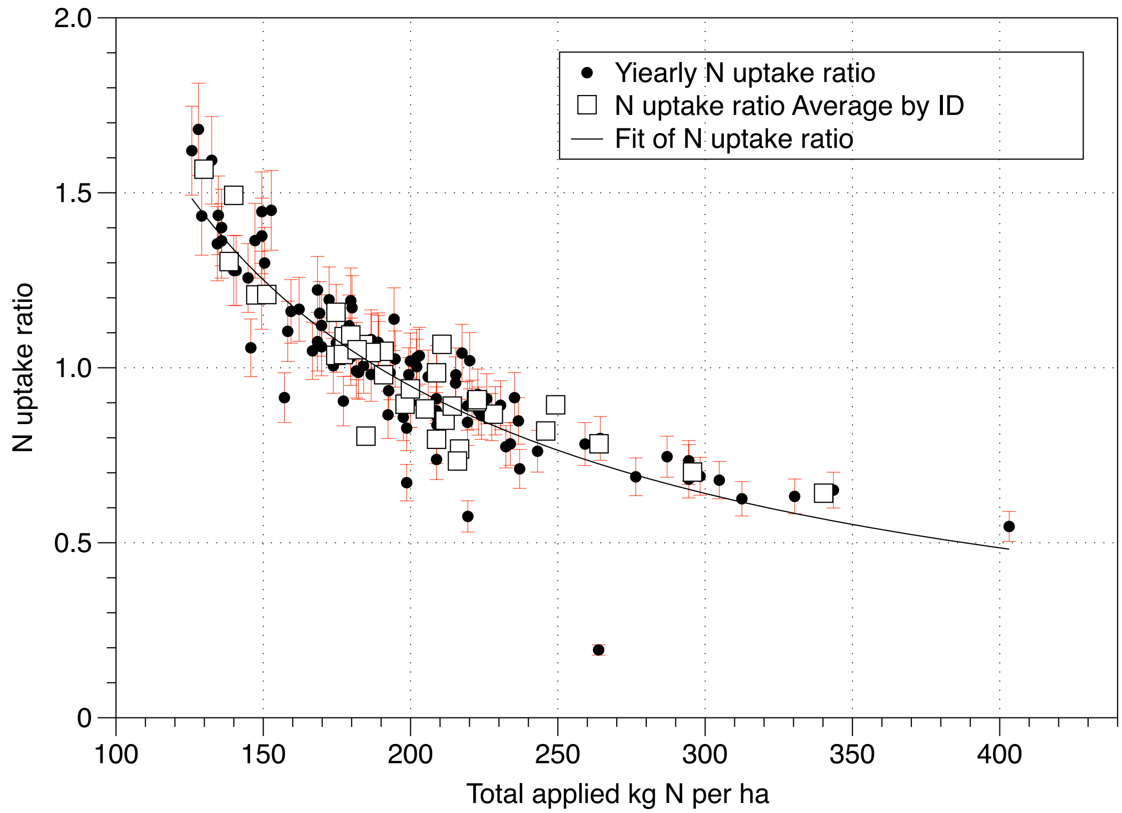


Figure 23. Nitrogen uptake ratio as a function of nitrogen application rate

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[6]See discussion of nitrogen balance and nitrogen uptake ratio in previous section entitled Nitrogen balance for survey respondents.

Figure 24 shows a histogram of distribution of nitrogen uptake ratios for the respondents. The target we are aiming for is an uptake ratio of 1, a goal already achieved by a substantial number of farmers for the three years of data reported. Figure 23 points to a nitrogen application rate of around 180 kg of nitrogen per hectare for a nitrgoen uptake ratio of 1.0. The error bars in this uptake ratio calculation, however, are substantial because of the high level of variation in published estimates for nitrogen content. While uptake rates of nitrogen cannot be greater than one (by definition), ratios above one in this case reflect at least two factors: 1) significant levels of residual nitrogen in the soil; and, 2) the error range in our nitrogen content estimates.

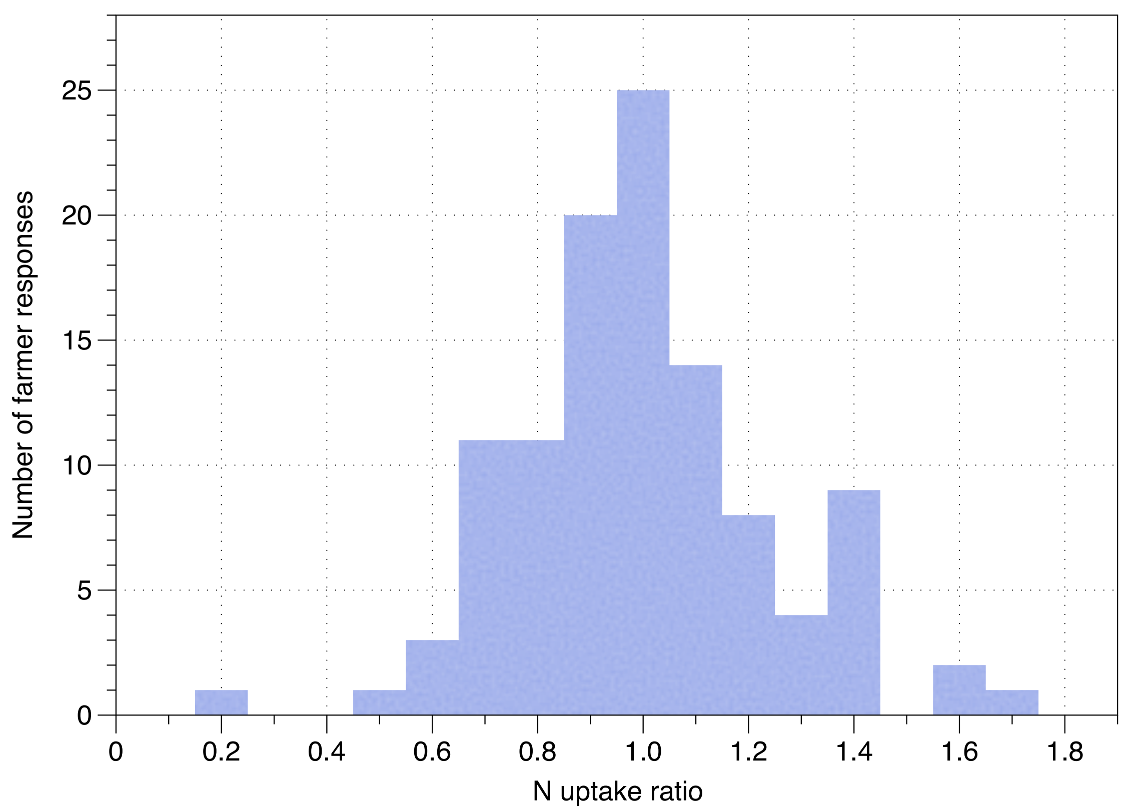


Figure 24. Distribution of N uptake ratios

Variations in phosphate fertilizer use

The next largest demand for fertilizer in corn production is phosphate. While phosphate is not a contributor to greenhouse gases and is not as fossil energy intensive to produce compared to nitrogen fertilizer, tracking its use is important for several reasons. First, phosphate is non-renewable. It is a mined product. USGS and others have suggested that declining levels of phosphate reserves could become critical in the next 50 to 100 years. Second, runoff of phosphate into ground water and surface waters is a significant pollution problem.

Figure 25 shows yield response to phosphate application rate. As with the nitrogen data, we have overlaid the Gevo data set on a global statistical model of corn yield response to phosphate addition. (Mueller et al 2012b) The match between the global model and the individual farm data is good, but not as good as it was for nitrogen. Managing phosphate is complicated by the fact that it's ability to remain in the soil is greater than that of nitrogen. This helps to explain why there are some data points from the survey that show phosphate addition rates of zero for which corn yield is still high. The general variability in addition rates is also higher than that for nitrogen. The findings suggest that there is still an opportunity to refine phosphate addition rates to find the sweet spot on the response curve corresponding to high yield and diminishing benefits of further addition, which occurs between 75 and 100 kg P_2O_5 per ha according to the global, climate-adjusted yield response curve.

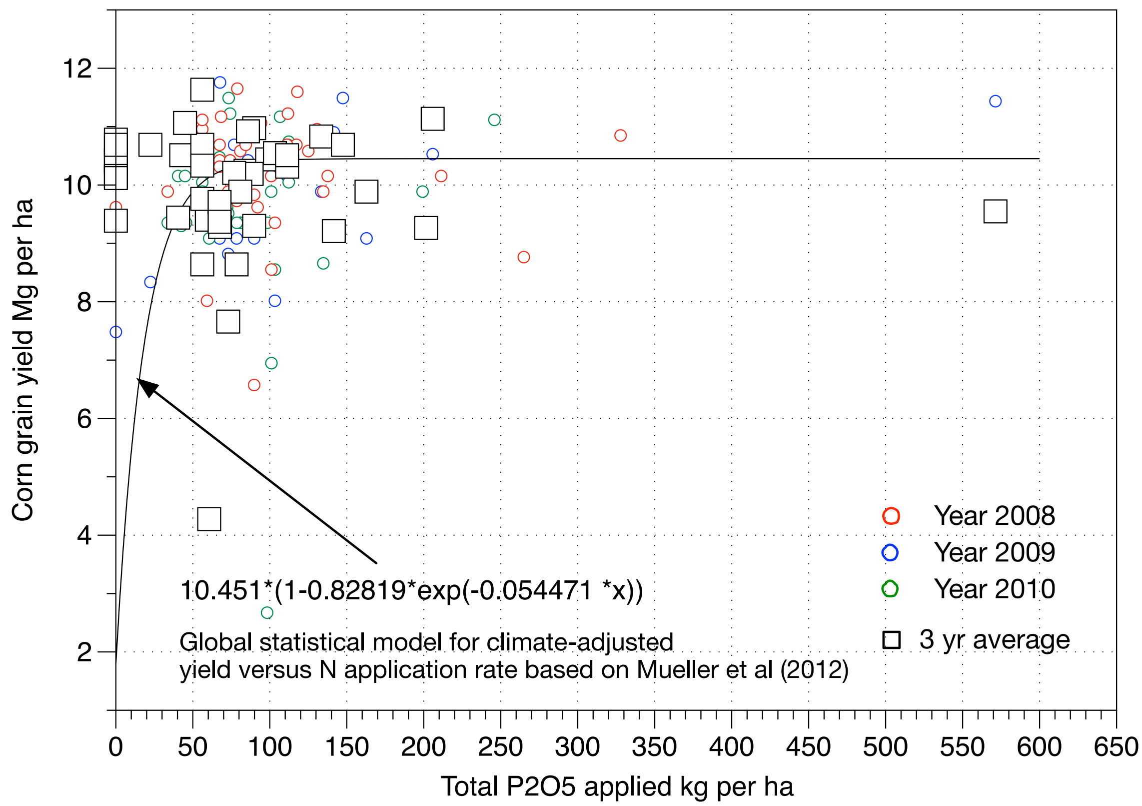


Figure 25. Gevo data for yield and phosphate usage overlaid on a global analysis of yield response to phosphate use for a climate zone equivalent to the Luverne, MN region

Figure 26 shows how the data from the survey respondents lies on a curve of phosphate uptake ratio as a function of phosphate application rate. Farmers in this survey are not concentrated around the uptake ratio of 1 as we saw for nitrogen fertilizer.

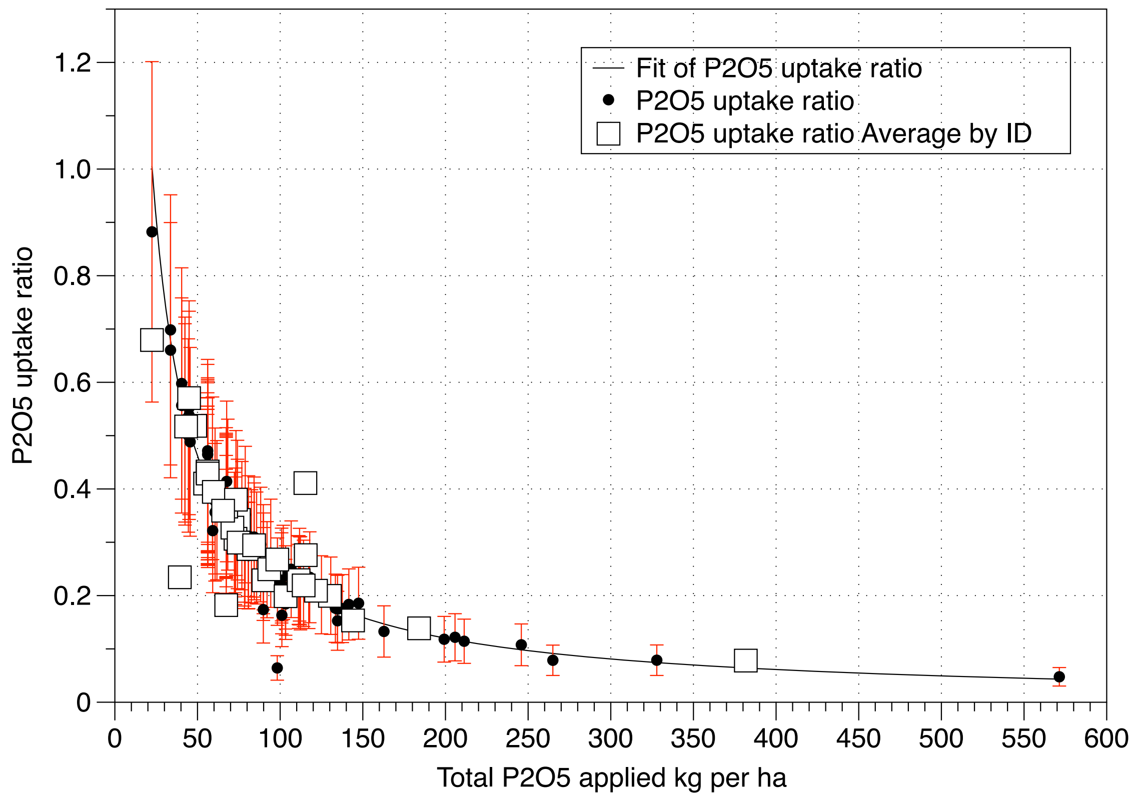


Figure 26. Phosphate uptake ratio as a function of phosphate application rate

The histogram of phosphate uptake shows a peak among farmers at around 0.3, suggesting that farmers are typically over-applying phosphate fertilizer by roughly a factor of three relative to the ability of the corn plant to utilize it. This could be due to phosphate's greater stability in the soil, and its resulting accumulation from year to year. Animal manure usage could also be an important contributing factor. The high phosphate-to-nitrogen levels in animal manure (relative to the proportion required for efficient plant utilization) could mean that, at higher levels of animal manure use, farmers are effectively over-applying phosphate.

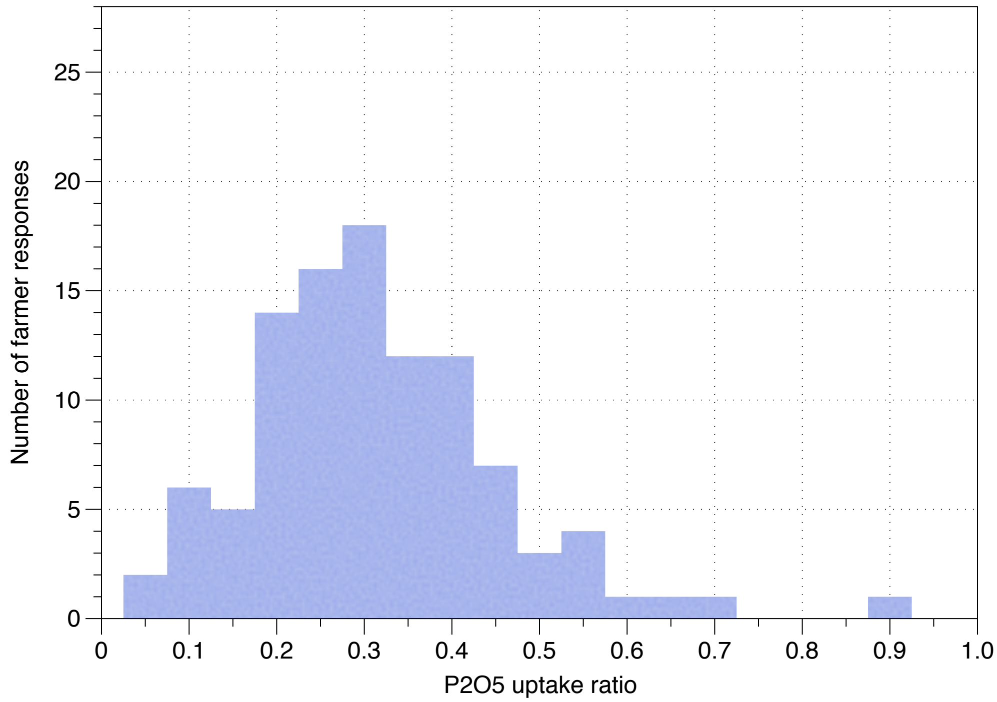


Figure 27. Histogram of phosphate uptake ratio for the Gevo farm responses

Variations in potassium fertilizer use

The third most important nutrient used to fertilize the farms' fields is potassium (K) usually in the form of potash. Figure 28 shows corn yield response to potassium application rate. As with the nitrogen and phosphate data, we have overlaid the Gevo data set on a global statistical model of corn yield response to potassium application rate. The scatter and fit for yield response for potassium is worse than those seen for phosphate, reflecting, perhaps, the greater difficulty of predicting addition rates to accommodate residual potassium in the soil.

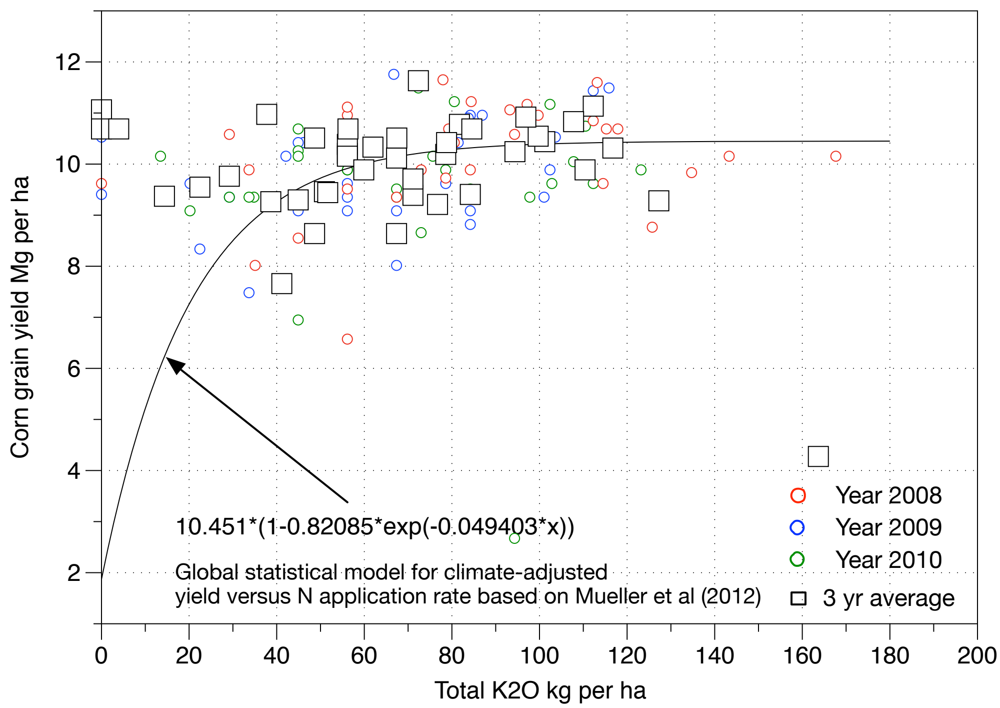


Figure 28. Gevo data for yield and potassium usage overlaid on a global analysis of yield response to potassium use for a climate zone equivalent to the Luverne, MN region

Most farms appear to be operating at potassium uptake ratios between 1 and 2, but there is a large spread in the ability of farmers to match addition rates to net crop demand (Figure 29 and Figure 30).

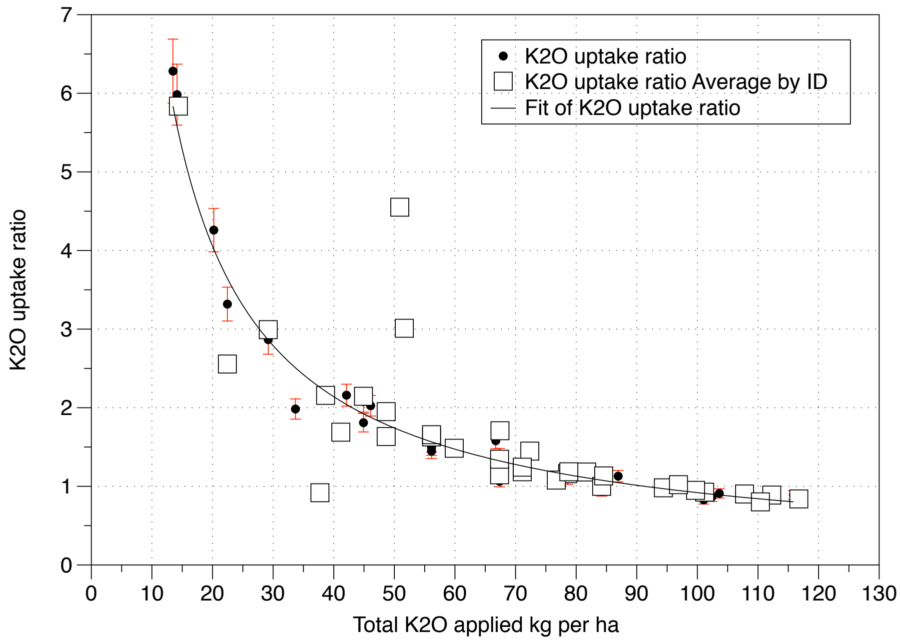


Figure 29. Potassium uptake ratio as a function of K2O application rate

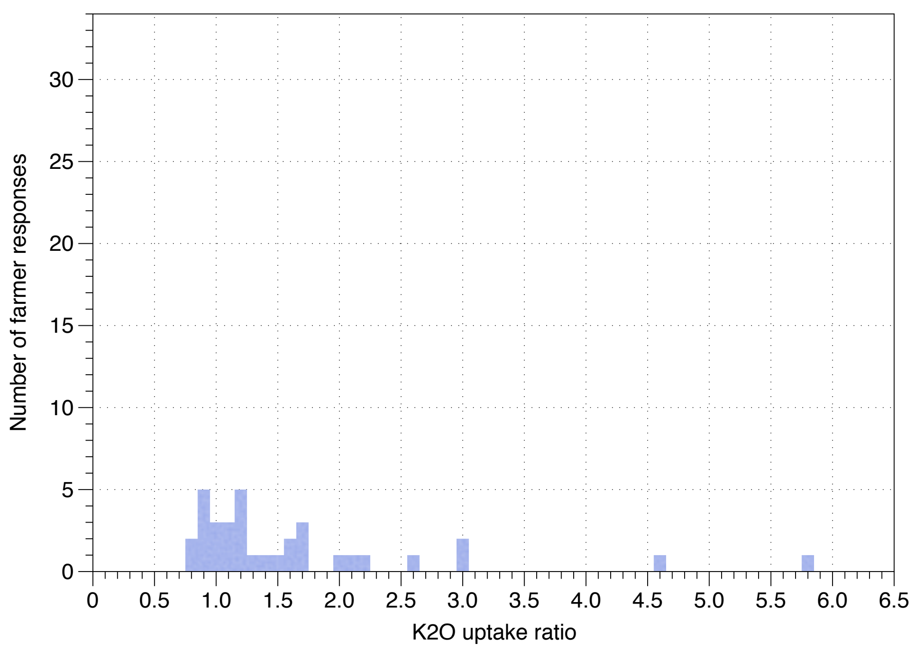


Figure 30. Histogram of potassium uptake ratio for the Gevo farm responses

Overall carbon footprint of the corn supply

Life cycle results

Table 12 shows the average inputs and carbon footprint for the surveyed farmers.

