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Energy and Climate Implications for Agricultural Nutrient Use Efficiency

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Adam J. Liska and Richard K. Perrin

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1 Executive Summary

Energy and climate change are beginning to dominate the global political agenda and will drive policy formation that will shape the future of agriculture. Energy issues threaten national security and economic stability, as well as access to low-cost nutrient inputs for agriculture. Climate change has the potential to cause serious disruption to agricultural productivity. Paradoxically, nutrient use in agriculture to increase crop yields has the potential to negatively impact climate. This chapter will discuss recent and future energy and climate trends, the relationships between agricultural nutrient use efficiency and biofuels, and how global land limitations will shape agriculture in the future. Comparative gross energy yield and nitrogen use efficiency for ethanol production from crop residue, switchgrass, grain sorghum, sweet sorghum, and corn grain is presented, showing small differences in nitrogen use efficiency, but large differences in gross energy yields. In addition to considering the need to increase crop productivity to meet the demands of a growing population and bioenergy, agricultural nutrient use efficiency must be reconsidered with respect to the important energy and climate challenges shaping agriculture today.

2 Energy and Climate Trends

Nutrient application in agriculture is essential to maintain a sufficient food supply for a growing global population and to meet an increased demand for bioenergy. The fixation of atmospheric nitrogen (N) by the Haber–Bosch process has enabled higher crop yields necessary to support the growth of global population by roughly three billion people in the twentieth century, or almost half of humanity.²⁰ Energy is required to process, deliver, and apply nutrients to land, which is costly and contributes to climate change. Increased nutrient use efficiency is essential to increase crop productivity and energy efficiency of bioenergy production in a sustainable manner while limiting negative environmental impacts and reducing costs.⁸

Energy issues are beginning to dominate the global political agenda. First, there is growing concern that global production of easily accessible oil is nearing its peak rate.^{13,56} Global oil production is dominated by giant oil fields, with the 500 largest fields contributing over 60% of production.²⁷ In 2008, 580 of the 651 largest oil fields globally were reported to have passed their peak production rate and are now producing an average of about 6% less oil per year.^{27,29} In accordance with reported declining trends, an independent analysis from Uppsala University in Sweden found that global oil production will decline from 84 million barrels per day (mb/day) (including natural gas liquids) in 2007 to roughly 76 mb/day by 2030.² In contradiction to these findings, official analysis from the International Energy Agency (IEA) optimistically anticipates that petroleum production will continue to increase through 2030, reaching a level 20% higher than current levels.³⁰ The U.S. Energy Information Administration (EIA) also anticipates an increase in production over this period of about 15%.¹⁵ Contrary to these assertions, the Swedish study states that historic trends of reduced field productivity will continue in the future at the same rate, which means lower productivity than other estimates that are more likely to be politically influenced. These conflicting expectations add uncertainty and volatility to world energy markets that are already vulnerable to political and economic vagaries.

Increases in oil demand that exceed rates of supply increase will cause oil prices to climb. By 2030, both the IEA and EIA project oil to reach about \$190 per barrel in nominal dollars (\$115–\$130 in 2008 dollars). Some suggest, however, that the recent oil price spike in 2008 to \$147 per barrel (compared to roughly \$80 per barrel in December 2009) has stimulated increased conservation and adaptation which may keep oil prices relatively lower in the near term due to reduced demand.⁴⁵ The current recession has also reduced demand for oil. Nonetheless, oil prices and the trend in total cost of U.S. crude oil imports are likely to continue to increase (Figure 1). In 2007 with oil at \$70 per barrel, the U.S. trade deficit in petroleum products was \$293 billion, or 36% of the total trade deficit of \$819 billion.⁶² Increasing production of nonconventional sources of petroleum such as oil (tar) sands from Canada will also help maintain petroleum supply,²⁹ while production from current major fields is declining. Oil sands could contribute as much as 20% of U.S. gasoline supply by 2020.⁴¹

Global growth in population and the world economy have required greater energy use to sustain improving living standards. With increasingly narrow margins between energy supply and demand, analysis suggests that disruption of the

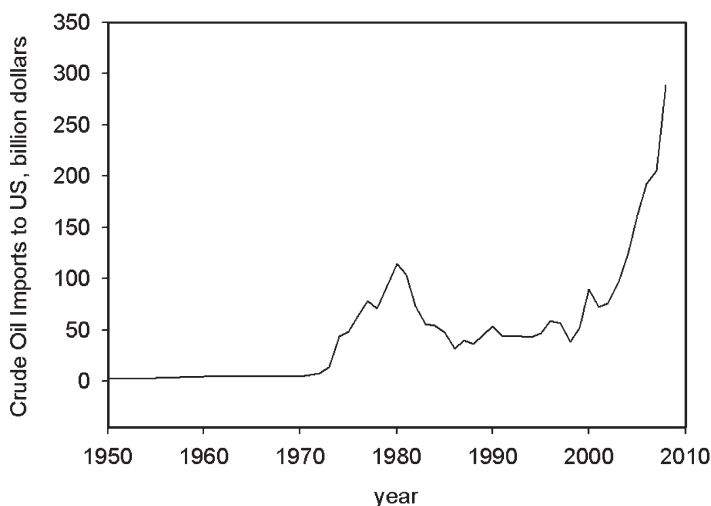


Figure 1. Inflation-adjusted annual value of crude oil imports into the United States in billions from 1950 to 2008 (in 2000 dollars). (From EIA, *Annual Energy Review 2008*, U.S. Department of Energy, Washington, DC, 2009.)

oil supply and accompanying oil price spikes can have significant negative impacts on the global economy.²⁶ While the interrelationships between the business cycle and petroleum price are complicated and not easily resolved,³⁶ Brown⁶ reports that 9 of the past 10 U.S. recessions since 1945 were preceded by significant oil price spikes. The relationships between oil price and the health of the economy suggest that current high and unstable oil prices could have broad implications for economic stability.

The high oil prices of 2008 led to the transfer of nearly \$1 trillion to members of OPEC, the Organization of the Petroleum Exporting Countries.¹⁷ National oil companies in OPEC and other countries, such as Saudi Aramco (Saudi Arabia), the National Iranian Oil Company (Iran), Petrochina (China), Petrobras (Brazil), and Gazprom (Russia), control approximately 90% of the world's oil reserves and 75% of global oil production—similar numbers apply for natural gas.⁶⁹

In conjunction with these trends, growing military intervention to ensure access to foreign oil has amplified the threat of international conflict. There is growing consensus in the economic and military communities that oil played a large part in the U.S.-led invasion of Iraq in 2003.^{4,26,44,50} Iraq has the third largest oil reserves globally at 115 billion barrels (~9% of global crude oil reserves), ranking below only Saudi Arabia and Iran.¹⁶ The full monetary cost of the Iraq war is projected by Stiglitz and Bilmes⁵⁸ to range between \$2.7 and \$5 trillion and the conflict has resulted in between 90,000 and 800,000 violent deaths of Iraqi civilians and more than 4000 U.S. military deaths since 2003.⁶³

As a corollary to the invasions of Iraq, ongoing U.S. military activities in Afghanistan are also motivated, in part, by proposed pipeline installation for transportation of oil and gas from Central Asia to the Indian Ocean.^{24,53,61} In that region, Kazakhstan contains three of the world's 10 largest giant oil fields (newly discovered), and they are now Chevron's leading source of petroleum, which is

exported via pipelines heading west through Georgia.^{38,39,56} In U.S. Congressional testimony in 2006, Steven Mann, Principal Deputy Assistant Secretary for South and Central Asian Affairs at the State Department, clearly outlined U.S. intentions concerning energy in the Afghanistan region:

“Since the independence of the new Caspian states 15 years ago, the United States has been in the forefront of oil and gas development in the region, and our efforts are paying off.” “With the completion of the first phase of the East-West Energy Corridor [through Georgia], we must now press on with the second phase of supporting new energy routes out of Central Asia.” “The United States and the countries of the broader region share an interest in the free movement of energy, people, goods, and information from the Kazakh steppes to the Indian Ocean. We want not only to support economic development along a north-south axis, but also afford Afghanistan access to a wider world, thus becoming a bridge, not a barrier.”⁶¹

In addition to these two costly military ventures with significant relationships to energy resources, costly military security for global oil transportation includes protection of unstable maritime oil transit routes, which has been recently estimated to cost between \$104 and \$138 billion per year.^{11,12,19}

Serious energy-related security issues also arise from the fact that international terrorism has been supported by tens of millions of dollars from the sale of Middle Eastern oil.^{7,47} Some of this money is thought to have been used to support the September 11, 2001 “9/11” terrorist attacks on the United States,⁴⁷ although it is recognized that relatively little money was actually required to carry out most terrorist attacks in the last 10 years.⁶⁷