Table 12. Life cycle inputs and estimated carbon emissions for the overall Gevo corn supply

Item	Units		kg CO2eq per ha	g CO2eq per kg corn
Hectares of corn planted (wt avg)	ha	371.00		
Corn Yield - weighted mean	kg / ha	10,277.		
Maize seed IP, at regional storehouse/CH U	kg / ha	20.78	37.27	3.63
Fertilizers			581.83	56.62
Ammonia, liquid, at regional storehouse/RER U	kg-N/ha	57.17	116.34	11.32
Ammonium Sulfate, as N, at regional storehouse	kg-N/ha	1.66	4.09	0.40
Urea, as N, at regional storehouse/RER U	kg-N/ha	87.21	415.16	40.40
Diammonium phosphate, as P2O5, at regional storehouse/RER U	kg-P2O5/ha	13.51	20.36	1.98
Monoammonium phosphates	kg-N/ha	4.19	10.71	1.04
Potassium chloride, as K2O, at regional storehouse/RER U	kg-K2O/ha	40.26	15.08	1.47
Ammonium polyphosphate, as N	kg-N/ha	0.59		
Ammonium thiosulfate, as N	kg-N/ha	0.06		
Zinc sulfate	kg / ha	0.06	0.11	0.01
Lime – acre-weighted mean	kg / ha	189.74	203.02	19.76
Pesticides	kg / ha	1.60	21.51	2.09
Energy Use				43.79
Diesel, total	liter/ha	68.22	227.39	22.13
Gasoline	liter/ha			
LPG, weighted mean	liter/ha	83.93	152.96	14.88
Natural Gas, weighted mean	m3/ha	0.01	0.00	0.00
Electricity, weighted mean	MJ per kg grain	0.0325	69.62	6.77
Soil emissions				
Soil carbon	gCO2/sq m	(58.45)	(584.53)	(56.88)
Soil nitrogen, total	gCO2/sq m	98.52	985.16	95.86
Depreciable capital	gCO2/kg grain	5.8	60	5.8

The numbers are based on area-weighted averages for all aspects of the farms that responded to the survey. Embodied life cycle energy and carbon emissions associated with farm inputs are derived from the SimaPro life cycle software package (Pre 2012). Soil emissions are derived using the DayCent model as described previously. Table 13 provides a more detailed breakdown of the non-fertilizer ag chemical inputs and their related carbon emissions.

Table 13. Life cycle inputs related to agricultural chemicals (non fertilizer)

Item	Units		kg CO2eq per ha	g CO2eq per kg corn
Organophosphorus compounds (Glyphosate+Glufosinate-ammonium)	kg / ha			
Glyphosate - total	kg / ha	0.79	15.00	1.46
Glufosinate-ammonium	kg / ha	0.01	0.10	0.01
[Sulfonyl]urea compounds	kg / ha	0.00	0.00	0.00
Phenoxy compounds	kg / ha			
2,4-D	kg / ha	0.00	0.01	0.00
Triazine compounds	kg / ha			
Atrazine and atrazine-related compounds	kg / ha	0.18	0.99	0.10
Acetamide-anillide compounds	kg / ha			
Acetochlor	kg / ha	0.52	4.70	0.46
Metolachlor	kg / ha	0.03	0.26	0.03
Benzoic compounds	kg / ha			
Dicamba	kg / ha	0.00	0.00	0.00
Clopyralid	kg / ha	0.01	0.06	0.01
Pesticide unspecified	kg / ha	0.03		
Herbicide unspecified	kg / ha	0.02	0.19	0.02
Isoxazole compounds (Isoxaflutole)	kg / ha	0.00	0.01	0.00
Triketone compounds (Mesotrione)	kg / ha	0.02	0.15	0.01
Semicarbazone compounds (Diflufenzopyr)	kg / ha	0.00	0.00	0.00
Triazolopyrimidine compounds (Flumetsulam)	kg / ha	0.00	0.03	0.00
Strobilurin compounds - Pyraclostrobin (fungicide)	kg / ha	-	-	-
Insecticides (none applied according to farmers)	kg / ha			
Total	kg/ha	1.60	21.51	2.09

Table 14 and Figure 31 provide a comparison of the carbon emissions for the Gevo supply with estimates for the average US corn supply as estimated in the GREET model. The average greenhouse gas footprint for the survey sample of farmers is 55% lower than that of the average footprint for US corn ethanol as reported by Argonne National Laboratory's GREET model. The substantially lower emissions for the Gevo supply is due to a combination of higher yields observed for these farms—something we see in both the survey sample and in reported historical yields for the region (as discussed in the previous section of this report)—and lower inputs and soil emissions per kg of grain. The average yield in the survey sample was 10.3 metric tons per hectare (193 bushels per acre) versus 8.5 metric tons per ha (158 bushels per acre) for the US. Per hectare emissions are still 45% lower. This figure is not influenced by yield. The higher yields contribute an additional 10% to the reduction in carbon emissions.

Table 14. Comparison of carbon footprint for the Gevo corn supply with US average corn supply

GREET input	Gevo		GREET		Percent change	
Yield bu/acre	192.3		158		22%	
Yield (kg per ha)	10277		8500		21%	
	kg CO2eq per ha	g CO2eq per kg grain	kg CO2eq per ha	g CO2eq per kg grain		
Total soil emissions	401	39	1,360	160	-21%	-76%
Soil carbon emissions	(585)	(56.88)	nr	nr		
Soil nitrogen emissions	985	96	1,360	160	-28%	-40%
Ag chemicals (non fertilizer)	21.5	2.1	81	10	-73%	-78%
Lime	203	19.8	502	59	-60%	-67%
Fertilizer	583	56.7	678	80	-14%	-29%
Diesel/gasoline	227	22.1	307	36	-26%	-39%
LPG	153	14.9	67	7.9	128%	89%
Natural gas	0.00036	0.000035	50	5.9	-100%	-100%
Electricity	70	6.8	58	6.8	21%	0%
Deprec. Capital*	60	5.8	49	5.8	21%	0%
Total	1718	167.1	3152	371	-46%	-55%

*Reflects an assumed annual carbon emission associated with production of equipment and annualized over the life of the equipment. The value is from GREET and is reported as 246 gCO2eq per annual bushel harvested.

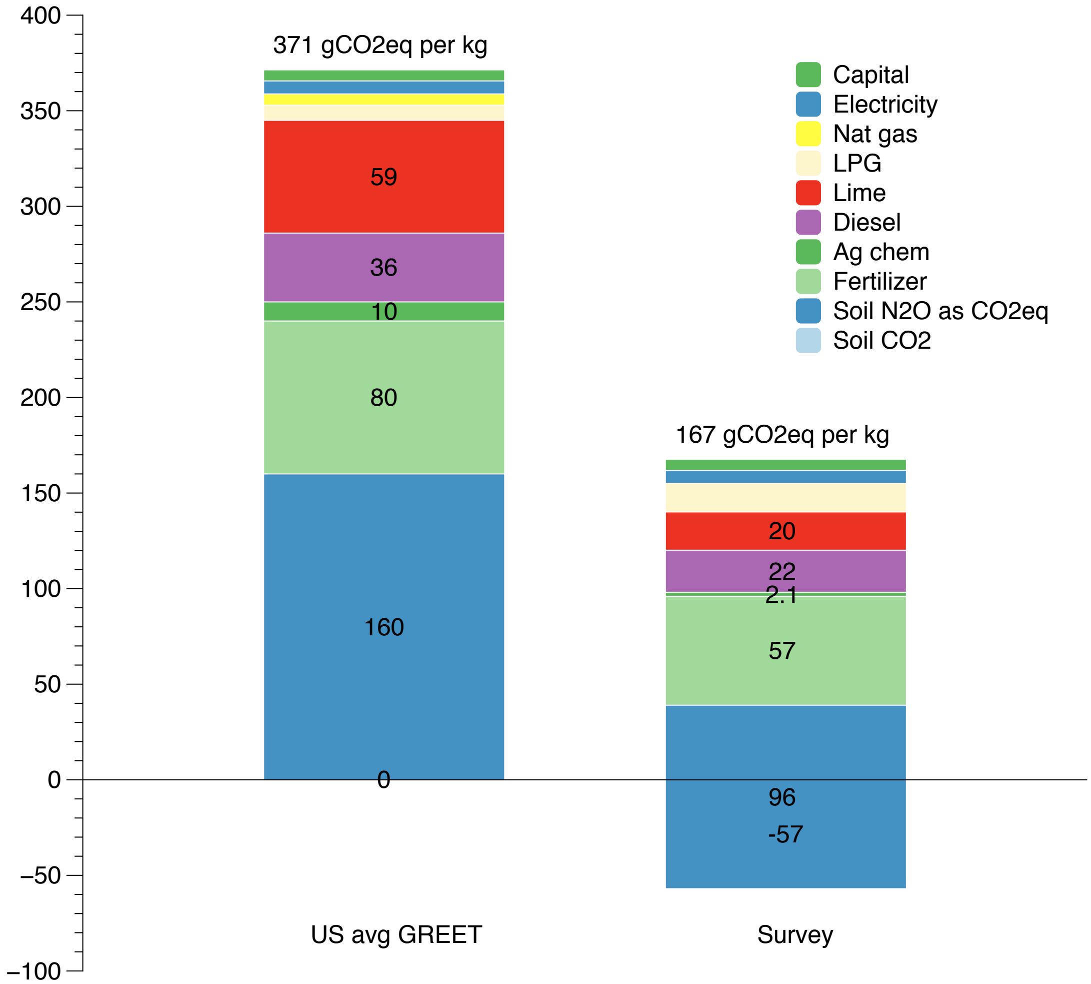


Figure 31. Comparison of Gevo corn supply and US corn supply carbon footprint

Figure 31 also shows the relative contribution of different factors to the greenhouse gas emissions for both the Gevo supply as characterized by our survey-based LCA and the US corn supply as characterized by GREET. Their relative proportion of contributions are similar. Largest is the release of nitrogen oxides from the soil, reported here as CO_2 equivalents. Nitrous oxide accounts for 43% and 57% of the carbon footprint, respectively, for the US and Gevo corn supplies. If we ignore soil carbon sequestration effects (which are not calculated in the GREET model), the contribution of nitrous oxide emissions to carbon footprint of the surveyed farms is the same as that estimated by the GREET model (43%).

Next largest are emissions associated with production of fertilizers used on the farm (22% and 34%, respectively, of the carbon footrpints for the US and the Gevo supplies). Eliminating soil carbon sequestration in our estimated carbon footprint for the surveyed farms brings the contribution of fertilizer to 25%, again comparable to the contribution estimated for the US supply using GREET.

Fuel for planting, tilling, harvesting and grain transport contribute around 10% to the carbon footprint of the grain (in both the US average and the Gevo supply estimates) when we exclude the effect of soil carbon sequestration in the surveyed farms.

The impact of lime usage in the US carbon footprint is substantial—16% of the total emissions. In the Gevo supply, lime usage contributes only 9% to the total emissions in the survey group when soil carbon sequestration is excluded (more discussion of this later). The remainder of the carbon footprint is associated with electricity, natural gas and LPG usage for drying and storage and a small contribution from emissions associated with manufacture of equipment and other capital items on the farm.

Note that we did not collect data from Gevo suppliers on capital equipment turnover. Furthermore, data on electricity use was frequently not provided by the survey respondents. In order to make our results comparable to those reported for the US corn supply, we adopted the US GREET values for carbon emissions due to electricity consumption and to capital replacement for all farms in the survey data set.

So, where do the rest of the carbon savings come from—that is, the emission reductions not directly proportional to increased yield? The largest sources of savings in the Gevo supply come from reduced soil nitrogen emissions, high rates of soil carbon sequestration and reduced lime usage. As shown in Table 14, on a per hectare basis (which is independent of yield), soil emissions among the Gevo farm respondents are 71% lower than the estimate for soil emissions calculated in the GREET model for the US corn supply—401 kg CO_2eq per ha for the Gevo supply versus 1,360 kg CO_2eq per ha for the US corn supply. This is due to lower soil nitrogen emissions and a substantial CO_2 offset associated with a net increase in soil organic matter.

Emissions from lime treatment of corn fields in the Gevo supply are only a third of the emissions estimated for the US corn supply on a per kg of grain basis. However, we do not have a reliable measure of lime usage among the Gevo respondents because of the way we asked for data on lime usage (see the discussion in previous section Lime usage). As a result, the Gevo LCA estimate is based on an average lime application rate for the state of Minnesota, which is substantially below the US average for lime application rates.

Taken together, soil emissions and lime emissions account for almost three-quarters of the reduction in carbon emissions for the Gevo supply versus the US supply. In both cases, it is difficult to say if the reductions are "real." The methodologies used to calculate soil nitrogen emissions are different. And, the GREET analysis took no account of soil organic matter changes. As discussed already, there is significant uncertainty in the lime application rates. Since lime addition rates may simply be due to regional differences in soil acidity and not a specific management-related option, there is a reasonable argument to be made that we should ignore the apparent carbon savings associated with the lower lime rates when comparing the carbon footprint of our survey group with the US.

Lower levels of synthetic fertilizer and agricultural chemical use among the Gevo suppliers also contribute to a more favorable comparison with the US average (beyond the effect of higher yield). Some of the reduced fertilizer use is due to a significant amount of animal manure use as a substitute for industrial fertilizer. The remainder of the emissions savings for the Gevo corn supply are not significantly different from the savings associated with the higher yields.

Given the caveats just discussed about the reduced emissions from soil nitrogen and lime application, we conclude that the overall carbon footprint of the corn supply available to the Gevo facility is at least 20% smaller than the footprint of the broader US corn supply as estimated by the GREET model—based simply on the fact that the Gevo suppliers are achieving higher yields of grain compared to the US average. If the differences in emissions from soil and lime use are real, then the reduction in footprint could be as much as 55%. But given the ambiguities with respect to the comparison of these two sources of emissions, we think this higher estimate of carbon savings should be viewed with caution.

Putting soil emission estimates in perspective

In this study, we rely entirely on modeled estimates of soil organic matter and soil nitrogen emissions to predict soil contributions to the net greenhouse gas emissions of each farm. We do not have specific measurements of soil carbon or soil emissions for these farms. The same may be said for the US average greenhouse gas estimates reported by GREET. In our study, we use a mechanistic model that assesses soil carbon dynamics within the top 30 cm of soil. In the case of the GREET model, soil carbon changes are ignored, a de facto assumption that soil carbon emissions are unaffected by tillage practices or by higher yields. For nitrogen emissions, we also use a mechanistic model of nitrogen dynamics in the top 30 cm of the soil. In the case of the GREET model, soil nitrogen emissions are estimated using a simplistic assumption that soil N_2O is proportional to nitrogen application rates.

We acknowledge that the modeling of soil emissions, particularly with respect to the effects of tillage, has some ongoing uncertainty and controversy. Baker et al (Baker et al 2007) argued that when the total soil carbon to 1 m is counted, they see no statistical difference in soil carbon. The issue, which is addressed in several recent papers (Kravchenko, & Robertson 2011; Syswerda et al 2011), is that a) there is high variability in soil carbon contents at depth, and b) most soils have a lot of carbon relative to the changes theoretically attributable to tillage (or other management practices). Hence tillage effects are characterized by a low "signal-to-noise" ratio. Thus when you simply sum all soil carbon to a 1 m depth, the high spatial variability swamps any differences that might exist in the surface layer (e.g. 0-30 cm).

There is evidence from long-term field experiments around the world showing that – in most cases – no-till promotes additional soil C storage over intensively till systems, provided that the no-till system is agronomically appropriate – i.e., generates roughly similar (or higher) yields relative to the conventional system (West, & Post 2002; Ogle et al 2005; Johnson et al 2005; Ogle et al 2012; Franzluebbers 2010). Moreover, we know something about the mechanisms, based on laboratory and stable isotope studies, that explain increased carbon storage due to reduced soil physical disturbance when farmers do no till. This involves the role of soil aggregates in stabilizing organic matter in forms and locations that are less susceptible to microbial attack and mineralization to CO_2 (Paustian et al 2000; Six et al 2000).

Co-author Paustian's lab conducted a meta-analysis of tillage effects for the International Panel on Climate Change (Ogle et al 2005)based on data from about 130 long-term experiments, globally. The analysis included data from experiments where there was sampling to at least 30 cm depth and analyzed for any differences below 30 cm as well. The implied mean change in total soil carbon stocks to 30 cm depth, for temperate-moist cropland, was a 15% increase in stocks over a 20 year time period. For the Luverne farms with ca. 50-60 tonnes C (top 20 cm), using that value would give an average annual C increase rate of 0.375-0.45 tC/ha/yr. That is consistent with average rates of 0.45 tC/ha/yr estimated by Johnson et al. (Johnson et al 2005) for the US CornBelt and the 0.34 tC/ha/yr average for the US from West and Marland (West, & Marland 2002). In the DayCent runs for this study, simulated differences between intensive and no till farms were around 0.32 tC/ha/yr, well within the range of empirical data.

To summarize, our findings would be much stronger if they were accompanied by actual field measurements. Such measurements were well outside the scope and funding available for this work. Our modeled results are, however, in line with reported values for soil carbon effects of tillage practices in the Midwest.

The carbon footprint of individual farms

Figure 32 summarizes the carbon footprint of Gevo's corn supply based on an LCA analysis of each farm's operation. Results are reported in grams of carbon dioxide equivalent per kg of harvested corn grain. This complete listing of results shows an extraordinary range of values. The best performing farm actually has a negative carbon footprint of -117 gCO_2eq per kg of grain—132% lower than the US corn supply average. This farm has three major advantages over many of the other farms in the survey. It relies almost exclusively on animal manure for its fertilizer, it uses no till practice, and it manages soil nutrient additions carefully. Use of animal manure avoids fossil emissions from commercial fertilizer production. In our analysis, no till practice results in very high modeled rates of soil organic carbon build-up (of around 240 gCO2 sequestered per kg of grain) and possibly lower rates of soil nitrous oxide emissions. Finally, the careful management of fertilizer reduces release of soil nitrous oxide emissions. The largest carbon footprint corresponds to 304 gCO_2eq per kg of grain, but is still less than the US average carbon footprint for corn. This farm applies aggressive tilling practices and uses excessive amounts of nitrogen fertilizer, all from commercial sources.

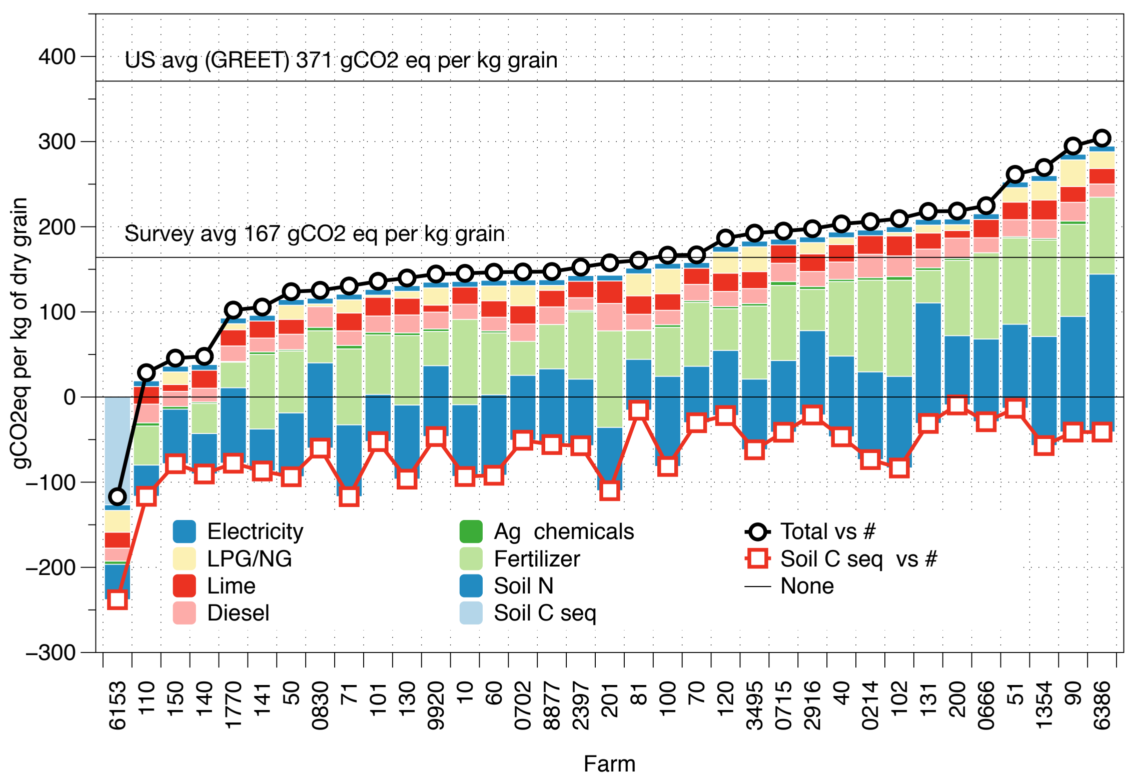


Figure 32. Grading on a curve—individual farm performance in terms of carbon footprint

Scenarios for reducing the carbon footprint of corn

The analysis of the individual farms points to three critical levers for reducing greenhouse gas emissions in the Gevo corn supply:

1. Encouraging adoption of no till or low till practices

2. Improving nitrogen management to achieve higher yields with lower nutrient inputs
3. Integrating livestock systems with crop production in order to make use of manure as a nutrient supply.

Obviously, the combination of these three strategies (as seen in farm 6153 in Figure 32) would allow for the greatest reduction in the survey group's emissions if they were adopted by all of the farms. More importantly, these strategies are not likely to be strictly independent of each other. In the following sections, we tease out a more quantitative understanding of the potential impact of these three factors.

Tillage impacts

From the outset, we assumed that tilling practices would play a major role in mitigating the carbon footprint of corn production through their effect on both soil carbon and soil nitrogen emissions. The results of the Daycent model prove this out, though we hasten to say that the number of data points available from the survey to evaluate no till practices turned out to be quite small. The conclusions we draw here are thus very preliminary, and will require much more analysis and data collection to improve the precision and accuracy of the findings.

A statistical analysis of the data for tillage effects is problematic since we had only three farms reporting no till in one of their tilling cycles, and only four farms reporting moderate tillage. All the rest of the farms indicated that they intensively till after the corn harvest in the fall, though they do tend to use more moderate tillage practices before corn planting and in planting and harvesting cycles for soybeans.

Nonetheless, the results in Figure 33 offer some interesting insights. We can compare the average soil N_2O emissions for the no-till farms with the moderate and intensively tilled farms. The plot suggests that N_2O emissions decline steadily in moving from intensive to moderate to no till practices. The error bars (representing one standard deviation) suggest, however, that the emissions for moderate tillage are not statistically different than those of either the no till or intensive till operations. There is a a statistically significant difference between no till and intensive till farm practices. Soil N_2O emissions may be as much as one half lower when farmers choose no till operations over intensive till.

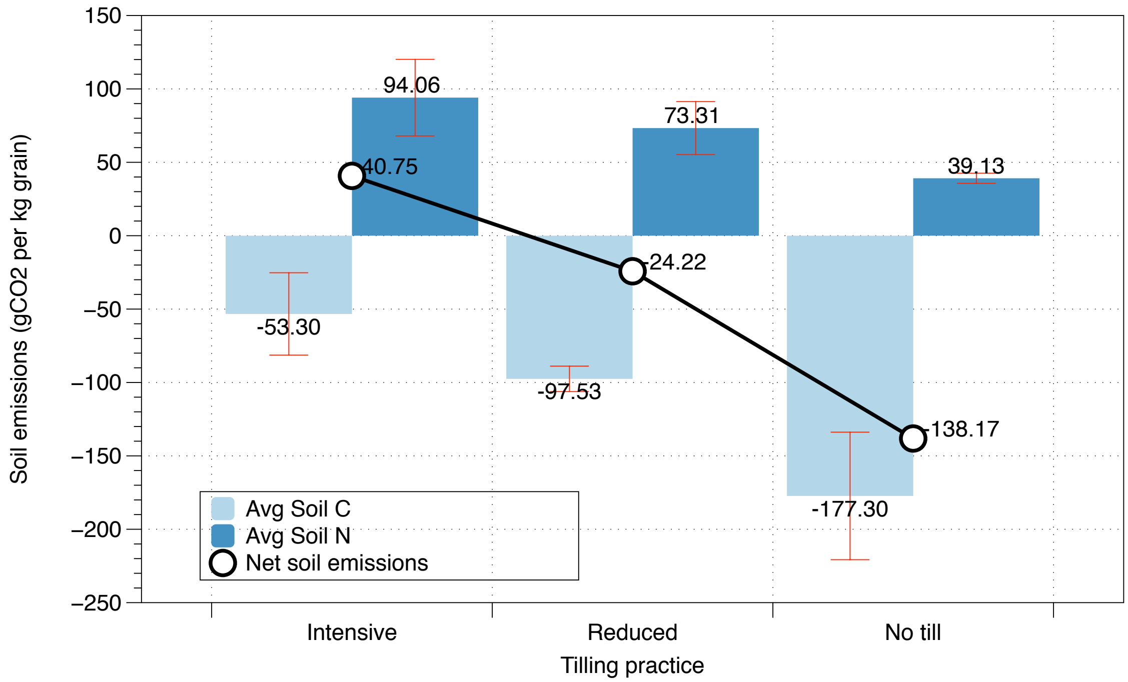


Figure 33. Modeled Soil N_2O and CO_2 emissions for farms under different tilling practices.

The model results for each farm show that almost all farms have experienced net increases in soil organic matter. This translates into a net negative flow of CO_2 from the soil (the movement of CO_2 in the atmosphere into the soil in the form of organic carbon). The rate of carbon capture into the soil rises as farms shift from intensive to no till practices. The net effect of combined carbon and nitrogen flows is that soil in intensively tilled farms have a net positive flow of greenhouse gases into the atmosphere, while both reduced and no till corn fields have negative flows of greenhouse gases.

Nutrient uptake ratio

Nitrogen uptake efficiency turns out to be a very important driver of the greenhouse emissions from the production of corn. As discussed previously, we estimate nitrogen uptake as the ratio of nitrogen taken up in the leaves, stalks, cob and grain in the plant to the amount of total nitrogen applied as industrial fertilizer and/or manure. Higher ratios should (and do) correspond to lower nitrogen losses from the soil and thus lower greenhouse gas emissions. Figure 34 illustrates this point very clearly.

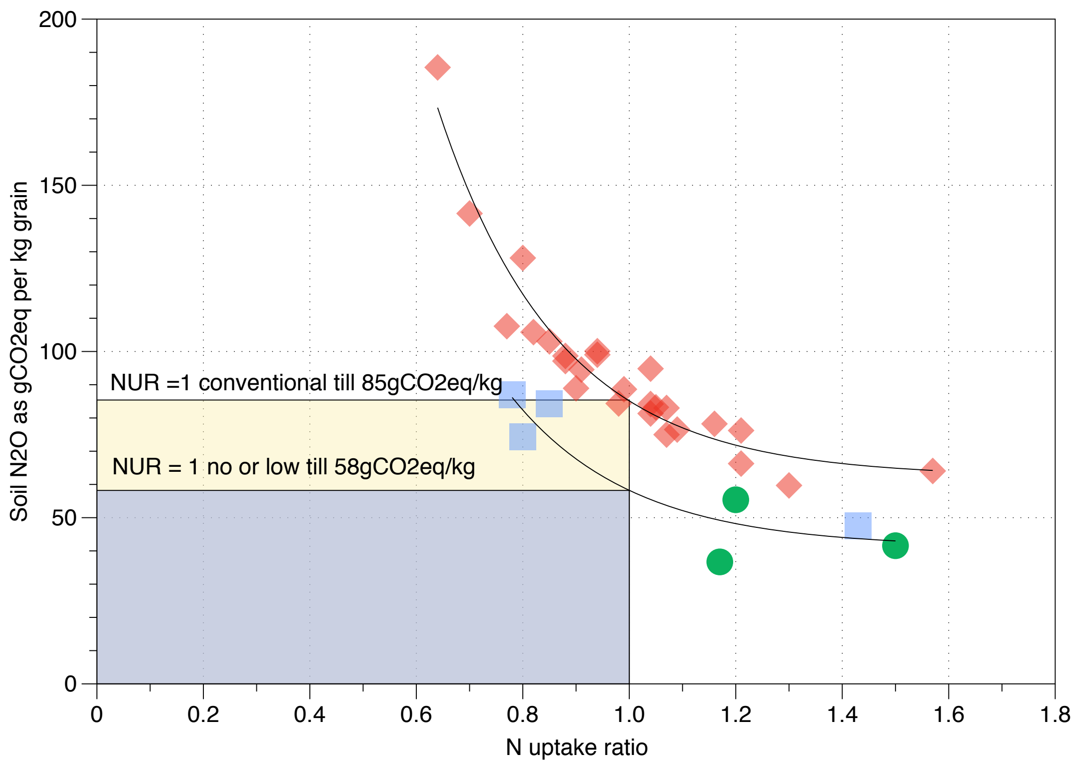


Figure 34. Effect of nitrogen uptake rate on soil emissions of nitrogen oxides

The response we see is intuitively sound. Soil emissions rise dramatically as soon as the uptake ratio drops below 1.0. For intensively tilled farms (for which we have the most data), as the N uptake ratio drops from 1.0 to 0.6, soil N_2O emissions roughly double from 85 to around 190 gCO_2eq per kg of grain. Conversely, the response of soil emissions to NUR becomes much weaker when the uptake ratio is greater than 1. As the uptake ratio rises from 1.0 to 1.6 the change in soil N_2O is more modest, dropping from 85 down to 70 gCO_2eq per kg of grain. Though the number of farms not using intensive tilling is small, these farms appear to show the same kind of response to NUR, but at a consistently lower level of emissions. At an uptake ratio of 1.0, N_2O emissions are 58 gCO_2eq per kg of grain.

Envisioning sustainable scenarios

We now have a basis for constructing a series of scenarios for the Gevo corn supply that could lead to improved and more sustainable operations, as measured by the carbon footprint of the supply. These scenaros are described in Table 16. Figure 35 compares these scenarios with the US average carbon footprint based on the GREET model.

Table 15. Scenarios for reduced carbon footprint

Scenario	Nutrient management
Survey	Base case average results for the surveyed farmers
Animal manure	Credit for fossil energy savings associated with replacing commercial fertilizer with animal manure. Corresponds to zero fossil CO_2 emissions from fertilizer.
Animal manure with improved nutrient management	Same as above with assumption of nutrient uptake ratio = 1.0 and intensive tilling. Corresponds to a drop in soil N_2O emissions to 85 g CO2eq per kg of grain based on Figure 34.
Animal manure with improved nutrient management and reduced tillage practice.	Same as above with reduced tillage practice, with increased soil carbon sequestration (-97.5 gCO2 per kg grain (see Figure 33).
Animal manure with improvemd nutrient management and no till practice	Corresponds to a soil carbon sequestration rate of -138 gCO2 per kg grain (see Figure 33.

If all farmers in the survey group were to replace commercial fertilizer with animal manure, this cohort of farmers would see a 34% drop (from 167 to 110 gCO_2eq per kg grain) in carbon footprint for their harvested grain. In this scenario, the savings are due entirely to the elimination of fossil CO_2eq emissions associated with commercial fertilizer production. We estimate a small additional benefit associated with reducing soil N_2O emissions if farmers apply manure more judiciously (that is, if they apply fertilizer at a level corresponding to a nitrogen uptake ratio of 1.0). But the impressive opportunities for GHG savings are in tillage practice. If these farmers adopt reduced tillage practices, their carbon footprint would shrink by 72% to only 46 gCO_2eq per kg of grain. No till adoption turns these farms from net carbon sources to net carbon sinks. The full gamut of livestock integration (manure use), improved nutrient management and no till adoption results in a 128% reduction in GHG emissions (from 167 to -48 gCO2eq per kg grain). These scenarios are based on relatively simple extrapolations of the survey data. More rigorous analysis is needed to substantiate these estimates.

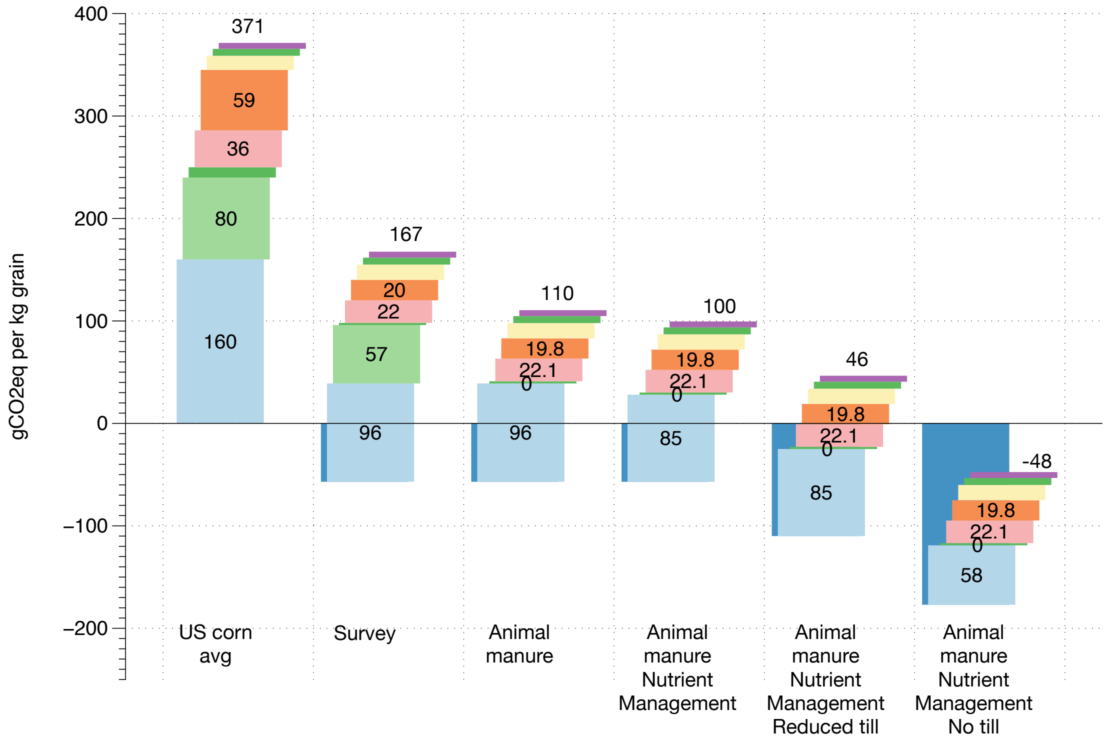


Figure 35. Greenhouse gas footprint for US corn, average survey results and four farm management scenarios

Chapter 3. Comparative advantage of land for corn, sugarcane or natural ecosystems

Introduction

Though the production of biofuels has potential to reduce the dependence on fossil-fuels, biofuel production is land intensive. Land use impacts are of central importance in the debate over the sustainability of biofuels. A consistent theme throughout the history of biofuels is the "food versus fuel" dilemma (US DOE 1980; Runge, & Senauer 2007). While that debate continues and has been made more salient by current drought-related shortfalls and the expansion of mandates for biofuels in the US and the European Union, land impacts also raise issues about climate change and biodiversity. Expansion of agriculture onto forests and grasslands can release carbon, generating a carbon debt that can take years, decades or centuries to repay through concomitant reductions in fossil CO_2 emissions (Fargione et al 2008; Searchinger et al 2008). Conversion of natural habitats to biofuel production can also have negative impacts on biodiversity and ecosystem services (Fargione et al 2010).

Land use decisions for biofuels are framed around the idea of comparative productivity. Comparative productivity is a way of explaining why individuals, countries, or regions of the world would do better if they produced goods where their productivity is higher.

The specific contributions of this approach are to show the relationship between the comparative productivity of bioenergy feedstocks and where they are grown at a global scale. We present these results as a function of latitude, gaining insight into the relative efficiency with which plants convert solar energy on the surface of earth. We believe next generation biofuels will tend to use by-products from current generation technologies, and we explicitly account for these by-products in our analysis. Finally, we show the trade-offs of growing feedstocks for biofuels versus the ecosystem services of unmanaged land producing biomass.

In a simple model where labor is the only factor of production, comparative productivity is measured by how much output is gained per unit of labor applied. The more labor required for output the lower is the comparative productivity. Here we express comparative productivity that reflects trade-offs involving land (rather than labor) in the production of biofuels. We do so in two ways. The first and simplest is a measure of the net amount of bioenergy measured in gigajoules (GJ) produced per hectare. The second is a measure of the net amount of bioenergy produced per unit of NPP in unmanaged ecosystems. This second measure attempts to capture the lost opportunity for use of solar energy to support natural (undisturbed) ecosystems that deliver a variety of environmental and ecological benefits, or "ecosystem services" (Daily 1997; Kareiva et al 2011).

In this analysis, we focus on the two dominant sources of bioenergy for current biofuels production—maize and sugarcane. First generation biofuels technology relies on the well-established conversion of starch-derived sugars in maize and sucrose in sugarcane into biofuels. While expectations are that expansion of the biofuels industry will have to rely on new, more sustainable, cellulosic feedstocks (especially with regard to maize), these new technologies and feedstocks will likely first develop around the current infrastructure for biofuels production, making it important to understand the comparative productivity of maize and sugarcane grown at different latitudes.

This incremental evolution and continued reliance on maize and sugarcane is driven by economies of scale and space. For example, a large maize-based biorefinery in Iowa will be optimally located close to its feedstock—that gives it access to supplies around the clock. Because of the large volume to energy ratio, a biorefinery using a cellulosic crop feedstock (such as switchgrass) would need to draw its supply from nearby. Getting Iowa farmers to switch from maize to switchgrass would be unlikely under any circumstances, but especially in today's market with high prices for maize. By contrast, if farmers supplying maize can sell corn stover (stalks, cobs, and residue) for advanced biofuels, these feedstocks will be available in the same area. In Brazil—the second largest fuel ethanol producer in the world—this will involve further utilization of sugarcane bagasse (the cane after the juice is squeezed out), which today is already used to produce heat and power.

We therefore chose to focus on a more narrowly defined comparison of maize and sugarcane as primary sources of fermentable sugars readily convertible using today's technology, while accounting for the energy value of their residual components, which could be used in second generation processes. The notion that these new technologies will first find their home near to—or as add-ons to—existing first generation plants has been well analyzed from an economic and engineering perspective (Wallace et al 2005; Efe et al 2005) . These residues have also shown promise from a life cycle perspective (Contreras et al 2009; Sheehan et al 2003).

Our analysis compares alternative feedstocks to a biorefinery and assesses the relative land and ecosystem costs of these two sugar sources for bioenergy. We compare fermentable sugar derived from maize and from sugarcane in terms of the amount of energy produced per unit land area and per unit of NPP. The last measure based on NPP is a way of assessing the comparative productivity of maize and sugarcane crops as biomass feedstocks in terms of the likely impact on a broader array of ecosystem services and biodiversity. We propose these measures not as substitutes for the already heavily debated impacts of bioenergy related to food supply and climate change but rather as additional measures for evaluating land use choices related to bioenergy production.

Finally, we stress (and illustrate) the geospatially explicit nature of such comparisons (Krugman 1997). Our analysis aligns well with three commonly recognized latitudinal belts around the globe. In the equatorial zone, approximately 15 degrees north and south of the equator, the natural ecosystems exemplified by the Amazon rainforest are highly productive sources of biodiversity and other important ecosystem services, although they also function as lower productivity sources of local food, feed and fuel. High productivity sugarcane production exists in belts located at 15-30 degrees latitude on either side of the equator. To the north, production occurs in South Asia and the Caribbean. To the south, the largest production occurs in Brazil, southern Africa and northwestern Australia. Maize has its highest productivity in two belts at 35 to 50 degrees on either side of the equator. This includes the US Corn Belt in the north and the Argentinian Pampas in the south.

Latitude, solar energy and biofuels

At a fundamental level, the reason that the comparative productivity of growing plants differs at different latitudes is explained by solar radiation levels and variations in these levels over the course of a yearly cycle. The quantitative relationship between solar energy intercepted per square meter and the amount of dry biomass produced was first expressed as "radiation use efficiency" (RUE) by Monteith (Monteith, & Moss 1977) as dry matter per mega joule of intercepted solar radiation (g MJ^{-1}). RUE is known to vary across crops and other plants. C4 species such as sugarcane, maize and sorghum have significantly higher RUE maximums than C3 species such as wheat, sunflower, rice and soybeans.

In a study of wine grape production, Ashenfelter and Storchmann (Ashenfelter, & Storchmann 2010) show how RUE varies across latitude and months of the year. At the equator, plants receive maximal solar energy of about 35 mega joules (MJ) per square meter per day, or 13.2 GJ per annum, which varies by only 3-5 MJs per day over the 12 calendar months. But as one moves into the more northerly latitudes, the energy flux over the course of the calendar year becomes concentrated at a maximum on June 21, which is above 40 MJs, and then declines on either side of this maximum as one moves toward December. The pattern is the same in the southern hemisphere, but the seasons are reversed, with maximum temperatures reached in temperate zones in December rather than June. At 40 degrees north, minimum energy levels in December are about 9 MJs per day with an average of 10.4 GJ per annum. The farther north in latitude one goes, the greater the fall off from peak summer energy to winter energy levels from the sun. This has agronomic implications as well: at the equator, the annual energy available for plant growth is highest, but the lack of a winter season means that fungal, bacterial and viral diseases and plant pests are not arrested by winter freezes, making cropping more problematic.

Measuring comparative productivity

Data

Our analysis is based on the M3 geospatial dataset for global agricultural land (Ramankutty et al 2008; Monfreda et al 2008) (http://www.earthstat.org). This dataset combines satellite-based land cover data with detailed (subnational) level agricultural census data. Reconciling these different sources of information produces a more accurate picture of global agricultural land supply than can be found from any data set based on one of these sources alone. The data provides a snapshot of agricultural land use and productivity for 175 crops on a 5 arc-minute x 5 arc-minute resolution based on the year 2000. We considered more recent trends in yield for maize and sugarcane, and find that each crop has seen essentially equal rates of improvement (see Detailed methods discussion at the end of this chapter) (UNFAO 2012). This suggests that the comparative productivity of the two crops based on year 2000 data is similar to comparative productivity at present.

Best attainable yield versus actual yield

The M3 dataset includes geospatially explicit information on actual yields and crop management practices. The recent addition of crop management information allows us to distinguish the influence of both climate and management practices on yield (Mueller et al 2012b). For a given climate, actual yields can vary as a result of differences in these management practices. A comparative analysis based on actual yields would thus be confounded by a variety of factors beyond those specific to the crop itself.

To correct for this, we estimate yields at each location on the basis of the best attainable yields for a given climate condition. The attainable yield for each crop was calculated using an empirical method initially described by Licker *et al* (Licker et al 2010) and later refined as described by Mueller *et al* (Mueller et al 2012b). In this approach, all cultivated land on the globe is divided into 100 discrete climate bins defined by characteristics such as rainfall, temperature and growing-degree days. For a given crop in a given climate bin, all yields are ranked from lowest to highest. The best attainable yield at a given location is then calculated from the 95th percentile yield achieved for the climate bin associated with that location.

Estimating the comparative productivity of maize and sugarcane

The amount of land needed to produce biofuels from sugar can be estimated from information about crop yield per hectare and amount of fermentable sugar per unit of crop. We used the M3 data set to calculate an area-weighted best attainable yield for maize and sugarcane over increments of latitude. Average yield by latitude is based on areas of land where each crop is actually grown. We did not extrapolate yield performance for land not currently in production for each crop. We also limited our comparison of natural ecosystems and managed systems for each crop to values estimated on land producing the specific crop (maize or sugarcane). Thus, our estimate of land productivity at each latitude relates to land actually managed for that crop.

To put each crop on an equal basis, we convert the yields in the M3 data set into an equivalent net energy of delivered fermentable sugars per unit of land. We can then evaluate the amount of fermentable sugars per hectare or per unit of NPP.