These various challenges for the petroleum economy consisting of limited and fragile supply, wealth transfer, contribution to national deficits, costly military operations, and terrorism are all serious national security and economic issues. These issues have stimulated support for the development of alternative energy sources.^{14,71} Biomass resources are of particular importance because they can be converted to liquid fuels to substitute for petroleum which can be used in existing infrastructure with limited modification. The U.S. *Energy Independence and Security Act of 2007* (EISA) mandates that 36 Bgal of biofuels be produced annually by 2022, of which 15 Bgal/year are to be grain ethanol, 16 Bgal/year are to be cellulosic ethanol, and 5 Bgal are to be other advanced renewable fuels. Furthermore, the U.S. Air Force, the world’s single largest consumer of petroleum, recently announced a plan to substitute 50% of their fuel use with alternative fuels, with particular emphasis on biofuels.³ Continued expansion of the biofuel industry will place greater demands on agricultural productivity and efficiency.

While limited energy supply is increasingly problematic, the impacts of atmospheric emissions from fossil-based energy sources on global climate change are becoming well established.³¹ Anthropogenic climate change from greenhouse gas (GHG) emissions from burning fossil fuels will impact agriculture in a number of ways. Some of the changes that will have negative impacts on agriculture include higher average night-time temperatures,⁵¹ greater frequency of heat waves, heavy rainfall events, destructive storms, and regional droughts.³⁵ In addition, rising sea level has the potential to submerge coastal agricultural regions, decreasing the availability of fertile agricultural land. Finally, rising temperature is

contributing to the global disappearance of glaciers that threatens the water supply of regions dependent on glacial meltwater for irrigation to support agricultural productivity.^{49,65}

The sum of these challenges for agriculture may be quite significant in the near-term future. Commodity prices will rise, and these price increases will stimulate adoption of more efficient production techniques as well as expansion of agricultural systems. Nutrient efficiency research will provide new information that will permit these adjustments to be made, which otherwise would not be possible with lower food and biofuel prices.

3 Agricultural Nutrient Use Efficiency and Biofuels

Energy price increases raise both the cost of field operations and the prices of crop inputs. Most N fertilizers are manufactured from natural gas or petroleum, so their costs will obviously rise with oil prices. Even though potash and phosphate are not manufactured from fossil energy, substantial amounts of energy are required in their extraction and processing, and their prices have also recently followed oil prices (Figure 2a). The primary nutrient applied in the United States is N (Figure 2b), and its price is most closely related to oil price. Therefore, sustained oil prices above \$100 per barrel will lead to fertilizer prices substantially higher than previously experienced, and drive investment in practices to limit fertilizer expenditures and increase nutrient use efficiency.

Improved management has contributed to recent gains in nutrient use efficiency for corn in the United States to the extent that on average 37% of applied N is now taken up by the crop. From 1980 to 2000, N application remained relatively constant at 146 kg ha⁻¹ (Figure 2c) while the partial factor productivity (kg grain yield per kg of N applied) increased by 36% (from 42 to 57 kg kg⁻¹).⁸ Increasing agricultural nutrient use efficiency will also reduce the negative climate impact of crop production.

GHG emissions from agriculture are a large positive source of global warming potential. In 2005, nonfossil fuel emissions from global agriculture contributed 10%–12% of total of anthropogenic GHG emissions, with methane (CH₄) contributing a little over half of emissions and nitrous oxide (N₂O) emissions contributing the majority of the remainder.⁵⁷ These agricultural emissions contributed roughly 50% of global methane emissions and 60% of nitrous oxide emissions. Methane is produced when organic materials decompose in oxygen-deprived conditions, with significant sources from digestion in ruminant livestock, manure, and flooded rice. Nitrous oxide, on the other hand, is produced by the microbial transformation of N in soil and manure. Global agricultural N₂O emissions are projected to increase by 35%–60% by 2030 due to increased N fertilizer use and increased animal manure production. In the United States, however, synthetic N applications are projected to remain relatively constant, and increases in N₂O emissions are projected mainly from manure.⁵⁷ Large and uncertain net fluxes of carbon dioxide from global agriculture are not thought to contribute much to net GHG emissions from agriculture overall.