The annual harvested energy in the fermentable sugars in maize is calculated as a product of yield per hectare and energy per unit of yield:

Equation 2

$$E_{fs} = Y_{maize}(x_{starch} * H_{starch})$$

where

E_{fs} is the energy delivered as fermentable sugars per hectare

Y_{maize} is the dry yield of grain harvested in tons per hectare

x_{starch} is the dry weight fraction of yield that is starch

H_{starch} is the heating value of starch in units of GJ per ton of starch

We adjust this gross energy in the fermentable sugars produced per hectare by subtracting out the energy required to grow and harvest the grain, E_{farm}, based on life cycle estimates from the literature (Shapouri et al 2002). To allow for the utilization of maize stover as a source of heat and power and/or a source of fermentable sugars in second generation technology, we add the heat value of stover collected at a rate of 30% of the total available stover, a nominally acceptable level of sustainable stover removal (Sheehan et al 2003):

Equation 3

$$E_{net} = E_{fs} - E_{farm} + E_{stover}$$

Equation 4

$$E_{stover} = x_{stover} Y_{grain} H_{stover}$$

Equation 5

$$E_{farm} = e_{grain} Y_{grain}$$

where

E_{net} is energy in fermentable sugars delivered to a biorefinery corrected for farm inputs and stover energy value per hectare

E_{farm} is the energy required to produce and harvest grain per hectare

E_{stover} is the energy value of delivered stover per hectare

x_{stover} is the fraction of stover that can be sustainably removed (assumed to be 30%)

H_{stover} is the heating value of the cobs, leaves and stalks of the corn plant (Domalski et al 1986).

e_{grain} is the farm energy input per unit of grain

Note that, in calculating E_{stover}, we are assuming a harvest index of 1 (Y_{grain} = Y_{stover}). In the case of maize, there is one more complication in the analysis of its comparative productivity. Maize contains protein, fats and other materials that are not converted to biofuels, but that have a value as animal feed (known as distillers' dry grains and solubles or DDGS). There is no simple way to add in a credit for this co-product. So, instead, we apply a land credit based on the weight fraction of this feed co-product. In other words, we increase the effective productivity by a factor of (1.0/0.72) to allow for the assumption that 28% of the product harvested would have displaced an equivalent amount of maize cropland dedicated to animal feed production (Wallace et al 2005; Arora et al 2010).

The calculation for sugarcane is much the same, and is, in fact, simpler. In this case, the net energy delivered to the biorefinery is:

Equation 6

$$E_{net} = Y_{cane}\left\lfloor x_{sucrose}H_{sucrose} + x_{bagasse}H_{bagasse} - e_{plantation}\right\rfloor$$

Sugar content and energy inputs for sugarcane production, as well as the amount and energy value of bagasse are based on a recent update of the life cycle inventory for sugarcane in Brazil (Seabra et al 2011).

Details of our methodology are available at the end of this chapter.

The comparative productivity of sustaining natural ecosystems

Measuring the comparative productivity of land as a resource for supporting biodiversity and ecosystem services is somewhat less straightforward. Not all hectares are equally productive in terms of the services or biodiversity they support. The difficulty in obtaining such measures has limited much of the analysis of bioenergy's impact on biodiversity, carbon sequestration and other natural ecosystem-derived services to either a qualitative approach at the regional, national and global scales or a quantitative and highly site specific approach at a very local scale (Daily 1997; Clark et al 2001; Kareiva et al 2011).

In order to arrive at a consistent and quantifiable measure at the global scale, we start with the concept of net primary productivity (NPP) as a general measure of the ability of a given piece of land to support a natural ecosystem (Clark et al 2001). Net primary productivity is defined as the net rate at which plants assimilate carbon, accounting for photosynthetic uptake as well as releases due to autotrophic respiration. In our analysis, it is calculated in units of metric tons of carbon per hectare per year on a section of unmanaged land. NPP thus serves as an indicator of net energy flow through an ecosystem by measuring its accumulation and the ecosystem's capacity to support biodiversity and ecosystem services (Roxburgh et al 2004).

We use a simple statistical model with temperature and precipitation as parameters to predict NPP. Originally developed in the 1970s based on a very limited set of data, the model has been updated to reflect data from field studies conducted around the globe (Zaks et al 2007). For each hectare of land in the dataset on which maize and sugarcane are grown, we use climate data for that location to estimate NPP using the updated NPP model (see details on methods at the end of this chapter).

The ecosystem capacity costs of maize and sugarcane

For the last set of comparisons between maize and sugarcane, we make use of the NPP calculations for each piece of land on which these crops are grown to calculate lost capacity to support a natural ecosystem.

Equation 7

$$E_{\text{net per ecosystem potential}} = \frac{E_{net}}{NPP}$$

where E_{net} is the same net energy in GJ per ha calculated previously for sugarcane and maize, divided by the capacity of the land to capture carbon (NPP in units of metric tons of carbon per hectare per year).

Comparative productivity of maize and sugarcane bioenergy feedstock production

Figure 1 compares the productivity of sugarcane and maize per hectare as biofuel feedstocks, as described previous section. The comparison is in terms of gigajoules of energy deliverable to a biorefinery in relation to latitude. The size of the circles reflects the quantity of each crop produced at specific latitudes. The dashed lines represent curves that were fitted to the data points utilizing a cubic function with the R-squares (explained variation) given.

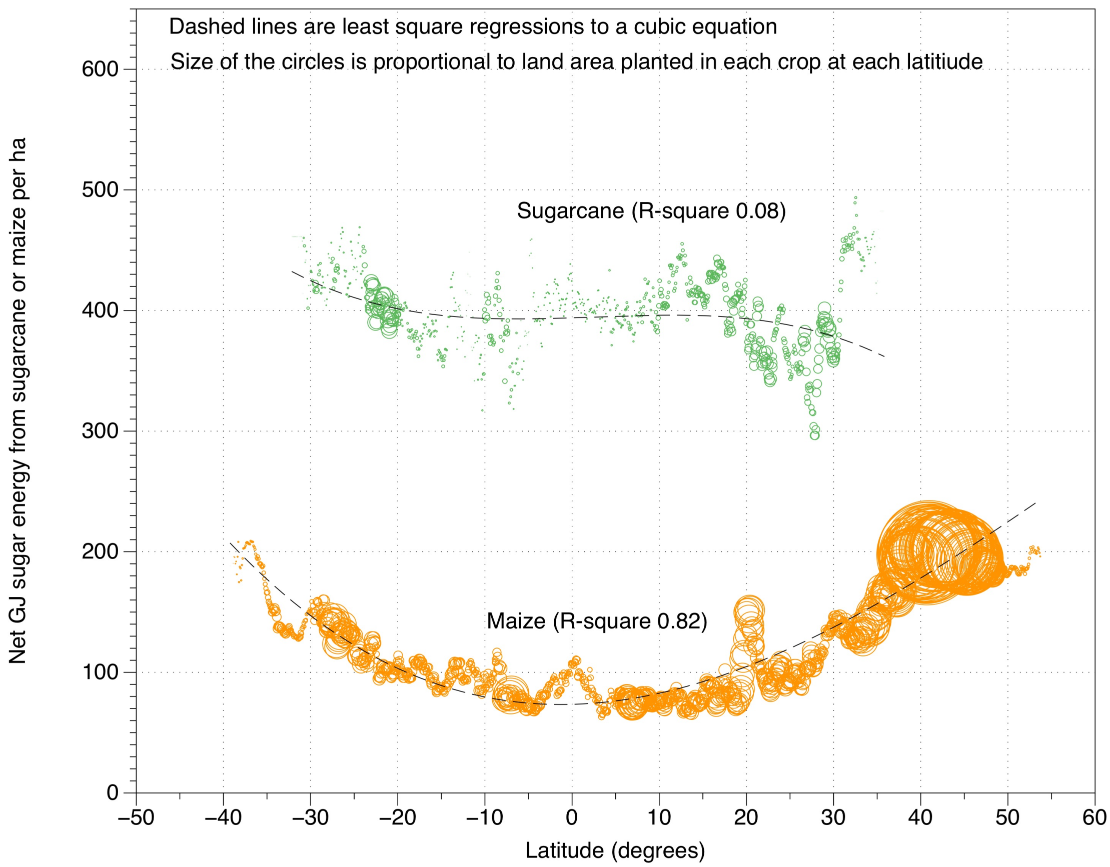


Figure 36. **. The comparative productivity of sugarcane and maize per hectare as a means of delivering energy (in gigajoules) to a biorefinery as a function of latitude.**

Sugarcane is more productive than maize at every latitude at which the former is grown (from approximately -30 to +30 degrees). Sugarcane produces three times more energy per hectare on average than does maize. On average (area-weighted across the globe), the current mix of land used for sugarcane production produces 392 GJ of energy per hectare, whereas for maize the figure is only 124 GJ. Maize productivity is higher in the temperate zones and declines as one moves towards the equator. The latitudes from 35-50 degrees North, which includes the U.S. Corn Belt, stands out in terms of both its higher yields and its large production, as reflected in the size of the circles. The concentration of sugarcane production in Sao Paulo state in Brazil can be seen from 20-25 degrees South. Latitude explains far more of the variation in maize productivity than for sugarcane, as shown by relevant R-squares. The very wide range in the productivity of sugarcane around 30 degrees North is likely a reflection of the very high yields achieved in the Southern United States and the low yields in locations such as Northern India.

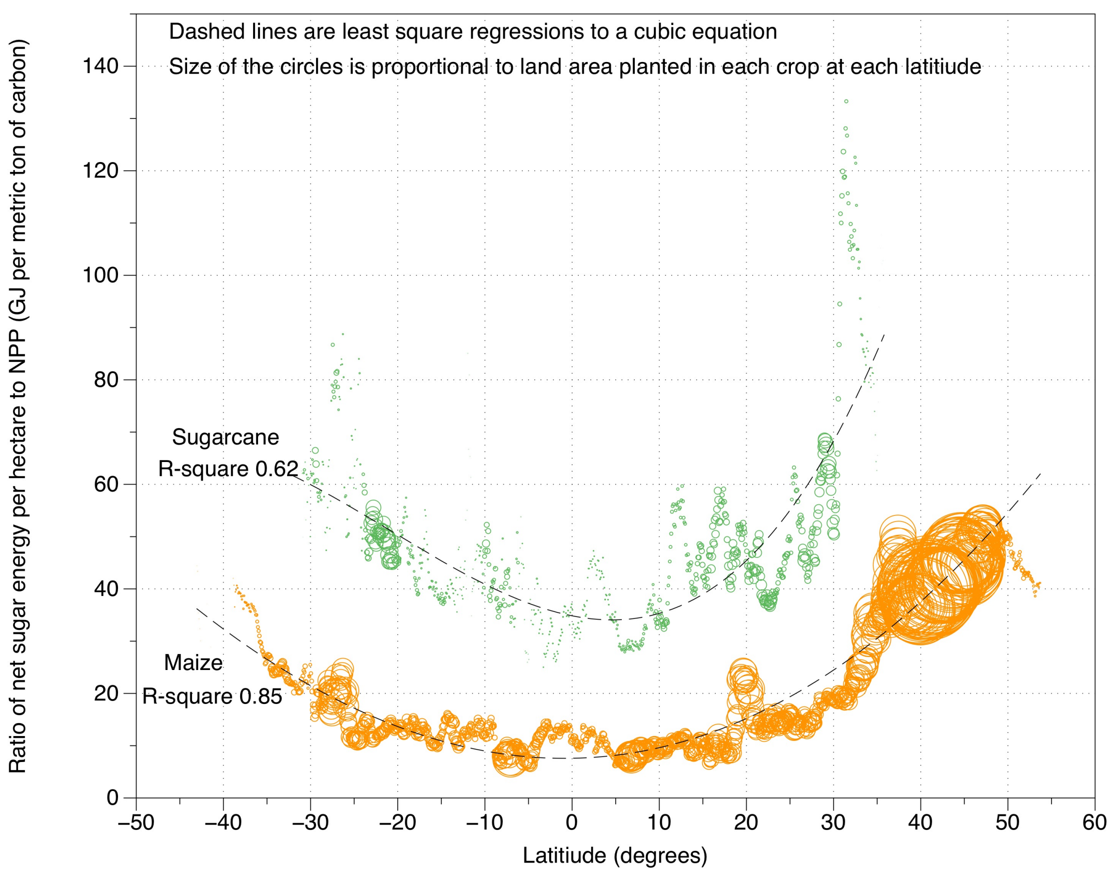


Figure 37. The comparative productivity of sugarcane and maize in relation to NPP (as a measure of eco-system services) in terms of delivering energy (in gigajoules) to a biorefinery, as a function of latitude.

Conclusions

Land use choices, as they pertain to questions of supplying food and fuel and ensuring an adequate flow of natural ecosystem services such as biodiversity and carbon capture, are always complicated by national interests and local demands. This analysis offers insight into land use choices for biofuels by considering the comparative productivity of sugarcane and maize at different latitudes. We have explored the comparative energy yields of maize and sugarcane based feedstocks for biofuels (including the value of their residues) per hectare and per unit of NPP, as a proxy for the natural eco-system services foregone. The limitation of energy (NPP) as a proxy of ecosystem services needs to be acknowledged, and in particular the importance of different types of biodiversity. We also want to emphasize that this comparative analysis is silent with regard to the many other ways in which land use decisions might be measured. Questions of food security and economic development are other important considerations and warrant an analysis of comparative productivity in their own right. In particular, the U.S. has elected to direct some 40% of its maize crop to biofuels, which has an effect on global stocks and prices of grains. If the most productive producer of maize in the world uses so much of it to produce biofuels, that leaves less efficient producers to fill the gap for feed and food.

Detailed methods discussion

Net primary productivity as a function of latitude

As discussed in the body of the paper, NPP is evaluated using a simple statistical model that predicts net capture of carbon in an ecosystem as a function of temperature and precipitation. Figure 38 shows the predicted distribution of NPP across the globe measured in grams of carbon per square meter per year.

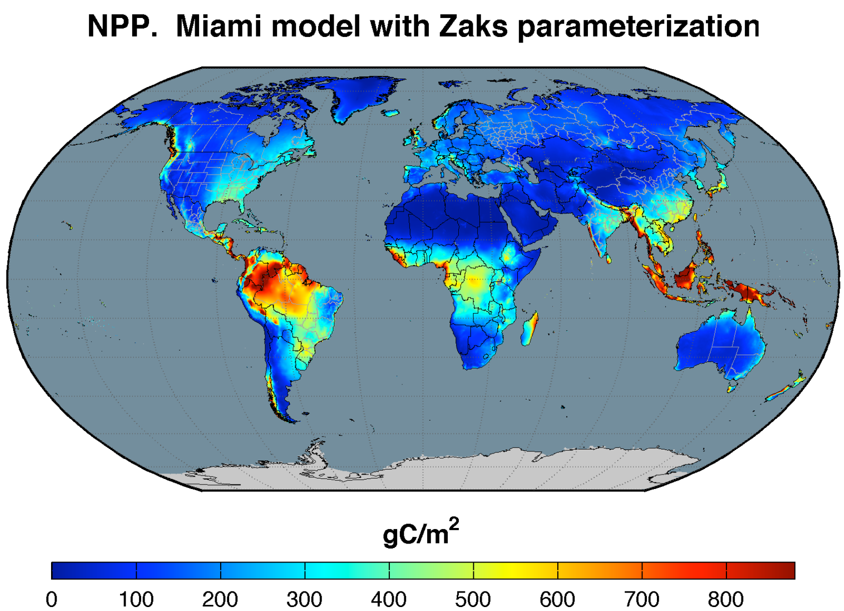


Figure 38. Geospatial distribution of Net Primary Productivity

NPP rates were estimated in the global model at a 5x5 minute pixel or "arc minute" resolution at latitudes ranging from 80 degrees North to 60 degrees South. The very high ecological value of the Equatorial zone is apparent with a rate of carbon capture between 500-800 grams carbon per square meter per year. The latitudes that encompass the highest rates lie within 10-20 degrees North and South of the Equator, depending on region. The most significant region with a very high NPP is the Amazon Rainforest.

Other important areas include the tropical forests of Central Africa and Southeast Asia, the Philippines, Indonesia and New Guinea.

For the purpose of evaluating the ratio of net sugar harvested per hectare to NPP, we estimated NPP values only in those pixels where each crop—maize and sugarcane—are grown. Figure 39 and Figure 40 show the NPP values and crop yields for each of the crops as area-weighted averages at increments of latitude.

Note that NPP is not the same for each crop. This is due to difference at each latitude where each crop is being grown. We would expect that maize would be grown in regions of milder conditions than sugarcane, and thus that the corresponding values of NPP would not be as high as the NPP for sugarcane regions.

Productivity measured as net energy in delivered sugars per hectare for each crop

Table 16 shows the assumed values for calculating the productivity of maize in terms of net energy of delivered energy in fermentable sugars to the biorefinery. The land credit is based on data from NREL and USDA (Wallace et al 2005), who report that 28% of the harvested grain is available in the form of an animal feed coproduct. This animal feed is assumed to displace an equal amount of corn as animal based, an assumption that is based on recent analysis of corn coproduct credits. (Arora et al 2010). Higher heating values are used as the basis for converting both the starch sugars and the stover to an equivalent energy basis. The weight fraction of starch in the grain is based on Wallace et al 2005. Available stover is based on a 1:1 harvest ratio (1 kg of stover per kg of grain) and a limit of 30% on the sustainably removable stover (Sheehan et al 2003).

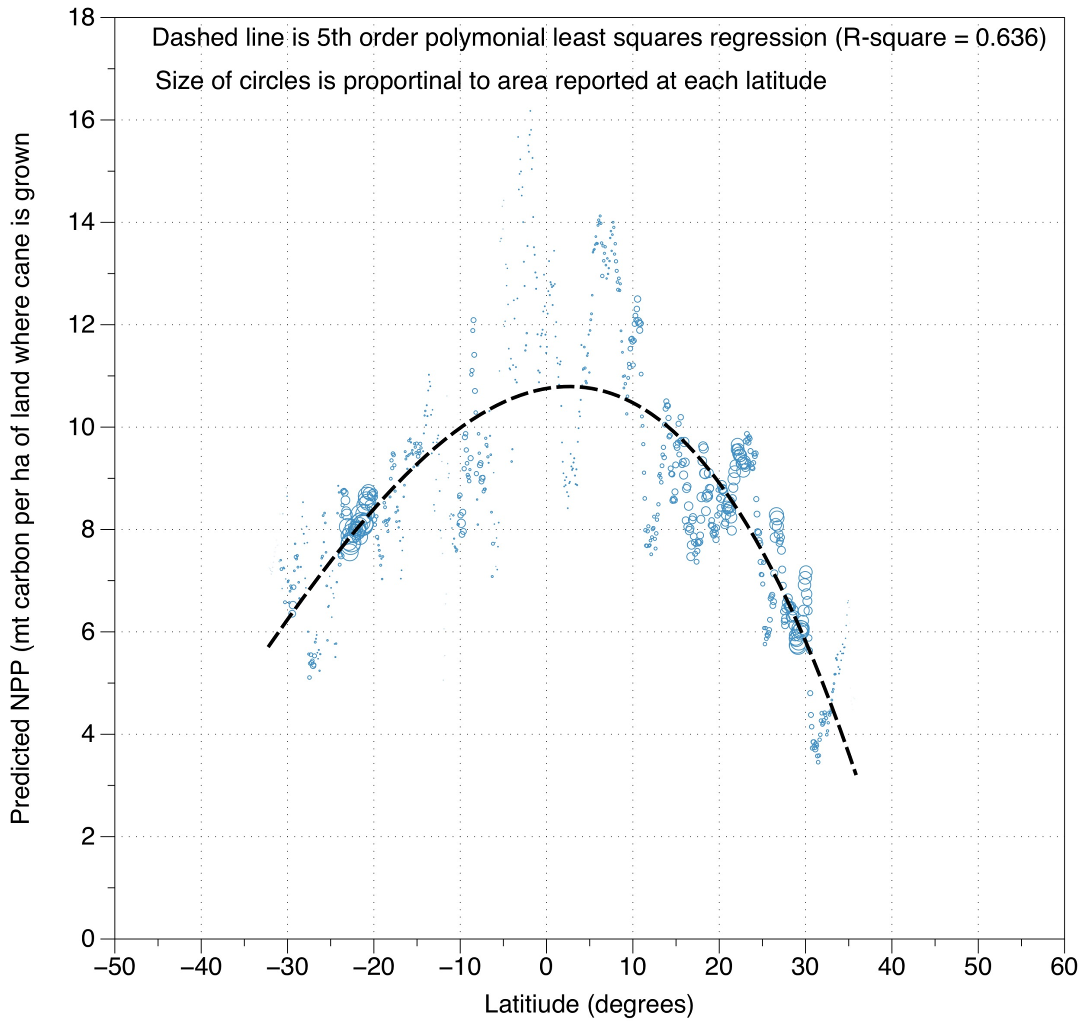


Figure 39. Net primary productivity (metric tons carbon per ha per year) as a function of latitidue on land where sugarcane is grown.

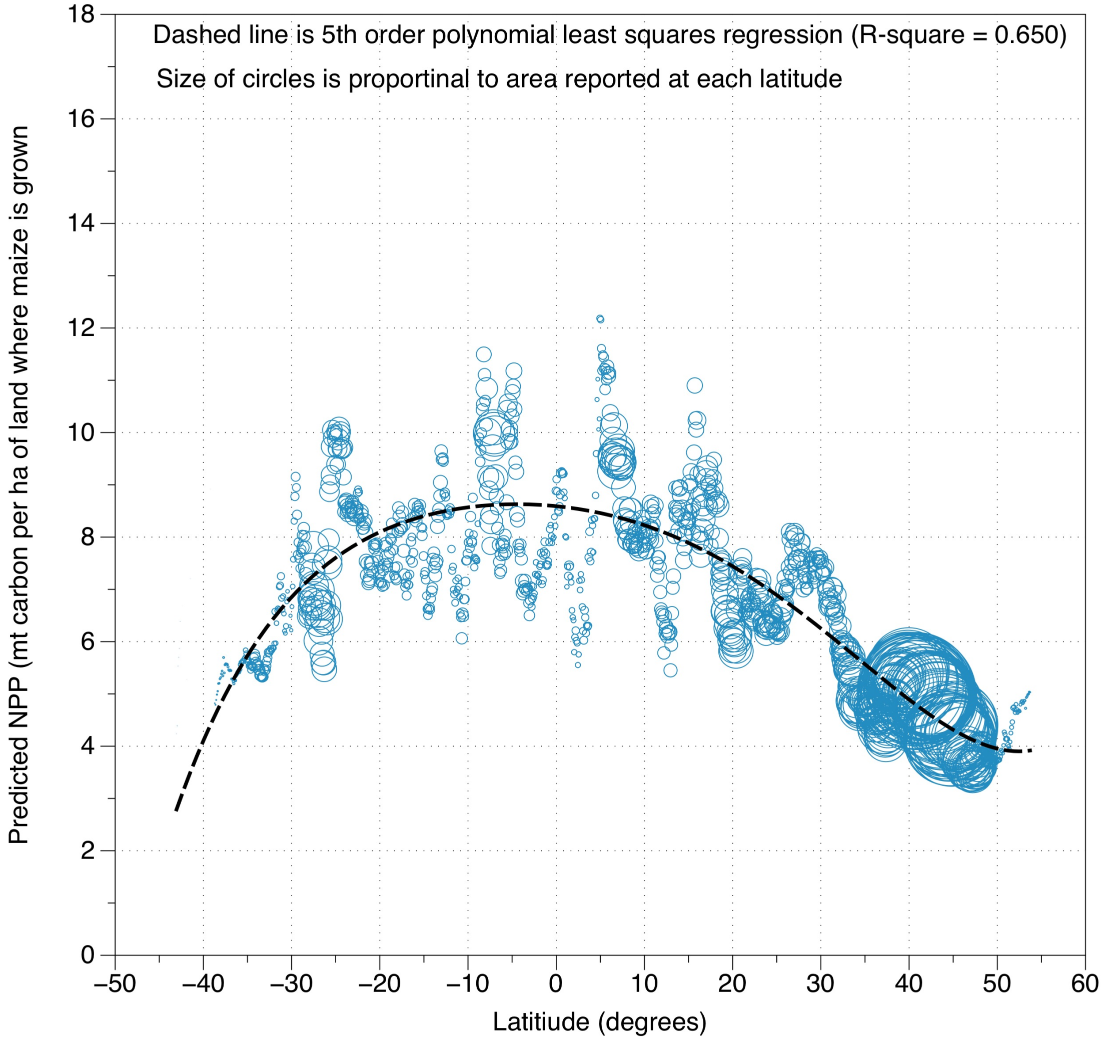


Figure 40. .Predicted NPP as a function of latitude on land where maize is grown

Table 16. Assumptions used in calculating net energy per hectare delivered to a maize biorefinery

Variable	Description	Value
DDGs land credit	Fraction of maize land displaced by DDGS	0.28
e_{farm}	Maize energy input MJ per kg harvested grain	2.220
H_{starch}	Higher heating value MJ per kg starch	17.58
H_{stover}	Higher heating value MJ per kg stover	19.0
x_{starch}	Ratio of kg of starch per kg grain	0.612
x_{stover}	Kg of dry stover per kg grain. 30% of the stover is collected, and of that, 15% is moisture. Thus, available stover is reduced by 15% to be consistent with higher heating value (which is reported on a dry weight basis)	0.30*0.85
Y_{grain}	Yield metric tons grain per ha per y (at harvested moisture content	10.17 reported at 43.042 deg north

The following is an example calculation of how the values in Table 16 are used to calculate the net energy productivity for maize. It is based on the reported yield for the latitude that corresponds to the US corn belt.