In addition to biogenic GHG emissions, additional GHG emissions from production and application of cropping inputs must also be considered. After totaling net biogenic and fossil fuel inputs for a corn grain cropping systems in U.S.

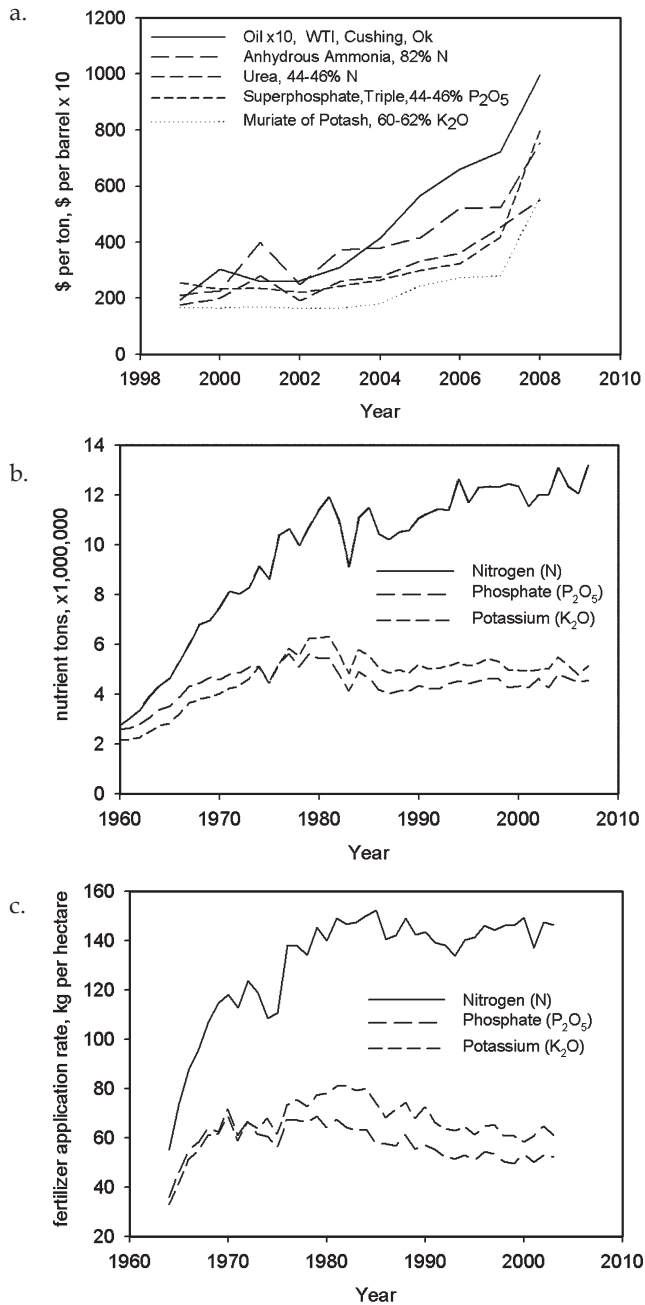


Figure 2. Average annual fertilizer and oil prices (a), total fertilizer consumption in the United States (b), and average fertilizer application rates per hectare for corn (c). (From EIA, Official Energy Statistics from the U.S. Government. Accessed at <http://tonto.eia.doe.gov> ; November 2009; ERS [Economic Research Service], USDA, U.S. Fertilizer Use and Price. Accessed at <http://www.ers.usda.gov/Data/FertilizerUse/> ; November 2009; USDA [United States Department of Agriculture], *Agricultural Prices Supplement*, August 2009. Accessed at <http://usda.mannlib.cornell.edu/usda/current/AgriPricSu/AgriPricSu-08-05-2009.pdf> ; November 2009.)

Table 1. Energy Inputs and Direct GHG Emissions from an Average Corn Cropping System in the Midwest, Assuming Soil Carbon Dynamics Are Neutral

	Energy Inputs, %	GHG Emissions, %
Nitrogen fertilizer	39.7	15.0
N ₂ O emissions from N fertilizer ^a : denitrification, volatilization, leaching, runoff	–	35.5
N ₂ O emissions from crop and biomass N: crop residue, roots, manure	–	12.7
Phosphorus fertilizer	2.2	3.2
Potassium fertilizer	3.7	1.5
Lime	0.2	6.3
Herbicides	11.5	5.2
Insecticides	0.5	0.2
Seed	1.2	0.6
Gasoline	3.8	1.7
Diesel	16.2	8.7
LPG	8.3	3.4
Natural gas	4.8	1.7
Electricity	6.0	3.1
Farm machinery	2.0	0.9
Total	100.0	100.0

Source: Liska, A. J. et al., *J. Ind. Ecol.*, 13, 58, 2009.

a. Of synthetic N fertilizer applied, 1.33% is lost as N₂O.

Emissions from “fertilizer[s]” are from fossil fuel use in upstream production.

Corn Belt, N₂O emissions from fertilizer N inputs (based on IPCC emission factors) were found to be roughly 36% of net GHG emissions^{32,42} (Table 1). Applications of N are also a significant fraction of energy inputs for corn grain production accounting for roughly 40% of agricultural energy inputs. By improving N use efficiency, energy inputs and emissions can be reduced. Evidence suggests that N₂O emissions can be reduced by 20% by increasing crop N use efficiency via crop management, by 10% via use of either soil N tests or fertilizer timing, and by 5% with the use of either nitrification and urease inhibitors or N fertilizer placement.⁹ Different types of N fertilizer may also have the potential to reduce N₂O emissions. Furthermore, efficient N use can be improved by adjusting application rates using GIS-based precision estimates of crop needs.

Crops accumulate their biomass carbon from atmospheric carbon dioxide and have the potential to be an energy source that does not contribute to net growth in atmospheric GHGs. If bioenergy is not to significantly contribute to GHG emissions, efficient collection and conversion to liquid forms is required for minimal use of fossil fuels. Ethanol production from corn grain in the United States and from sugarcane in Brazil are models for increased utilization of agricultural resources to meet societies’ energy needs while reducing GHG emissions relative to the gasoline they replace (although indirect GHG contributions of both gaso-

line and biofuel production are not yet accurately accounted for in current analytical methods).⁴¹ Significant research and development efforts are also underway to better utilize biomass resources for transportation fuels via production of cellulosic ethanol, and other so-called "second-generation" biofuels, although these systems are not yet profitable.⁴³

Biofuel production is a "system of systems"³⁴ composed of distributed independent complex systems for crop production, biomass transportation, biorefining, co-product use, fossil fuel production and delivery, fertilizer and chemical inputs, and end-use vehicle systems. The efficiency of the overall biofuel production system can be analyzed using life cycle assessment (LCA), which is used to compare biofuel performance with fossil fuel systems. In addition, LCA enables the environmental impacts of a production system to be analyzed to identify areas for improvements in efficiency.²⁵

The life cycle efficiency of biofuel production is primarily analyzed in terms of energy efficiency and net GHG emissions.^{42,43} Crop production contributes approximately 50% of positive life cycle emissions.⁴² In the past and now, research into the life cycle energy efficiency of biofuel production systems (particularly corn-ethanol) has been marked by conflicting results, but greater consensus from recent research shows positive energy and GHG benefits are derived from biofuel production and use.^{1,5,23,40,42} The EISA legislation now requires that biofuels must reduce life cycle GHG emissions, including indirectly caused emissions, compared to fossil fuels. Comparisons of the indirect GHG emissions resulting from gasoline production and corn-ethanol production are still primitive.⁴¹ EISA requires that corn-ethanol must reduce emissions by 20% compared to gasoline, but the precise methodologies for these life cycle calculations are still under development. Other recent state legislation, such as in California, will restrict market access if biofuels do not meet life cycle GHG emissions reduction targets.

Recent improvements in biorefinery energy efficiency have greatly influenced the life cycle energy efficiency of corn-ethanol production.⁴² In 2001, survey data reported that energy inputs for the biorefinery were 13.9 MJ L⁻¹ (primarily coal and natural gas) and comprised 67% of life cycle energy inputs.²³ Since 2001, the U.S. corn-ethanol industry has significantly expanded with new more efficient production capacity, composed primarily of natural gas powered dry mill biorefineries (Figure 3). Survey data from 2006 documents the increasing average energy efficiency of the industry, with biorefinery energy inputs reduced to 7.7 MJ L⁻¹, contributing 56% to life cycle energy inputs.^{42,52} Use of recent data suggest that corn-ethanol has a net energy return of 1.6 units of energy per unit of energy invested.⁴² Furthermore, compared to gasoline, corn-ethanol has been shown to reduce direct GHG emissions by approximately 47% on average^{5,40}; this estimate, however, does not include emissions from indirect land use change.⁵⁵