We start with calculating the energy value of the fermentable sugars, in this case assumed to be the net energy value of the sugars contained in the starch. This energy value is approximated as the higher heating value of the starch.

Equation 8

$$E_{fs} = Y_{maize}(x_{starch} * H_{starch})$$

Using the average yield of 9.0543 mt per ha reported at latitude of 43.042 degrees north from the M3 dataset,

$$E_{fs} = 10.17 * 0.612 * 15.58 = 109.45$$

The energy value of the collectible stover is

Equation 9

$$E_{stover} = x_{stover} Y_{grain} H_{stover}$$

$$E_{stover} = 0.30 * 0.85 * 10.17 * 19 = 49.27$$

Energy consumed on the farm is:

Equation 10

$$E_{farm} = e_{grain} Y_{grain}$$

$$E_{farm} = 2.220 * 10.17 = 22.58$$

Thus the net energy delivered from the farm per hectare is:

Equation 11

$$E_{net} = E_{fs} - E_{farm} + E_{stover}$$

$$E_{net} = 109.45 - 22.58 + 49.27 = 136.14$$

All energy values are in GJ per hectare per year since we are multiplying units of MJ per kg times a yield measured in metric tons per hectare per year (or thousands of kg per hectare). Thus the product of each term in the calculation is thousands of MJ per hectare, which is equivalent to GJ per hectare.

Calculation of net delivered energy in sugar for sugarcane is based on the assumptions shown in Table S-2. We show the calculation of net energy based on yields reported for the Sao Paulo region of Brazil.

Table 17. Assumptions used in calculating net energy per hectare delivered to a sugarcane biorefinery

Variable	Description	Value
$e_{plantation}$	cane energy input MJ per kg harvested cane	0.210
$H_{sucrose}$	Higher heating value MJ per kg sucrose	16.50
$H_{bagasse}$	Higher heating value MJ per kg bagasse	17.33
$x_{sucrose}$	Ratio of kg of sucrose per kg harvested cane	0.140
$x_{bagasse}$	Kg of bagasse per kg harvested cane	0.128
Y_{cane}	Yield Mg grain per ha per y (at harvested moisture content)	98.17 at 23 deg south

Equation 12

$$E_{net} = Y_{cane}\left[x_{sucrose}H_{sucrose} + x_{bagasse}H_{bagasse} - e_{plantation}\right]$$

$$E_{net} = 98.17*\left[0.14*16.5+0.128*17.33-0.21\right]=423.92$$

Again, the energy value is in GJ per hectare of cane harvested.

Updated assessment of relative yields for sugarcane and maize.

The data used in our model is specific to circa year 2000. It could be argued that our comparative analysis may not be relevant to the current situation if the relative yield performance of these crops has changed since then. We analyzed FAO data on Brazilian and US yields for cane and maize, respectively (the dominant producers of these crops) to evaluate this question. A summary of our findings can be found in Table S-3. For the period from 1962 to 1999, US corn yields grew more than 2.5 times as fast as Brazilian Sugarcane yields (3.33% versus 1.24%, respectively). However, in the period between the year 2000 and 2010, FAO data shows that US corn and Brazilian sugarcane yields grew at almost exactly the same rate (1.39% and 1.42%). We therefore conclude that the findings in our analysis are still pertinent today.

Table 18. Sugarcane and maize trends in Brazil and the US since the year 2000

	Brazilian Sugarcane	**US Maize**
1962-1999 Average	1.24%	3.33%
2000-2010 Average	1.39%	1.42%

Chapter 4. Opportunities for reducing the global land footprint of pasture

Background

Sustainably increasing agricultural production on existing managed lands is a key strategy for meeting anticipated food and energy needs from a finite amount of land (Garnett et al 2013). Use of climatically-defined "bins" is a leading approach for evaluating the potential of intensifying per hectare crop yields and related yield gaps (Mueller et al 2012b; Foley et al 2011; Licker et al 2010). In this study we apply the climate binning approach to global pastureland for the first time, and evaluate the potential for intensification of pastured livestock production using livestock density as a proxy for pasture yield

Pasture systems occupy twice as much land globally as crops (Ramankutty et al 2008), and their use for livestock production is by far the largest human demand for land (Steinfeld et al 2006). Intensification of the world's pastureland, that is increasing animal products per hectare per year, is of interest in the context of both increasing food production and making room for production of biofuels. (Martha et al 2012; Tilman et al 2002; Garnett et al 2013; Hertel 2011; Nassar, & Moreira 2013) . Furthermore, pasture management has important implications for environmental quality (Steinfeld et al 2006; Thornton 2010) and the economic prospects of many of the poorest regions of the world, which rely on pastoral systems (Thornton 2010; Thornton et al 2003).

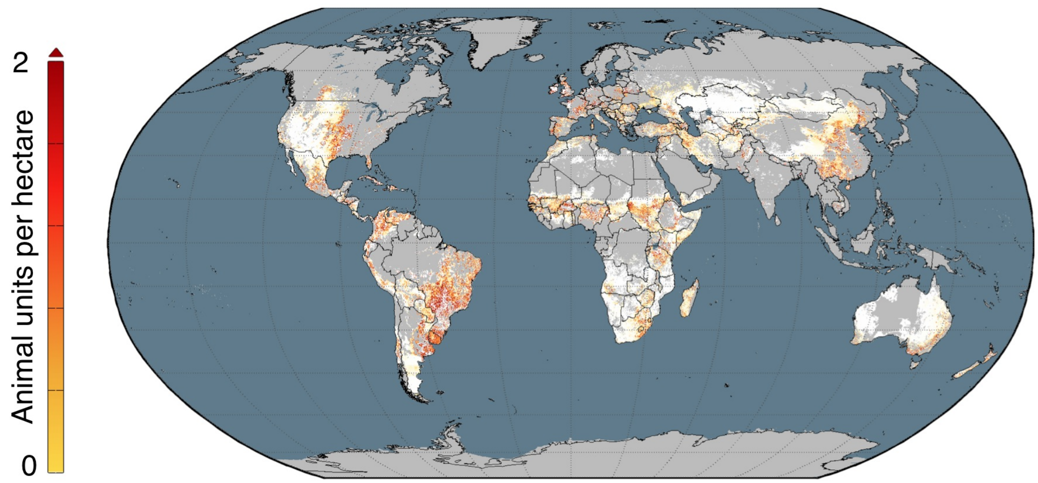
Overview of methodology

FAO's Gridded Livestock of the World (GLW) data (Wint, & Robinson 2007) were mapped at the 5 arc min x 5 arc min scale. We excluded animals located in grid cells with no pastureland, and redistributed animals within pasture-containing grid cells on the pasture fraction of each cell as reported by Ramankutty et al (Ramankutty et al 2008). We then filtered the data to exclude higher density mixed crop/livestock and feedlot systems, as well as high density values associated with forcing animals onto the permanent pasture fraction of land within grid cells containing relatively small amounts of pasture (see details in Supplemental Methods). Total livestock counts were calculated as aggregates of animal unit equivalents for each animal type. A yield gap approach (Mueller et al 2012b) was applied to this new data set to determine the maximum attainable livestock density within 100 climate bins and corresponding potentials for increased livestock population on pasture land. More detail on the methodology can be found in the last section of this chapter (see section Supplemental methods).

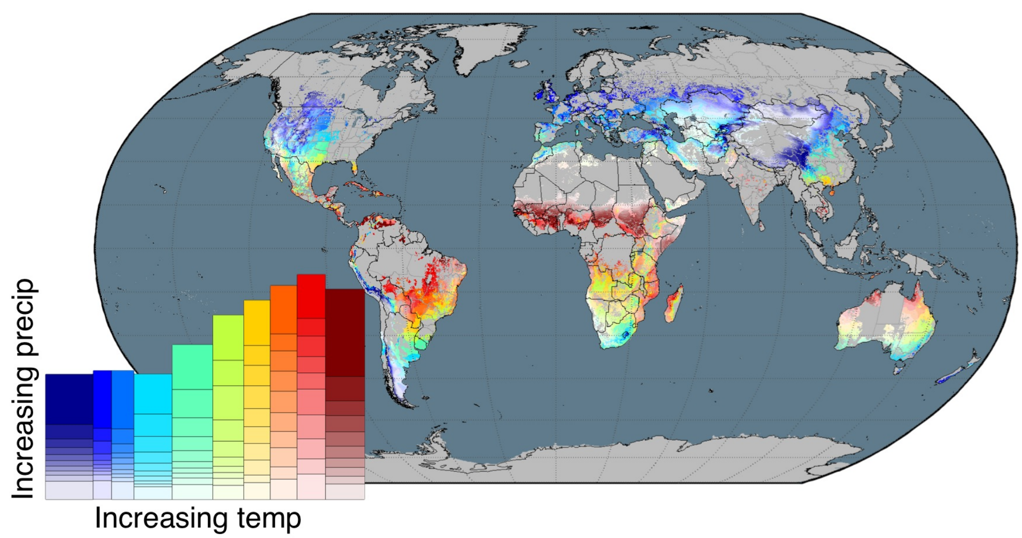
Estimate of current livestock distribution on global pastureland

We developed 5 arc min x 5 arc min global maps of cattle, sheep and goat animal density on global pasture based on this FAO data and data from Earthstat (www.earthstat.org) describing global pasture land (Ramankutty et al 2008). The results are shown in Figure 41A for aggregate animal unit (AU) equivalents of cattle, sheep and goats (Womach 2005) per hectare of pasture.

The unfiltered FAO data show 1.79 billion AUs of cattle, sheep and goats worldwide. (See Figure 46 and related discussion in Supplemental Analysis for more detail.) However, 51% of these animals (909 million AUs) are located in land designated as permanent pasture.



A. Livestock density distribution (aggregate of cattle, sheep and goats in AU per ha)



B. Climate zones containing equal areas of pasture land

Figure 41. Geospatial distribution of aggregate livestock and climate bins for global pastureland

.

Eliminating animals on pastureland containing more than 2 AU per ha to avoid including mixed crop/livestock systems, confined feedlots, and animals raised in residential settings (details in Supplemental methods section Aggregating livestock and setting maximum densities) leaves 629 million AUs in pasture systems (35% of the total population). The 2 AU per ha cutoff corresponds to an estimated cattle population that is similar to, although around 10% higher than, earlier estimates for "grazing-only" livestock populations published by the European Commission in 1996 and the FAO in 2006 (Steinfeld et al 2006; de Haan et al 1996) . Our estimates of pasture intensification potential, developed subsequently, showed very little sensitivity to the AU per ha cutoff (see Supplemental Analysis sections Sensitivity of maximum allowable animal density and Global intensification potential of individual cattle, sheep and goat systems for details).

Notably, we find that 43% of the 2.8 billion ha classified as pastureland (Ramankutty et al 2008) has no pastured animals on it according to the FAO dataset. This includes large stretches of the western US and Canada, sub Saharan Africa, Central Asia and Australia (Figure 41A), in regions associated with dry to moderately moist precipitation and moderate temperatures (see Figure 41B). We estimate the global average stocking density to be 0.39 AUs per ha for land actually occupied by livestock, and 0.22 AUs per ha for global pastureland.

Livestock distribution in climate space

Estimating global intensification potential for pasture systems relies on a transformation from geographic space to climate space—that is, an assigning of livestock population around the globe (Figure 41A) into their respective climate bins into their respective climate bins (Figure 41B). The distribution of average livestock stocking density in climate space is represented schematically in Figure 42A and compared to those of average wheat yields (Figure 42B) and maize yields (Figure 42C). (More details are available in Supplemental Methods section Defining climate bins for pastureland and Supplemental Analysis sections Characterizing pasture-based livestock systems in climate space and Analysis and comparison of wheat and maize systems with pasture systems.)

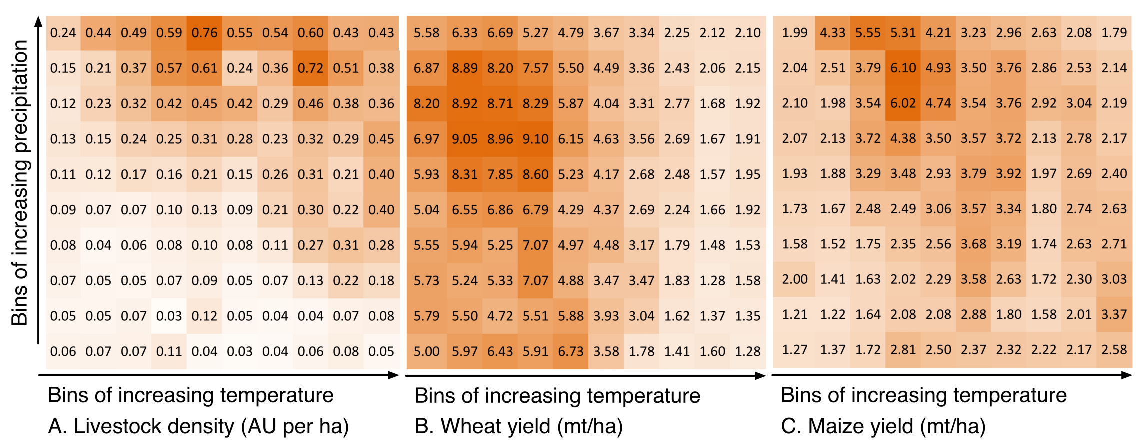


Figure 42. Livestock, maize and wheat patterns in climate space. Color intensity corresponds to livestock density or yield as appropriate.

Average livestock densities in the driest and coolest bins are roughly one-tenth those observed in warmer and wetter bins, indicative of the importance of controlling for climate. Compared to maize and wheat yields, pastured livestock stocking densities exhibit a much stronger dependence on both temperature and precipitation. The relatively weak dependence of maize and wheat yields on precipitation may be due to irrigation.

Ranking pastureland performance and pasture intensification potential

We sort and rank the pasture areas into percentiles of increasing performance (livestock density) within each bin (see Supplemental Methods section Defining climate bins for pastureland). Aggregate global potential population for each percentile is then calculated as:

Equation 13

$$P(x) = \sum_{i=1}^{N_{bins}} A_i p_i(x)$$

where $P(x)$ is global potential population at the *xth* percentile, A_i is the total area in bin i, and $p_i(x)$ is the livestock density at the *xth* percentile in bin i. Mueller et al (Mueller et al 2012b) define a maximum attainable yield for crops as the yield in a given climate bin achieved at the 95th percentile for cropland in each bin. We similarly define a maximum attainable livestock density as the density achieved at the 95th percentile of pastureland in each bin, denoted $P(95)$.

Figure 43A presents the ranked global potential livestock population as a stacked area chart where the height of each element of the stacked area is its contribution to $P(x)$ (corresponding to $A_i p_i(x)$) at a given percentile x. The current population is the total stacked area in Figure 43A, corresponding to the integral of *P(x)*. The maximum global intensification ratio for pasture is:

Equation 14

$$I_{\max} = \frac{Max}{Current} = \frac{P(95)}{\int_{x=0}^{1} P(x)\,dx}$$

Similar equations and interpretations for Figure 43B and Figure 43C apply for the wheat and maize systems. The maximum attainable intensification ratio for pastured livestock population is 3.83, compared with maximum intensification ratios of 1.71 and 1.64 for wheat and maize yields respectively.

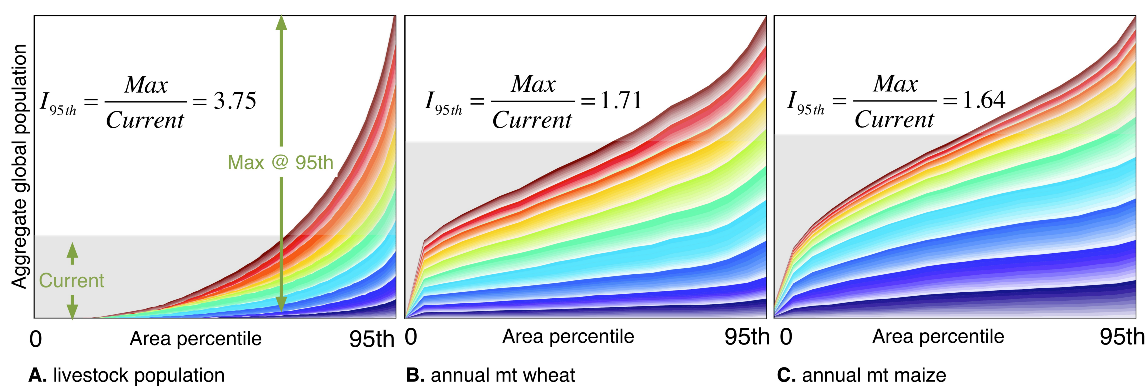


Figure 43. Global potential performance of livestock, wheat and maize. The heights of the gray shaded portion of the graphs correspond to the current population. The curve represented by the top surface of the stacked areas is performance as a function of percentile. The hue (from dark blue to dark red) and intensity (from low to high) of each of the 100 stacked areas correspond, respectively, to climate bins of increasing temperature (growing degree days) and increasing precipitation.

Closing the gap by raising the lowest performers

Figure 44 summarizes the incremental benefits of raising the lowest performing pasture up to a minimum level defined as a percent of the maximum currently attainable performance, with similar estimates for maize and wheat. (See Supplemental Analysis section Impacts of closing the yield gap *for details*). For all minimum performance levels considered, substantially larger intensification potentials are seen for pasture as compared to maize and wheat.

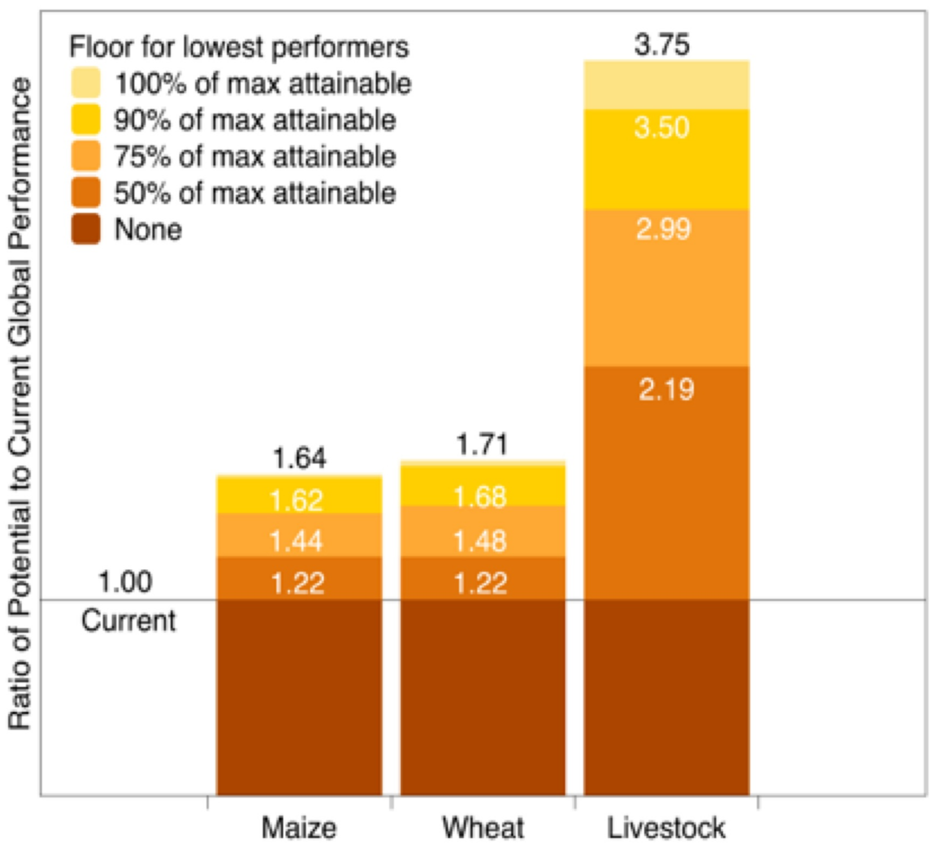


Figure 44. Improved performance in maize, wheat and livestock systems for different levels of closing their respective yield gaps

For example, raising pastured stocking densities to 50% of the climate-adjusted maximum attainable livestock density achieves an intensification ratio of 2.16, while raising maize and wheat to a minimum of 50% maximum attainable yield results in intensification ratios of only 1.12 and 1.11, respectively.

Discussion

For most of the 100 climate bins, plots of stocking density as a function of ranked area percentile exhibit a concave-upward shape (See Figure 47 and Figure 54 in Supplemental Analysis). The aggregate global population vs percentile plot (Figure 43A) exhibits this same pattern. Inferences from the shapes of these curves are: 1) most of the world's pastures are stocked substantially below their currently attainable maximum levels, and 2) estimates of currently attainable maximum stocking density entail substantial uncertainty because stocking density exhibits such a strong dependence on ranked area percentile at high percentile values. For example, the intensification ratio jumps from 2.75 to 3.75 when the maximum potentials are measured at the 90th and 95th percentile, respectively.

In contrast to the consistently convex shape of the aggregate livestock population curves, the aggregate production vs ranked area percentile curve for maize is concave up to a level of around the 80th percentile (Figure 43C and Supplemental Analysis Figure 54). Wheat crop systems show a roughly linear pattern of increase up to the 80th percentile (Figure 43B). Both maize and wheat show large jumps in performance in the low percentile range. These differences suggest not only that pasture-based livestock systems have much greater potential for intensification than grain crops, but that the incremental benefits of a strategy of sustainable intensification that goes after the "low-hanging fruit", recently endorsed by Garnett et al (Garnett et al 2013), are much greater for livestock than for row crops.

The climate binning strategy is designed to isolate performance-impacting factors other than precipitation and growing degree days, and in particular management variables. In the case of major grain crops, for example, Mueller et al (Mueller et al 2012b) found that 70 to 80% of the intrabin variability was due to fertilizer application and irrigation. Investigation of the causes of intrabin variability for pasture systems is an important topic for future research. Management variables to be considered in this context include improved forage and livestock varieties, pasture reseeding, animal rotation, fertilizer use, pH adjustment, irrigation, and supplemental feeding. Consideration should also be given to other variables including soil quality, seasonal or yearly climate variation, and political and economic factors. Further analysis of the environmental implications of pasture intensification is needed, noting that these implications may not necessarily be negative (Thornton 2010; Kemp, & Michalk 2007; Herrero et al 2010) .

By restricting our scope to pasture, our study does not address other management models responsible for the majority of global livestock production systems, particularly mixed crop/livestock systems. These systems represent the largest fraction of livestock production (Robinson et al 2011), but, as acknowledged by Ramankutty (Ramankutty et al 2008), are not captured by a simple crop/pasture land use classification. By including all permanent pasture in our estimate of the intensification ratio, we are assuming that the 43% of pasture that is unoccupied can be utilized and raised to its maximum attainable performance. If unoccupied land is excluded, the maximum attainable global intensification ratio for livestock on permanent pasture drops from 3.83 to 2.83. (See Supplemental Analysis section Impact of excluding unoccupied pastureland.) But in this scenario some of the unoccupied land could be available for uses such as biodiversity preservation, bioenergy production, or other ecosystem services. We speculate that pastureland unoccupied according to the gridded livestock study may be degraded, abandoned, marginal or part of a multi-year rangeland rotation not captured in a single snapshot of animal population. Greater clarity on the status of this land would be desirable, particularly considering that its area is comparable to total global cropland.

Brazil's experience in intensifying their predominantly pasture-based livestock systems is instructive (Martha et al 2012). From 1985 to 2006, Brazil increased beef output by 3.1-fold while reducing total pastureland area by 11% (see Supplemental Analysis section Brazil's predominantly pasture-based *livestock sector*). Over this period, increased stocking density (head/ha) was less important than increased animal performance (animal product per head per year) in explaining the 3.5-fold increase in per hectare pastured livestock yield seen in Brazil. If the potential for increased animal performance worldwide were comparable to that achieved in Brazil, this would more than double the pasture intensification ratios reported here. Stocking density is an approximate and incomplete surrogate for livestock yield. Global livestock yield data are not available but would be of great value.

This work presents the first quantitative estimate of the global pasture intensification potential using geospatially-specific data, provides a framework for refinements of such estimates in the future, and highlights uncertainties and needed research. If these findings are further supported by future research, they will have important positive implications with respect to providing food for an increasing population, using a fraction of pastureland for production of biofuels, and the feasibility of doing both simultaneously.

Supplemental methods

Merging EarthStat and FAO Gridded Livestock of the World (GLW) data.
Pasture systems represent the largest land footprint of all human activities. However, land use data sets tend to be simplistic—fundamentally organizing agricultural land as either cropland or pastureland. Production systems are also not exclusive. For example, feedlot systems rely on pasture systems for raising calves. Acknowledging that a large fraction of animals are associated with what are called mixed livestock/crop systems, the ability to adequately define and categorize these diverse systems is problematic at best. Bearing in mind these considerations, we used a dataset from FAO (Wint, & Robinson 2007) that is fundamentally neutral with regard to the type of production system and tied it to a land use/land cover dataset developed by Ramankutty et al (Ramankutty et al

2008) that provides a 5 arc min by 5 arc minute description of land designated as "permanent pasture." These data are available as part of the Earthstat dataset (http://www.earthstat.org).

The UN's Food and Agriculture Organization (FAO) 2007 Gridded Livestock of the World (GLW) report (Wint, & Robinson 2007) was the first, and to our knowledge still only, comprehensive global accounting of the location and densities of cattle, sheep, goats, poultry, pigs, and buffalo. This report compiled available national and subnational level data that had necessarily been collected at different scales, using different techniques over a number of different years roughly circumscribing the year 2005. Using a variety of statistical techniques to link livestock densities to a set of readily available predictor parameters to fill data gaps with modeled estimates, and combining these estimates with land use and land cover data used to avoid locating animals in unsuitable areas, FAO researchers generated livestock density estimates disaggregated from the original coarser data sources down to the 3 arc min x 3 arc min resolution.

We interpolated the GLW data from the 3 arc min x 3 arc min resolution to the 5 arc min x 5 arc min resolution so that it could be combined with pasture data in the EarthStat dataset. Interpolation was done using MATLAB's two-dimensional nearest neighbors interpolation algorithm. We confirmed that no significant changes in global animal populations were introduced with this interpolation step. Because of our focus on pasture systems, we only included GLW data on the three most populous ruminants—cattle, sheep and goats.

Aggregating livestock and setting maximum densities

An important parameter use herein to distinguish pasture-only systems from other livestock production systems is maximum animal density. It is not possible to identify whether populations of cattle, sheep and goats in a given grid cell are overlapping. We therefore take a conservative approach of setting the limit of animal density on the aggregate of cattle, sheep and goats in each grid cell, rather than on a maximum animal density for each animal type.

We express this aggregate in terms of animal unit (AU) equivalents. We define one AU as one beef cattle weighing 454 kg (Womach 2005). This is a legal definition often used by regulators around the world when establishing limits on the maximum number of animals that may be grazed (particularly on public lands). These regulators typically provide equivalencies for other animal types. In the case of sheep, a typical assumption is that one mature sheep is equivalent to roughly 0.2 AUs. For goats, values range from 0.1 to 0.2 AUs per mature goat. We conservatively assume an equivalency of 0.2 for goats. For each grid cell, total livestock density is calculated as:

Equation 15

$$d_i = \sum_{j=1}^{3} AU_{eq_j} d_{ij}$$

where d_i is total livestock density, AU_{eq} is the equivalency for animal type j, j=1,2 and 3 correspond to cattle ($AU_{eq,1}$ = 1), sheep ($AU_{eq,2}$ = 0.2) and goats ($AU_{eq,3}$ = 0.2).

Mixed crop/livestock systems and feedlot systems are capable of supporting higher densities of animals, and upper limits for grazing systems are highly dependent on local conditions. A maximum density of 2 AU per hectare was assumed for pasture systems, based on the judgment of two of the authors (G. Martha and C. West), whose experience suggests that animal densities above this level are rare in grazing-only systems. The sensitivity of our results to this assumption was tested and found to be small (see section Sensitivity of maximum allowable animal density), and our estimate for the total population of pastured animals obtained using a 2 AU per ha cutoff agrees well with prior estimates (see Estimates of current cattle, sheep and goat populations on permanent pasture).

Isolating livestock on permanent pasture.

The EarthStat dataset reports pasture land as a fraction (f_i) of the area (A_i). in a given grid cell i. The FAO GLW dataset reports the density of animals in a grid cell (d_i) averaged across the total area in the grid cell. Pasture area in a grid cell is:

Equation 16

$$A_{p_i} = f_i A_i$$

When f_i is zero, A_{pi} is equal to zero and thus we do not count any of the animals in the grid cell. This is equivalent to assuming that all animals in this grid cell are associated with other types of livestock production systems. Within each of the 100 bins, we analyze the animal density distributions to determine attainable animal densities. We first discard the smallest-area grid cells (for a total of 5% of the bin area), in order to remove potential outliers from the dataset per the methodology described by (Mueller et al 2012a). In this case, ($Ap_i < Ap_{5th\ percentile}$) the pasture area Ap_i is set to zero and all of the animals reported by FAO in this grid cell are excluded. Again, this equivalent to assigning any animals in the grid cell to another type of livestock production system.

Next, we redistribute the animals in each pasture-containing grid cell onto its pasture fraction. We effectively concentrate the animal density within the pasture fraction (p_i), per Equation 17:

Equation 17

$$p_i = \frac{d_i}{f_i}$$

There are two possible outcomes associated with this calculation, depending on the value of the pasture density, p_i. If p_i is greater than our 2 AU maximum aggregate density, all of the reported livestock in this grid cell are excluded from our estimate (once again, assigning the animals located on this grid cell to a mixed crop/livestock system supplemented in some way with feed beyond what is available for grazing). If p_i is less than or equal to our 2.0 AU aggregate maximum density, the animals are included in our analysis, and the grid cell's contribution to the pastured livestock population is calculated as the product of p_i and Ap_i.

Defining climate bins for pastureland

Details of the climate binning methodology can be found in Mueller et al 2012 (Mueller et al 2012b). The world is characterized in terms of 100 unique climate bins of equal land area exhibiting similar climate conditions. Two climate parameters, in the form of global, spatially-distributed maps at the 5'x5' resolution Total Annual Precipitation (TAP) and Growing-Degree Days Base 5ºC (GDD5) based on daily mean temperatures generated from WorldClim monthly mean temperatures (Hijmans et al 2005), were used to define climate bins, as was done by Licker et al (Licker et al 2010). Using these two variables, we further refine the dataset by discarding grid cells that are climate-outliers by defining a compact contour in precipitation GDD_5 space containing 95% of the pastureland area (see (Mueller et al 2012b) for details).

The resulting climate bins are shown in Figure 45. Each dot plotted in climate space represents a pasture-containing grid cell. The color-coding of each grid cell reflects the fraction of pastureland contained in each grid cell. High concentrations of pastureland are found in low-to-moderate rainfall areas with cool to moderate temperature conditions. There is also a high concentration of pasture found in relatively warm and dry regions of climate space. The blue lines are the boundaries in climate space for each of the 100 bins, and correspond to the bin legend shown in the main body of the paper in Figure 41B.

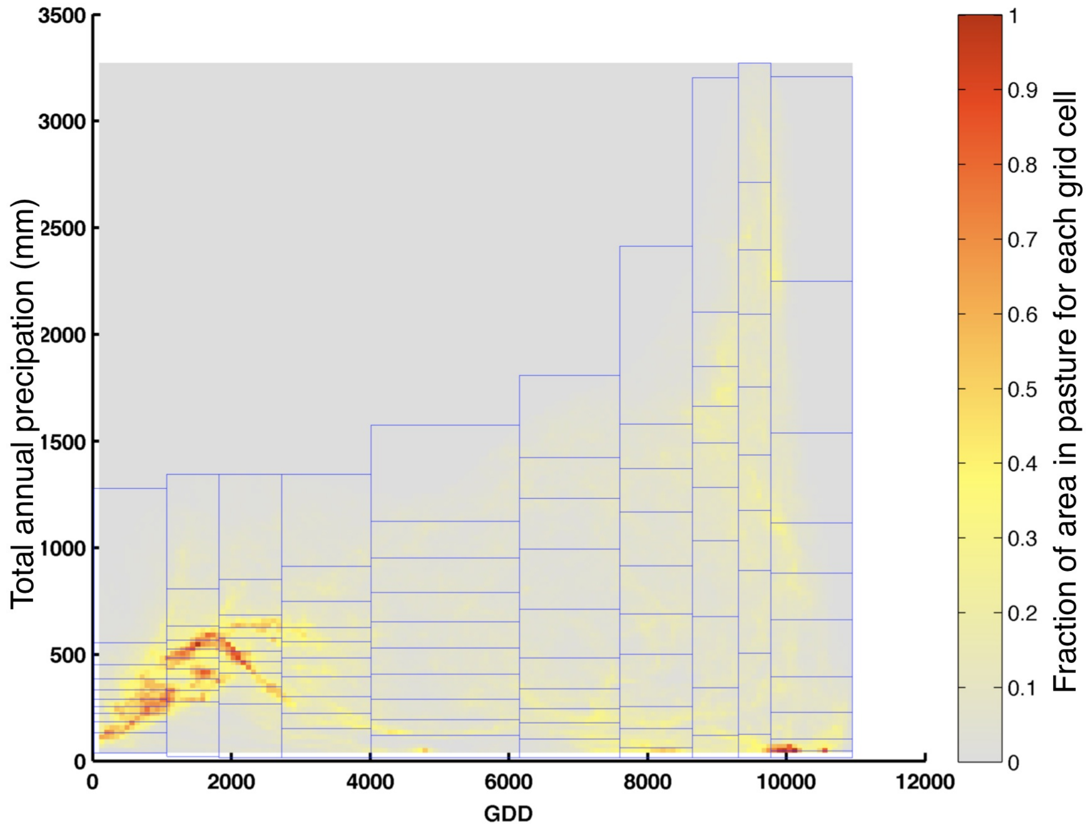


Figure 45. Pasture area distribution in climate space

Supplemental analysis

Net global population and distribution of livestock raised on pasture

The maps in Figure 46 show the distribution of cattle, sheep, goats and total livestock at each stage of redistribution and filtering of animals. Maps a, b and c correspond to different levels of filtering of the FAO data for cattle. Likewise, maps d, e and f show animal distributions for sheep; and, maps h,i and j for goats.

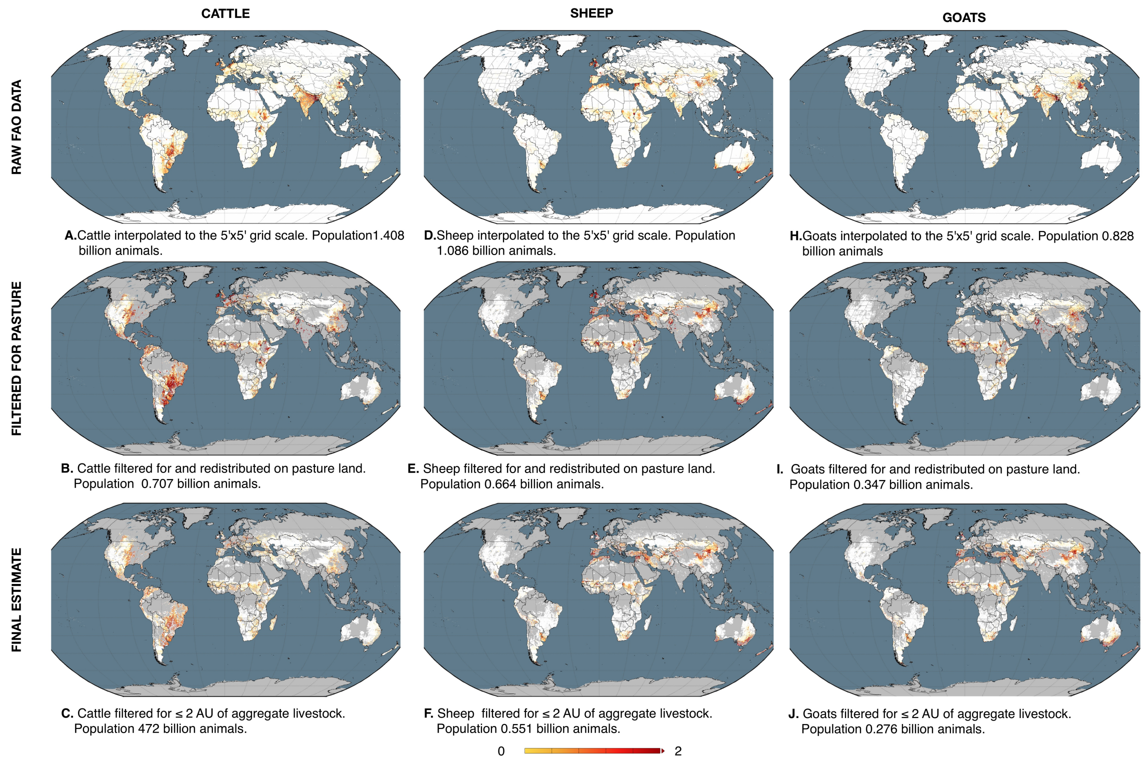


Figure 46. Cattle, sheep and goat distribution at different stages of filtering

The bulk of the 1.79 billion AU equivalents animals are cattle (1.41 billion AUs) are cattle, which make up 80% of the aggregate. FAO's data shows large concentrations of cattle in Latin America, the eastern Sahel, South Asia, northern Europe, the British Isles and northeastern China (Figure 46a). Moderate concentrations of cattle occur in North America, Western Europe, and across much of Asia.

When we remove cattle located in grid cells containing less than 5% pasture, we see a 50% drop in the estimated total population of cattle (Figure 46b), driven largely by the discounting of animals in South Asia and northeastern China, as well as across much of Asia and Southeast Asia. Redistributing cattle on pasture also leads to increases in the effective density of animals, especially in the US Midwest, southern Brazil, northern Europe, the British Isles, the western Sahel, and parts of southern China.

As shown in Figure 46c, the combined effect of eliminating grid cells with no significant pasture land and grid cells with high densities (greater than 2 AUs per ha on pasture) restricts the estimate of cattle population in grazing-only pasture systems to one third of the total original FAO estimate of global population (0.47 billion head of cattle).

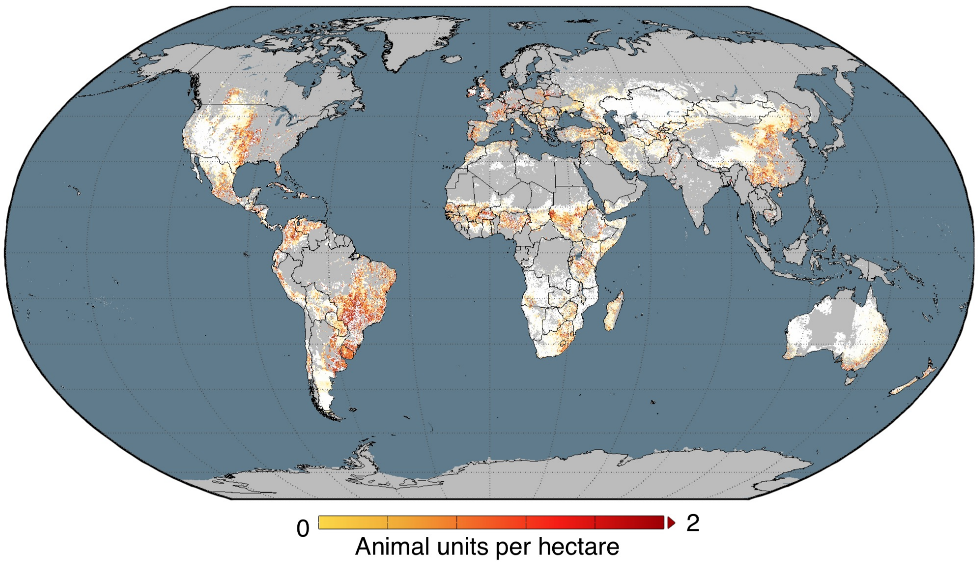
The 1.09 billion head of sheep reported by FAO are most heavily concentrated in the British Isles, southern Australia and New Zealand (Figure 46d). Moderate populations occur throughout Europe, the Middle East, South Asia and central Asia, as well as the Sahel. As with cattle, removing sheep from non-pasture grid cells substantially reduces our estimate of the grazed sheep population. This step in the data filtering leaves only 60% of the original population (0.66 billion head of sheep) (Figure 46e). Redistribution of sheep on pasture accentuates the level of sheep in southern Europe, central Asia and southern Australia/New Zealand. But applying the density cutoff shows much less effect (Figure 46f), reducing the count by another 10%, and leaving about half the original population—0.55 billion head of sheep.

The FAO-estimated 0.83 billion goats are concentrated in South Asia and Central Asia, with moderate levels found throughout the Sahel and East Africa (Figure 46g). Removing goats found in non-pasture grid cells removes 50% of the population. While most of India's goat population is removed by this step in filtering the data, the high concentrations of goats in Afghanistan and Pakistan remain. When filtered for the maximum aggregate animal density, the estimate of goats on pasture drop by another one-third, to final count of 0.28 billion animals.

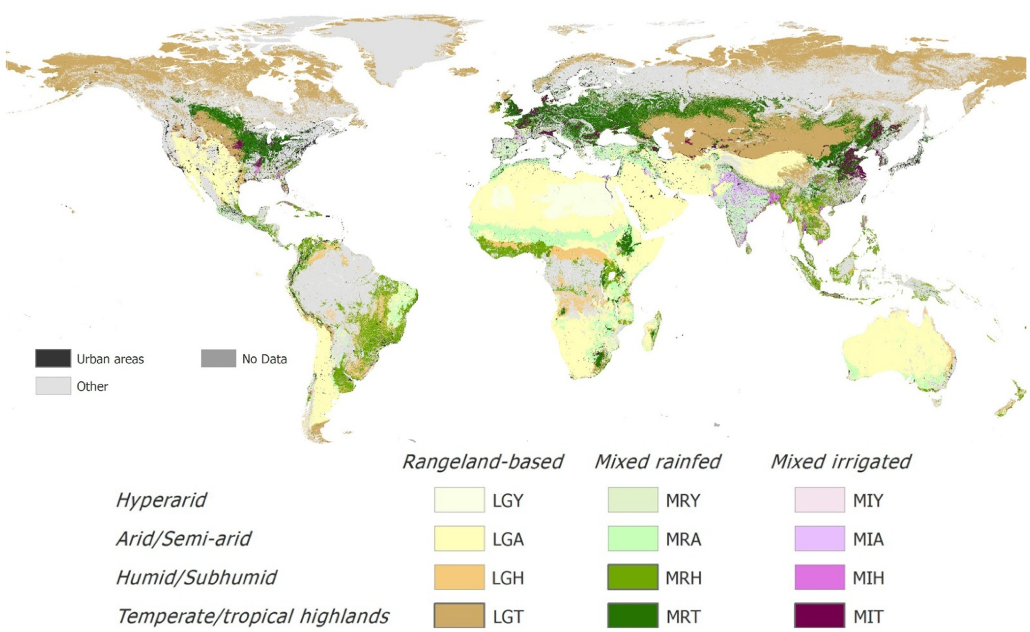
Figure 47 compares our final geospatial distribution of pasture-based livestock with the most recent global map of livestock production systems developed by FAO and the International Livestock Research Institute (ILRI) (Robinson et al 2011). Their analysis confirms our conclusion that much of the livestock found in South Asia, Eastern Asia and Southeast Asia is not strictly pasture or grassland based. They classify most of the production in these regions as some form of mixed crop and livestock production, systems often associated with smallholder, low-income farms. Our map of pasture-based livestock does show some differences with the FAO/ILRI map, particularly in Brazil and other parts of Latin America. In those regions, we estimate much larger areas of pasture-based production. FAO and ILRI categorize much of these same areas as mixed crop-livestock production systems. Finally, there are many areas of the globe where we show no pasture-based production, but FAO and ILRI show extensive rangeland livestock production.

There are a number of explanations for the differences between our analysis and the FAO/ILRI analysis. Because the methodology used by FAO and ILRI is based empirically on human population and climate conditions, they tend to classify many arid regions of the world as livestock grazing areas.

Our analysis, based on Ramankutty's assessment of permanent pastureland, excludes many of these same areas. FAO and ILRI may be over-estimating mixed crop-livestock systems in Latin America because they use a severe climate-based cutoff to separate livestock-only systems from mixed systems. Livestock systems located in what they call “cultivatable” regions (with growing periods greater than 60 days) were lumped in with mixed systems in areas with human populations greater than 20 per km^2.



A. Aggregate livestock distribution on pasture from this study



B. Global distribution of livestock production systems per FAO/ILRI

Figure 47. Comparison of our geospatial distribution of pasture-based livestock with FAO/ILRI distributions of livestock production systems

Characterizing pasture-based livestock systems in climate space

Ranked distributions of livestock density in each climate bin are shown in Figure 48a.

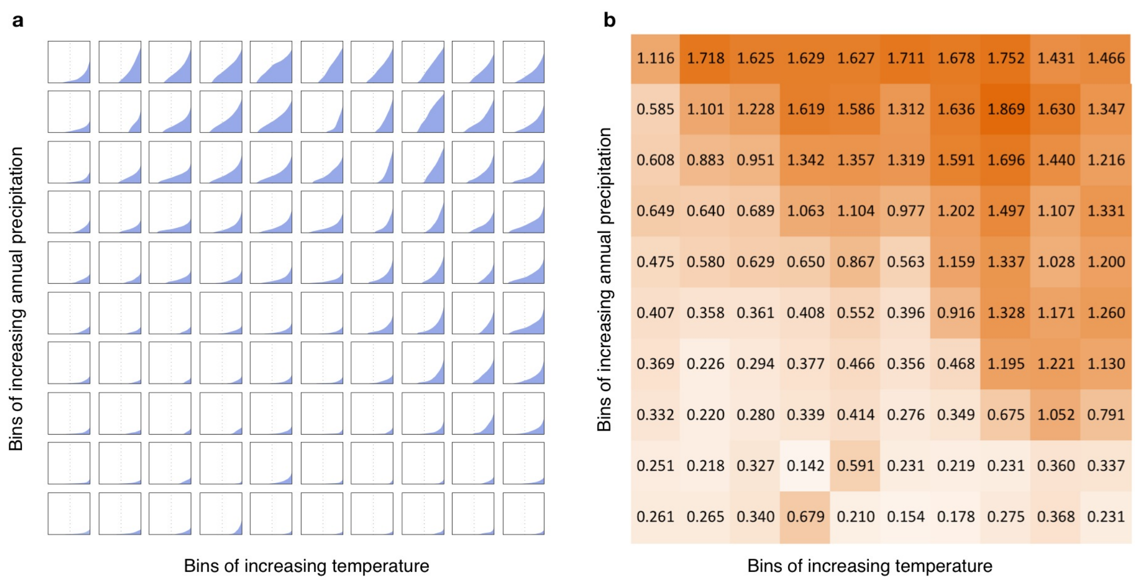


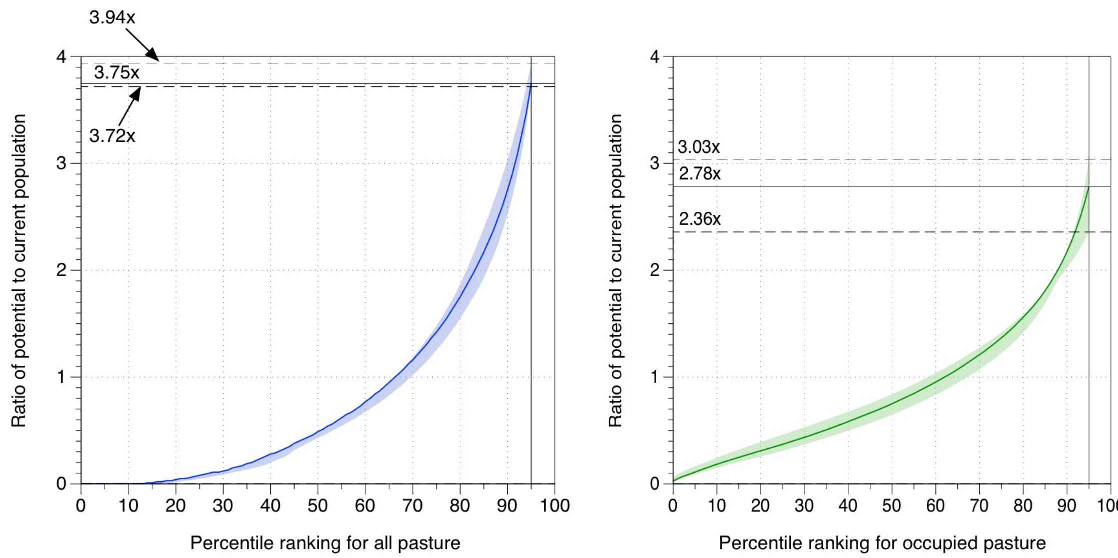
Figure 48. Distribution of aggregate livestock density (AU per ha) for each climate bin. a, Ranked area-percentile distribution of livestock density. x-axis in each bin is 0 to 95th percentile. The y-axis in each bin has a scale of 0 to 2 AU per ha, which is the maximum AU per ha cutoff used to distinguish pasture-only livestock production systems from other livestock production systems. b, Distribution of maximum attainable livestock density in climate space.

Several important observations can be drawn from these ranked density profiles. First, the majority of the bins do not come close to the 2 AU per hectare maximum limit we set for defining pasture systems. In fact the colder and drier climate bins, corresponding to what are often called rangeland systems, have maximum densities that are on the order of 0.2 to 0.4 AU per ha (see Figure 48b). Profiles for each bin are mostly concave up, indicating that the poorest performing areas have the greatest potential for improvement and that the overall opportunity for improvement is large.

Sensitivity of maximum allowable animal density to assumed animal density cutoff for pasture

One of the largest sources of uncertainty in this analysis lies in distinguishing pasture-only systems from other (especially mixed crop/livestock) systems. In broad terms, FAO (Robinson et al 2011) breaks out livestock production into landless and land-based systems. Within the land-based systems, there are pasture-based production systems and mixed pasture and crop systems. The latter offers significant synergies that can lead to higher levels of productivity for both the crop and the animal systems. We have drawn the line between pasture and mixed systems using a value of 2 AUs per ha. Because the maximum density for pasture is dependent on many variables (particularly climate related ones), the choice of cutoff is somewhat arbitrary. We therefore tested the influence of this assumption on our estimate of maximum global intensification potential.

Figure 49a shows the effect of cutoff on the global livestock intensification potential estimated at different levels of ranked percentile performance in each bin. Our estimate of maximum global intensification potential is robust across the range of cutoff values tested, which included 0.5, 1,2,3,4,5 and 10 AU per ha. The solid blue line represents the global intensification potential as a function of performance level, with a value of 3.75 at the 95th percentile. The shaded area shows the variation for the range of cutoffs (from 0.5 to 10 AU per ha). For an intensification ratio measured at the 95th percentile, the estimates vary from 3.72 to 3.93. This low variability is consistent across all levels of performance.



a. Intensification potential for aggregate livestock on all pasture land.

b. Intensification potential for aggregate livestock on occupied pasture land only

Figure 49. Global intensification potential as a function of performance level and assumed maximum density cutoff for all pasture land

Impact of excluding unoccupied pastureland

As noted in the main paper, we estimate that more than 40% of the land designated as permanent pasture does not have animals on it. There are any number of reasons for this. If the unoccupied land is highly degraded and not useable, we may not want to include it as part of our estimate of global intensification potential. We therefore considered the effect of excluding all unoccupied land on the global intensification potential (see Figure 49). Our results are more sensitive to the choice of including or excluding occupied land than they are to the choice of animal density cutoff. The maximum global intensification ratio drops by 25% from 3.83 to 2.78. Variability with respect to assumptions for animal density cutoff is larger for the occupied-only scenario than for the all-pastureland scenario. Low and high values in the former scenario are 2.36-fold to 3.03-fold.

Impacts of closing the yield gap

Figure 50 illustrates in more detail what happens under different scenarios of raising the worst performing pasture systems up to a minimum level defined as a percentage of maximum attainable density in each climate bin. Because of the convex nature of the current livestock ranked performance, raising the floor to only 50% of the maximum has a very large effect.

Global intensification potential of individual cattle, sheep and goat systems

We have highlighted results for aggregate animal populations of cattle, sheep and goats. Here we explore the differences observed among the three animal types. We can only evaluate individual animal results for occupied pastureland, since it is not possible to classify unoccupied land as belonging to any given animal type. In Figure 51 we compare the global intensification potential for each animal type as a function of ranked percentile from 0 to the 95th percentile performance level. Sheep and goat systems exhibit higher intensification potentials at the higher performance levels than do cattle systems. One possible explanation for this difference is that sheep and goats are more likely to be supplemented with feed. The differences are, nonetheless, not dramatic (roughly 10 to 20% higher for sheep and goats compared to cattle at the 95th percentile of performance).

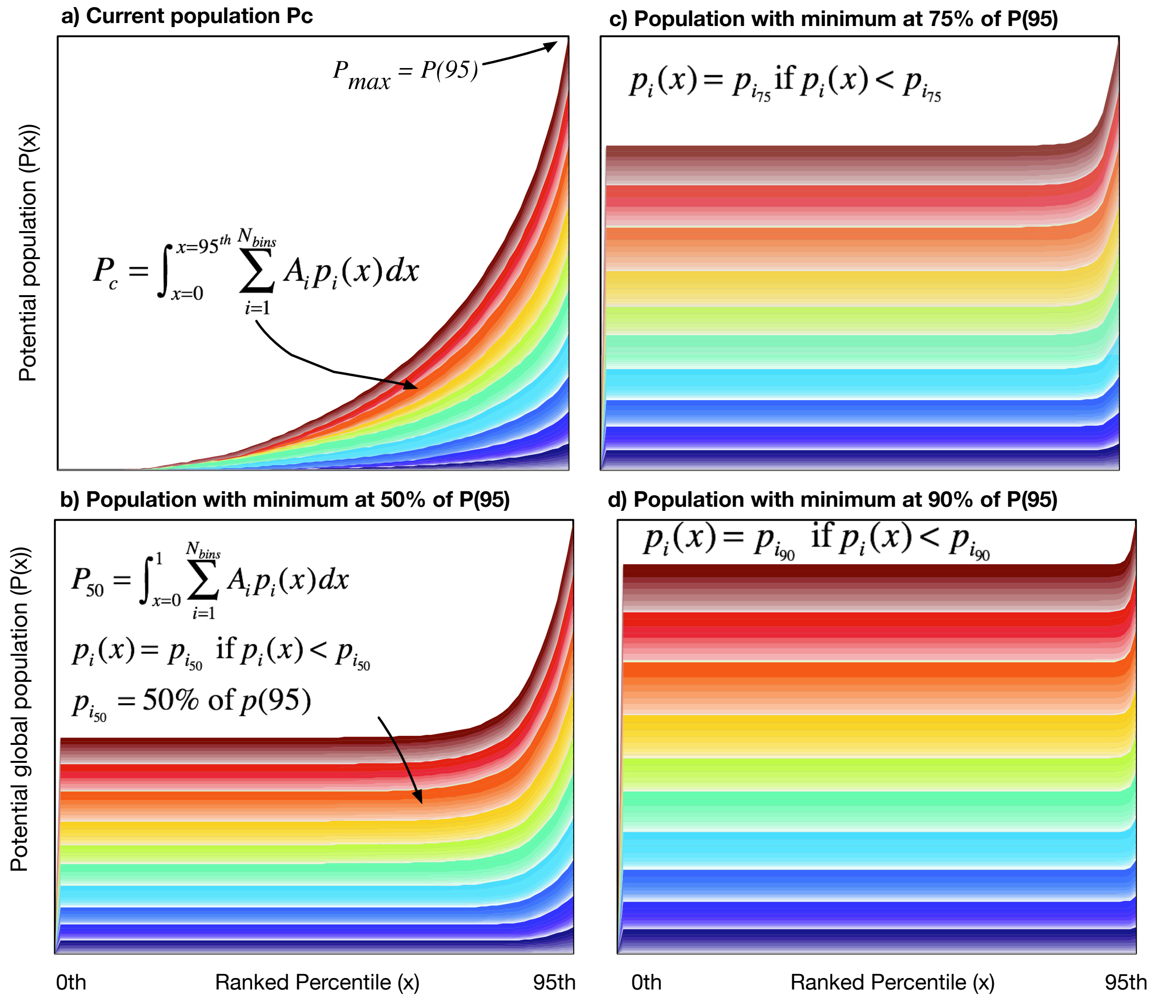


Figure 50. Four scenarios for reducing the yield gap.
Each area unit of pastureland is rank ordered from lowest to highest percentile based on its animal density. a) Maximum intensification ratio is calculated as the ratio of potential population at the 95th percentile to total current population (stacked area under the curve). b) animal densities in each climate bin in each area unit of pastureland that are less than half the animal density associated with the 95th percentile are raised to a level equivalent to 50% of the animal density achieved at the 95th percentile. The ratio of the new total area under the curve to the original area under the curve in chart a) represents the intensification ratio c) same as b) but for a minimum animal density equivalent to 75% of the animal density at the 95th percentile. d) same as b for 90% value of animal density at the 95th percentile.

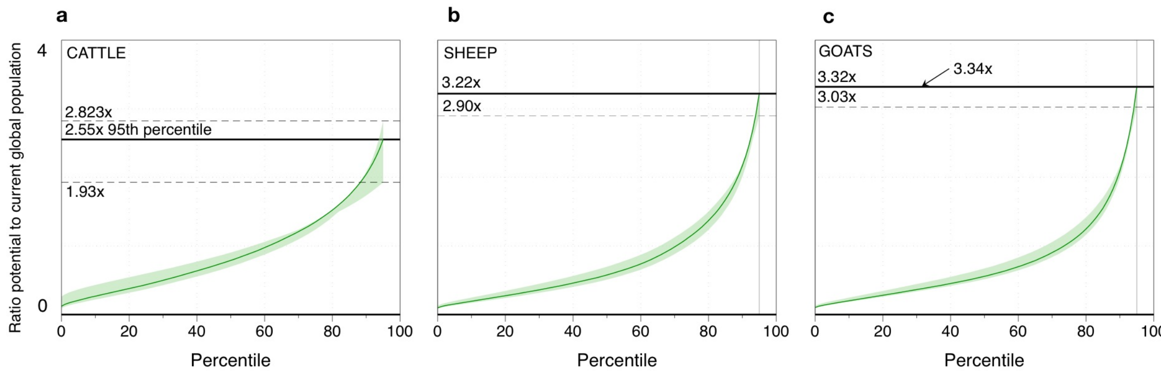


Figure 51. Global intensification potential as a function of performance level for individual animal types.

Estimates of current cattle, sheep and goat populations on permanent pasture

The lack of good data for classifying livestock production systems makes it difficult to quantify the number and type of animals associated with pasture (grazing only) systems. A 1996 FAO report estimated the population of cattle in grazing systems at just under 400 million (de Haan et al 1996). The 2006 FAO report *Livestock's Long Shadow* (Steinfeld et al 2006) estimated that the number of grazed cattle and buffalo was around 430 million. Figure 52 shows the effect of different animal density cutoffs on global populations of cattle, sheep and goats. For each data point, we excluded pixels containing animals greater than the cutoff (ranging from 0.5 to 10 AU per ha). Cumulative global populations were then estimated in each case as the product of pastureland area and animal density in each pixel, summed across all pixels. Note that excluding animals not located on land designated as pasture has already substantially reduced the population estimates. These estimates are surprisingly insensitive to density cutoff over the range of

5 to 10 AU per hectare. The response becomes quite strong below 3 AU per hectare. At our assumed density cutoff of 2 AU per hectare, the estimate of 430 million cattle is reasonably close to FAO's estimates.

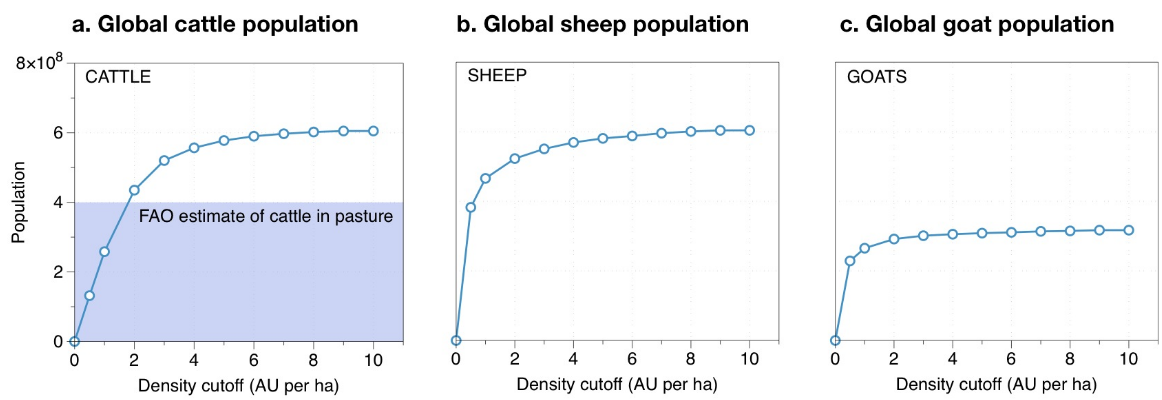


Figure 52. Global populations as a function of assumed maximum aggregate livestock density

Analysis and comparison of wheat and maize systems with pasture systems

We analyzed intensification potential of two of the major grains, wheat and maize, to provide a basis for comparison with our findings for livestock. Our findings for these two crops are consistent with results reported by Mueller et al (2012) (Mueller et al 2012b). Figure 53 a through c show boundaries in climate space for equal-area bins of pasture, maize and wheat land. There is considerable overlap in the climate space occupied by the three agricultural systems of pasture, maize and wheat, with some differences in distribution worth noting. Both maize and pasture show higher concentrations of land area (narrower bins) in milder climates around 2,000 growing degree-days along the x-axis of climate space. Maize shows higher concentrations of land area in annual precipitation zones ranging from 500 to 1,000 mm, while pasture land tends to concentrate along drier annual precipitation zones below 500 mm. Pastureland is consistently more concentrated in drier zones across most of the temperature range in which pasture is distributed, reflecting the tendency for livestock production to occur in less productive "rangeland" systems. Wheat cropland seems to concentrate in slightly warmer zones (2,500 to 3,000 growing degree-days) and drier zones (300 to 700 mm), compared to maize. The overall range of temperatures where wheat cropland is found is as broad as pasture, but in a higher range.

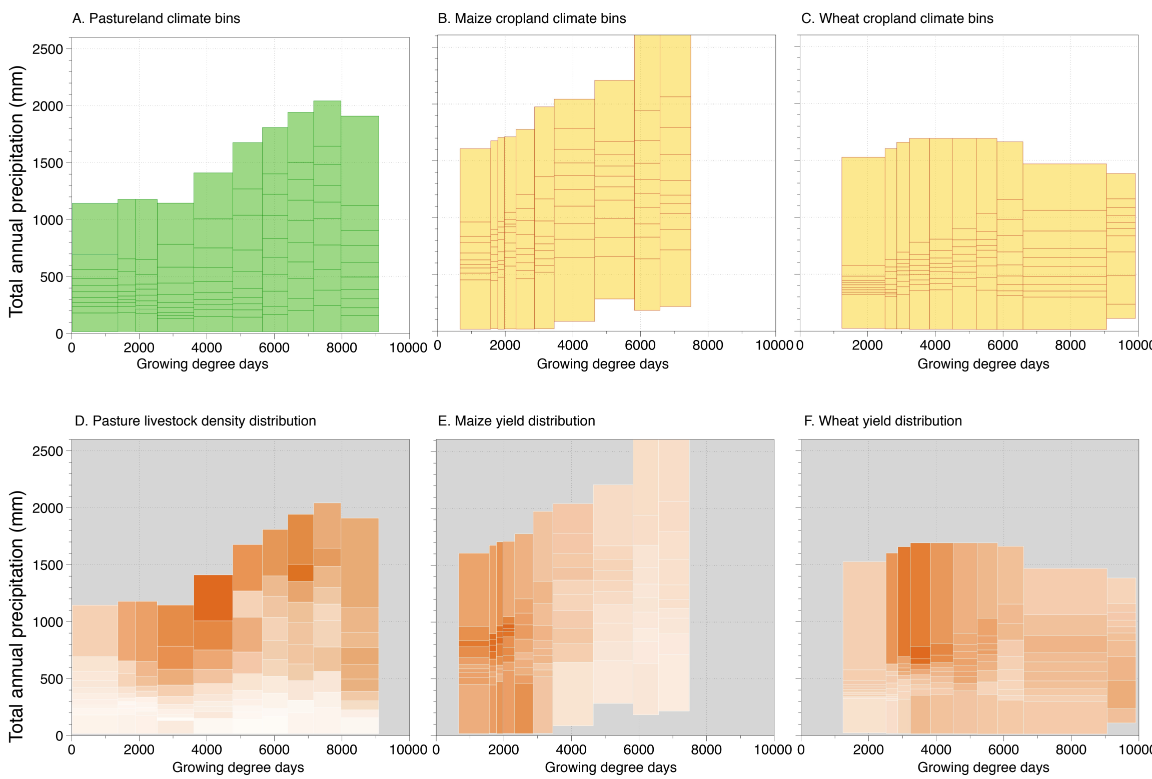


Figure 53. Distribution of climate bins and livestock densities in climate space

The livestock and crop systems each show distinct differences in performance in response to climate (as indicated in the color-intensity coded plots in Figure 53 d through f). Livestock density shows a strong inverse response to precipitation. Drier climates have many fewer animals per ha then wetter climates. A major drop off in livestock density occurs below around 300 to 500 mm of rainfall per year. By contrast, the maize and wheat systems are much less sensitive to rainfall levels. As indicated in the main text of this paper, we may be seeing the effect of irrigation practices for these crops, which would reduce the influence of local precipitation levels in arid and semi-arid regions. Indeed, these two crops seem to exhibit narrow bands of lower yields in what may be the transition between rain fed and irrigated systems. For maize, this transition occurs between 500 and 700 mm of annual rainfall. For wheat the transition occurs between 300 and 500 mm of annual rainfall. In areas with adequate rainfall, maize and wheat perform best under conditions of around 2,000 and 4,000 growing degree days, respectively, Livestock density seems less sensitive to temperature and growing season length, but seems to peak around 4,000 growing degree days.

Figure 54 compares the ranked area-percentile performance bin-by-bin in pasture, maize and wheat climate space. The curves for each climate bin are normalized to the maximum attainable performance (performance at the 95th percentile) in each bin, which allows for rapid visual identification of the relative potential for improvement in each bin. Simply put, the more the area under the ranked performance curve fills the space in each plot the less improvement in performance is available in that bin. The livestock data is presented for aggregate livestock on all land and for aggregate livestock on pasture actually occupied with cattle.

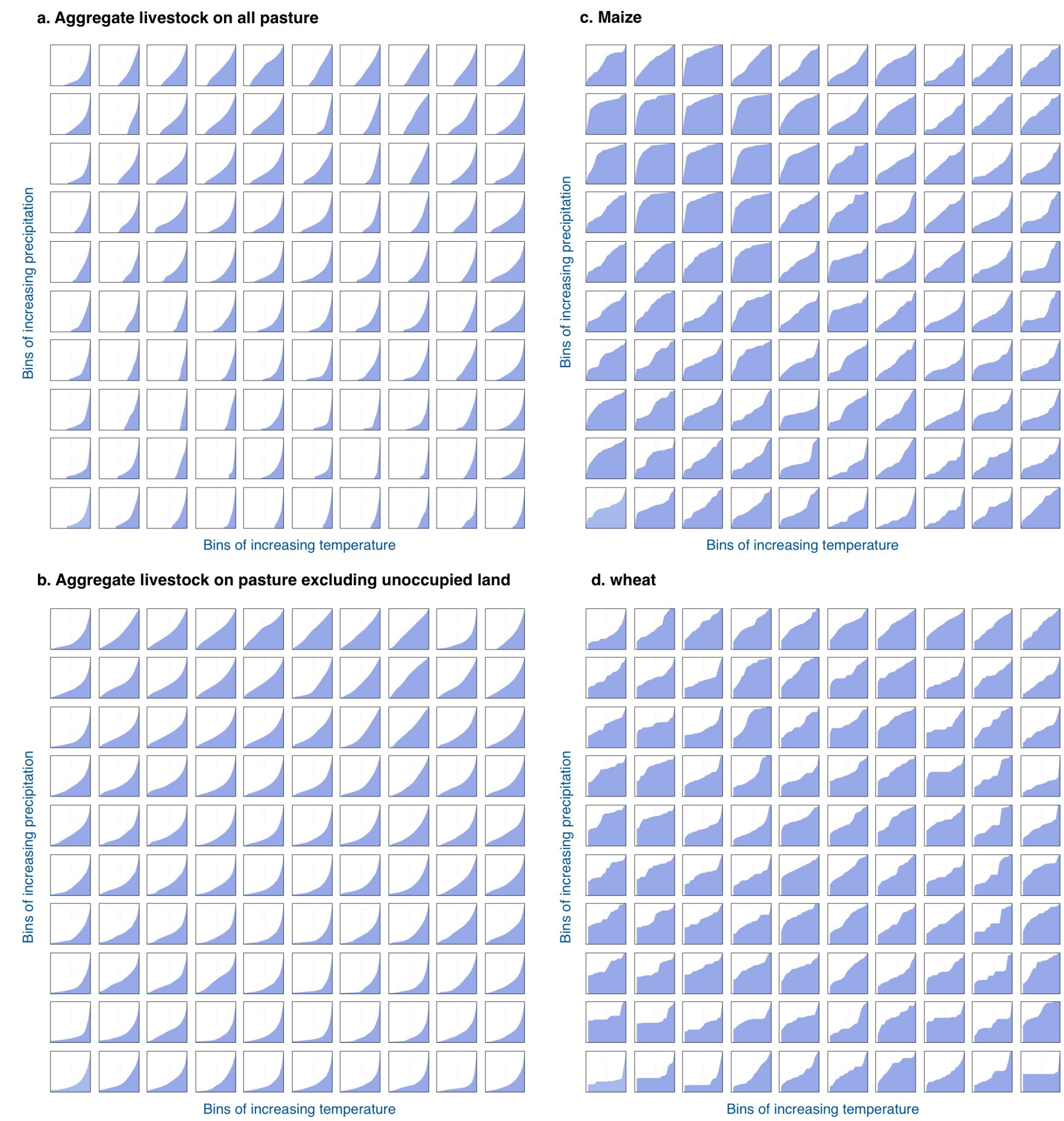


Figure 54. Comparison of individual bin normalized profiles of ranked performance curves for livestock, maize and wheat

The available room for attainable increases in performance for wheat and maize is fairly low in a substantial number of the climate bins. Pasture based livestock systems, by contrast, have a great deal of room for expansion, especially when looking at all land available as pasture (occupied and unoccupied). Even when we restrict the analysis to pasture actually occupied with animals, it is clear that the vast majority of the bins are "less than half full" with regard to their climate-specific performance space.

Finally, as noted previously, all but a hand full of the pasture climate bins show the concave upward pattern that indicates the greater potential for improvements available at lower levels of performance.

Brazil's predominantly pasture-based livestock sector

In just a little over a half-century, its output of beef grew by more than six-fold. While it is often assumed that this growth came mostly at a high cost in land clearing and expansion (Nepstad et al 2009; Soares-Filho et al 2006) , the story is more complex (Martha et al 2012). From 1950 to 1985, expansion of pasture was indeed a significant contributor to the beef industry's increased output (Figure 55). The 2.05 fold increase in output was accompanied by a 1.66 fold increase in pasture area and a 1.61 fold increase in the annual number of animals per hectare maintained on pasture. The increased stocking rate actually coincided with a loss in net productivity during this period, suggesting that ranchers were overgrazing the land.

But, from 1985 to 2006 (Figure 55), there was an additional 3.1-fold increase in output accompanied by a shrinkage in pastureland. Improved animal performance during this time was more than double that of increased stocking rate. The combined effect of improved animal performance and stocking rate resulted in a 3.5-fold increase in overall productivity during this period.

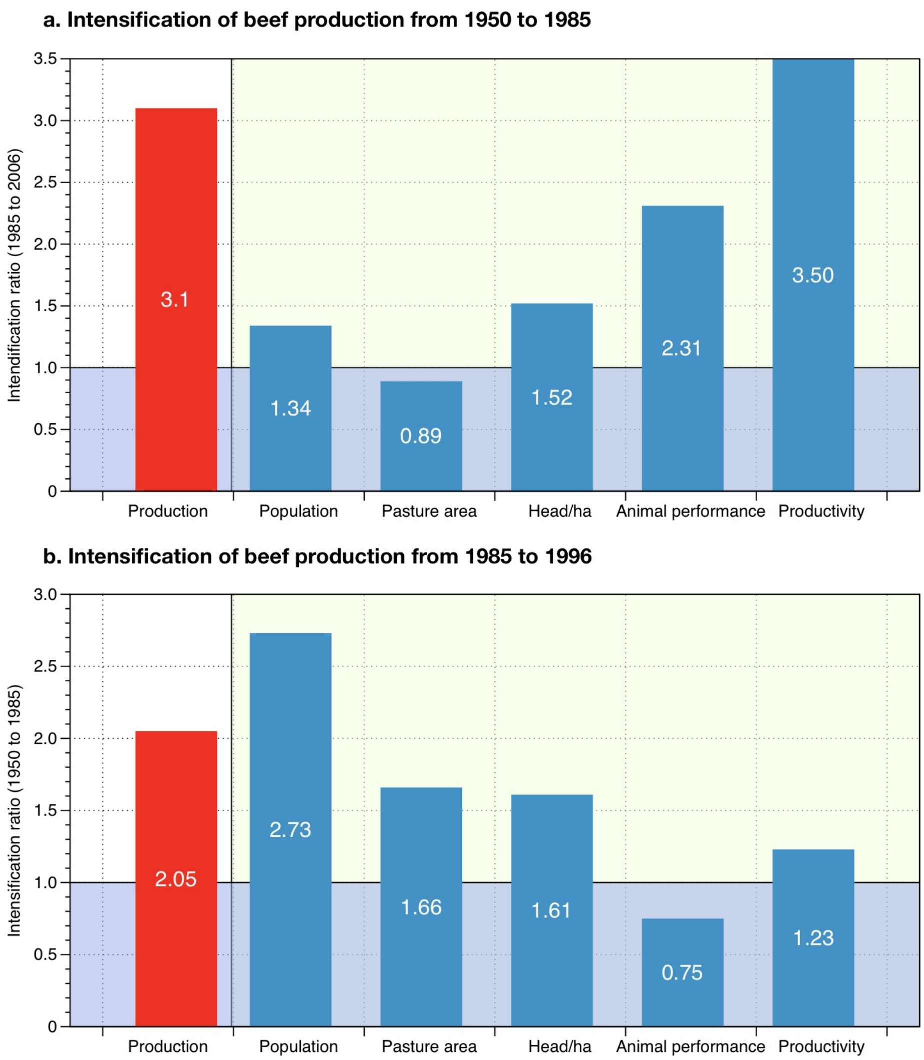


Figure 55. Factors influencing increased production output of Brazil's beef industry

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Appendix: Gevo farm survey

Agri-Energy Corn Supplier Survey

Red Section: Soil, Acreage, and Yield

Survey Instructions

Please provide answers in the shaded boxes below to the best of your knowlege.

Please provide answers that represent average rates or operations across your operation.

If some questions do not apply to your farming operation, leave them blank.

Upon Completion, return survey to Agri-Energy using the self-addressed stamped envelope provided.

Your response will be kept confidential by Gevo and its partner institution, the University of Minnesota. Your name as printed on your return address envelope will be used to track who has submitted responses, and allowing us to send your $50 Visa gift card.

If you wish to complete the survey online, go to:
https://www.surveymonkey.com/s/AgriEnergySurvey

County and townships with your cropland:

County	Township

Dominant 5 soil types on managed cropland over last 3 years:

Soil type	Percent of acres	
		%
		%
		%
		%
		%

Slope of cropland soils managed over last 3 years:

Average slope	Percent of acres	
0-2%		%
2-4%		%
4-6%		%
6-8%		%
>8%		%

Total cropland acres planted in last 3 years:

	Corn acres	Soybean acres	Acreage in other	Total cropland acres in conservation programs
2010:				
2009:				
2008:				

Total cropland acres harvested in last 3 years (if different than planted acres):

	Corn acres	Soybean acres	Acreage in other	Total cropland acres in conservation programs
2010:				
2009:				
2008:				

Average corn and soybean yields in last 3 years (please specify bushels/acre in boxes):

	Corn	Soybean
2010:		
2009:		
2008:		

Average grain moisture at harvest for corn and soybean in last 3 years (% moisture):

	Corn	Soybean
2010:		
2009:		
2008:		

Average corn and soybean seeding rates in last 3 years (please specify seeds/acre in boxes):

	Corn	Soybean
2010:		
2009:		
2008:		

Blue Section: Fertilizer and Manure

Starter fertilizer source and rate for corn (if used):

	Starter source	Starter rate	
2010:			pounds or gallons of product per acre
2009:			pounds or gallons of product per acre
2008:			pounds or gallons of product per acre

Average N fertilizer use over all corn acres for corn in 2010 (excluding starter fertilizer):

	Nitrogen Source	lb N/acre applied with this application		Method of application	Time of application (fall, spring, or in-season)
1st N fertilizer application:			lb N/acre		
2nd N fertilizer application:			lb N/acre		
3rd N fertilizer application:			lb N/acre		

Average fertilizer rates in the fall or spring before the 2010 corn crop (excluding starter fertilizer):

	Fertilizer source	Fertilizer rate	
Phosphorus fertilizer application:			lb P_2O_5/acre
Potassium fertilizer application:			lb K_2O/acre
Sulfur fertilizer application:			lb S/acre

Average N fertilizer use over all corn acres for corn in 2009 (excluding starter fertilizer):

	Nitrogen Source	lb N/acre applied with this application		Method of application	Time of application (fall, spring, or in-season)
1st N fertilizer application:			lb N/acre		
2nd N fertilizer application:			lb N/acre		
3rd N fertilizer application:			lb N/acre		

Average fertilizer rates in the fall or spring before the 2009 corn crop (excluding starter fertilizer):

	Fertilizer source	Fertilizer rate	
Phosphorus fertilizer application:			lb P_2O_5/acre
Potassium fertilizer application:			lb K_2O/acre
Sulfur fertilizer application:			lb S/acre

Average N fertilizer use over all corn acres for corn in 2008 (excluding starter fertilizer):

	Nitrogen Source	lb N/acre applied with this application		Method of application	Time of application (fall, spring, or in-season)
1st N fertilizer application:			lb N/acre		
2nd N fertilizer application:			lb N/acre		
3rd N fertilizer application:			lb N/acre		

Average fertilizer rates in the fall or spring before the 2008 corn crop (excluding starter fertilizer):

	Fertilizer source	Fertilizer rate	
Phosphorus fertilizer application:			lb P_2O_5/acre
Potassium fertilizer application:			lb K_2O/acre
Sulfur fertilizer application:			lb S/acre

Total acres that received lime in last 3 years:

2010:		acres
2009:		acres
2008:		acres

Average lime application rate on acres that received lime in last 3 years:

2010:		tons/acre
2009:		tons/acre
2008:		tons/acre

Primary manure type applied in the fall or spring prior to the 2010 crop:

Type of manure (check one of the boxes below):
- ☐ Liquid swine manure
- ☐ Liquid dairy manure
- ☐ Dry dairy manure
- ☐ Dry beef manure
- ☐ Solid chicken manure
- ☐ Solid turkey manure
- ☐ Other (please specify)

# of acres this manure was applied on: ☐ acres

Average application rate of this manure: ☐ tons/acre or gallons/acre

Main method of applying this manure (check one of the boxes below):
- ☐ Broadcast (incorporated within 12 hours)
- ☐ Broadcast (incorporated within 4 days)
- ☐ Broadcast (not incorporated within 4 days)
- ☐ Injected with knives
- ☐ Injected with sweeps

Sercondary manure type applied in the fall or spring prior to the 2010 crop:

Type of manure (check one of the boxes below):
- ☐ Liquid swine manure
- ☐ Liquid dairy manure
- ☐ Dry dairy manure
- ☐ Dry beef manure
- ☐ Solid chicken manure
- ☐ Solid turkey manure
- ☐ Other (please specify)

# of acres this manure was applied on: ☐ acres

Average application rate of this manure: ☐ tons or gallons/acre

Main method of applying this manure (check one of the boxes below):
- ☐ Broadcast (incorporated within 12 hours)
- ☐ Broadcast (incorporated within 4 days)
- ☐ Broadcast (not incorporated within 4 days)
- ☐ Injected with knives
- ☐ Injected with sweeps

Primary manure type applied in the fall or spring prior to the 2009 crop:

Type of manure (check one of the boxes below):
- ☐ Liquid swine manure
- ☐ Liquid dairy manure
- ☐ Dry dairy manure
- ☐ Dry beef manure
- ☐ Solid chicken manure
- ☐ Solid turkey manure
- ☐ Other (please specify)

# of acres this manure was applied on: ☐ acres

Average application rate of this manure: ☐ tons/acre or gallons/acre

Main method of applying this manure (check one of the boxes below):
- ☐ Broadcast (incorporated within 12 hours)
- ☐ Broadcast (incorporated within 4 days)
- ☐ Broadcast (not incorporated within 4 days)
- ☐ Injected with knives
- ☐ Injected with sweeps

Sercondary manure type applied in the fall or spring prior to the 2009 crop:

Type of manure (check one of the boxes below):
- ☐ Liquid swine manure
- ☐ Liquid dairy manure
- ☐ Dry dairy manure
- ☐ Dry beef manure
- ☐ Solid chicken manure
- ☐ Solid turkey manure
- ☐ Other (please specify)

# of acres this manure was applied on: ☐ acres

Average application rate of this manure: ☐ tons or gallons/acre

Main method of applying this manure (check one of the boxes below):
- ☐ Broadcast (incorporated within 12 hours)
- ☐ Broadcast (incorporated within 4 days)
- ☐ Broadcast (not incorporated within 4 days)
- ☐ Injected with knives
- ☐ Injected with sweeps

Primary manure type applied in the fall or spring prior to the 2008 crop:

Type of manure (check one of the boxes below):

- [ ] Liquid swine manure
- [ ] Liquid dairy manure
- [ ] Dry dairy manure
- [ ] Dry beef manure
- [ ] Solid chicken manure
- [ ] Solid turkey manure
- [ ] Other (please specify)

# of acres this manure was applied on: ______ acres

Average application rate of this manure: ______ tons/acre or gallons/acre

Main method of applying this manure (check one of the boxes below):

- [ ] Broadcast (incorporated within 12 hours)
- [ ] Broadcast (incorporated within 4 days)
- [ ] Broadcast (not incorporated within 4 days)
- [ ] Injected with knives
- [ ] Injected with sweeps

Sercondary manure type applied in the fall or spring prior to the 2008 crop:

Type of manure (check one of the boxes below):

- [ ] Liquid swine manure
- [ ] Liquid dairy manure
- [ ] Dry dairy manure
- [ ] Dry beef manure
- [ ] Solid chicken manure
- [ ] Solid turkey manure
- [ ] Other (please specify)

# of acres this manure was applied on: ______ acres

Average application rate of this manure: ______ tons or gallons/acre

Main method of applying this manure (check one of the boxes below):

- [ ] Broadcast (incorporated within 12 hours)
- [ ] Broadcast (incorporated within 4 days)
- [ ] Broadcast (not incorporated within 4 days)
- [ ] Injected with knives
- [ ] Injected with sweeps

Orange Section: Pest Management

Herbicide information for corn in 2010:

Herbicide application	Herbicide #1 in tank	Rate of herbicide #1	Herbicide #2 in tank	Rate of herbicide #2	Herbicide #3 in tank	Rate of herbicide #3
1						
2						
3						

Herbicide information for corn in 2009:

Herbicide application	Herbicide #1 in tank	Rate of herbicide #1	Herbicide #2 in tank	Rate of herbicide #2	Herbicide #3 in tank	Rate of herbicide #3
1						
2						
3						

Herbicide information for corn in 2008:

Herbicide application	Herbicide #1 in tank	Rate of herbicide #1	Herbicide #2 in tank	Rate of herbicide #2	Herbicide #3 in tank	Rate of herbicide #3
1						
2						
3						

Herbicide information for soybean in 2010:

Herbicide application	Herbicide #1 in tank	Rate of herbicide #1	Herbicide #2 in tank	Rate of herbicide #2	Herbicide #3 in tank	Rate of herbicide #3
1						
2						
3						

Herbicide information for soybean in 2009:

Herbicide application	Herbicide #1 in tank	Rate of herbicide #1	Herbicide #2 in tank	Rate of herbicide #2	Herbicide #3 in tank	Rate of herbicide #3
1						
2						
3						

Herbicide information for soybean in 2008:

Herbicide application	Herbicide #1 in tank	Rate of herbicide #1	Herbicide #2 in tank	Rate of herbicide #2	Herbicide #3 in tank	Rate of herbicide #3
1						
2						
3						

Folilar fungicide information for corn in 2010:

Fungicide application	Fungicide product	Fungicide rate
1		
2		

Folilar fungicide information for corn in 2009:

Fungicide application	Fungicide product	Fungicide rate
1		
2		

Folilar fungicide information for corn in 2008:

Fungicide application	Fungicide product	Fungicide rate
1		
2		

Folilar fungicide information for soybean in 2010:

Fungicide application	Fungicide product	Fungicide rate
1		
2		

Folilar fungicide information for soybean in 2009:

Fungicide application	Fungicide product	Fungicide rate
1		
2		

Folilar fungicide information for soybean in 2008:

Fungicide application	Fungicide product	Fungicide rate
1		
2		

Folilar insecticide information for soybean in 2010:

Insecticide application	Insecticide product	Insecticide rate
1		
2		

Folilar insecticide information for soybean in 2009:

Insecticide application	Insecticide product	Insecticide rate
1		
2		

Folilar insecticide information for soybean in 2008:

Insecticide application	Insecticide product	Insecticide rate
1		
2		

Green Section: Tillage and Residue Management

Percent of corn acres with corn harvested as silage:

2010: ____ %
2009: ____ %
2008: ____ %

Percent of corn acres with corn residue baled and removed after grain harvest:

2010: ____ %
2009: ____ %
2008: ____ %

On acres where corn residue is removed after grain harvest, estimate the % of total corn residue removed:

2010: ____ %
2009: ____ %
2008: ____ %

Are corn stalks shredded in the fall (yes or no):

2010: ____
2009: ____
2008: ____

Is a ground roller used in the spring for soybean (yes or no):

2010: ____
2009: ____
2008: ____

Tillage operations in fall after corn harvest:

Operation #1 (check one below):	Depth of tillage operation #1 (inches):
☐ Disk	____ inches
☐ Moldboard plow	____ inches
☐ Disc-ripper	____ inches
☐ In-line ripper	____ inches
☐ V-ripper	____ inches
☐ Disc-chisel	____ inches
☐ Strip-till machine	____ inches
☐ No tillage in fall	

Operation #2 (check one below):	Depth of tillage operation #2 (inches):
☐ Disk	____ inches
☐ Moldboard plow	____ inches
☐ Disc-ripper	____ inches
☐ In-line ripper	____ inches
☐ V-ripper	____ inches
☐ Disc-chisel	____ inches
☐ Strip-till machine	____ inches
☐ No tillage in fall	

Tillage operations in spring after corn harvest:

Operation #1 (check one below):
- [ ] Disk
- [ ] Field cultivator
- [ ] Soil finisher
- [ ] No tillage in spring

Depth of tillage operation #1 (inches):
- ____ inches
- ____ inches
- ____ inches

Operation #2 (check one below):
- [ ] Disk
- [ ] Field cultivator
- [ ] Soil finisher
- [ ] No tillage in spring

Depth of tillage operation #2 (inches):
- ____ inches
- ____ inches
- ____ inches

Tillage operations in fall after soybean harvest:

Operation #1 (check one below):
- [ ] Disk
- [ ] Field cultivator
- [ ] Soil finisher
- [ ] Disc-chisel
- [ ] In-line ripper
- [ ] V-ripper
- [ ] Disc-ripper
- [ ] Strip-till machine
- [ ] No tillage in fall

Depth of tillage operation #1 (inches):
- ____ inches
- ____ inches
- ____ inches
- ____ inches
- ____ inches
- ____ inches
- ____ inches
- ____ inches

Tillage operations in spring after soybean harvest:

Operation #1 (check one below):
- [ ] Disk
- [ ] Field cultivator
- [ ] Soil finisher
- [ ] Strip-till machine
- [ ] No tillage in spring

Depth of tillage operation #1 (inches):
- ____ inches
- ____ inches
- ____ inches
- ____ inches

Operation #2 (check one below):
- [ ] Disk
- [ ] Field cultivator
- [ ] Soil finisher
- [ ] Strip-till machine
- [ ] No tillage in spring

Depth of tillage operation #2 (inches):
- ____ inches
- ____ inches
- ____ inches
- ____ inches

Percent of corn and soybean acres that are row cultivated (please specify the percentage of acres):

	Corn	Soybean
2010:		
2009:		
2008:		

Purple Section: Energy Use

Total diesel fuel used on farm:

2010:		gallons
2009:		gallons
2008:		gallons

Percent of corn and soybean acres delivered wet to grain purchaser (please specify the percentage):

	Corn	Soybean
2010:		
2009:		
2008:		

Percent of corn and soybean acres dried on farm (please specify the percentage):

	Corn	Soybean
2010:		
2009:		
2008:		

Type of on-farm grain dryer used (specify 'continuous flow' or 'bin dryer'):

2010:	
2009:	
2008:	

On-farm energy use for grain drying in last 3 years:

	LP (gallons)	Natural gas (standard cubic feet)	Electricity (kWh)
2010:			
2009:			
2008:			

Average distance from field to ethanol plant or elevator:

2010:		miles
2009:		miles
2008:		miles

Primary method of grain transport (please check one of the boxes below):

	Tractor + wagon
	Grain truck
	Semi