Other agricultural biofuel production systems are under development, but most other systems suffer from relatively lower energy yield per hectare and lower energy yield per unit of nutrient applied compared with ethanol produced from corn and sorghum grain. For example, in the United States, soybean-biodiesel produces on average 15% of the biofuel volume per hectare compared with corn-ethanol.⁴³ Correcting for energy density differences, soybean-biodiesel yields 23% of the gross energy yield of corn-ethanol on average. Cellulosic ethanol produced from crop residues and perennial grasses is currently under devel-

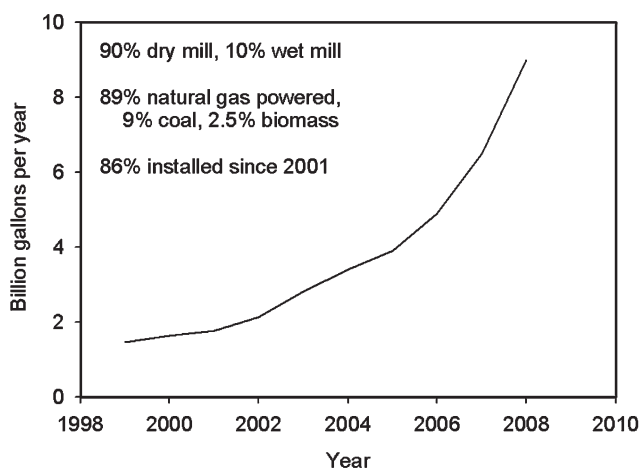


Figure 3. Increasing ethanol production capacity utilizing corn grain in the United States. Total installed capacity in 2009 is 12.5 Bgal/year. Industry statistics provided by Cooper. (From Cooper G., Personal communication, Renewable Fuels Association, Washington, DC, 2009.)

opment, and only a very limited production capacity is installed. Ethanol from sweet sorghum provides an alternative cropping system that shows potential to be competitive with corn grain.⁷⁰

State-level production statistics and field trial data provide a comparison among these selected ethanol production systems in Nebraska (Table 2). Gross energy yield per hectare as ethanol was found to range from 10 to 95 GJ ha⁻¹, with use of both corn grain and residue being the most productive system. Despite this wide range in productivity per area, the N use efficiency only varies from 0.47 to 0.70, with an average of 0.586 GJ ethanol per kg N applied (Figure 4). As a stand-alone component, residue is the least productive system, but had the highest efficiency, while the most productive system (corn grain plus residue) only had a slightly higher efficiency than the average. Ethanol from grain sorghum and switchgrass had N use efficiencies below average for the five systems. Of these systems, sweet sorghum stood out as having the third highest energy yield, but field trials found no significant response to N applications over a 2 year trial period.⁷⁰ This response is suggested because of a more gradual rate of nutrient uptake in sweet sorghum, and N uptake later in the season compared with the grain crops. This is significant because it indicates that with appropriate crop rotations, a relatively high yielding system could exist with limited N fertilizer inputs. Sweet sorghum should be researched further in the future to explore the lower limits of N applications for high-yield biofuel systems.

Nutrient use efficiency is just one important aspect in defining the life cycle GHG emissions and energy efficiency of biofuel production systems. Another important consideration for nutrient use and GHG emissions is changes in soil carbon.^{37,68,70} Removing crop residue for biofuels also removes soil phosphorus (P) and potassium (K); one metric ton of corn residue harvested removes 8 kg of N, 0.79 kg of P, and 6.74 kg of K.²⁸ If ethanol production from crop residue and energy crops such as switchgrass is pursued in the future, appropriate nutrient replacement will be vital to maintain crop productivity.⁶⁶

Table 2. Nutrient Use Efficiency of Selected Cropping Systems for Ethanol Production in Nebraska

	Nitrogen Rate, kg ha ⁻¹	Biomass Yield, Mg ha ⁻¹	Biofuel Conversion Efficiency, LM g ⁻¹	Gross Energy Yield, GJ ha ⁻¹	Nutrient Use Efficiency, ^a (GJ kg ⁻¹) N
Corn residue, 20% removal	14.4	1.62	294	10.0	0.70
Switchgrass	78.1	7.10	294	44.0	0.56
Grain sorghum	96.0	4.29	501	45.3	0.47
Sweet sorghum	0	3.54	665	49.7	—
Corn grain	144.0	8.09	501	85.4	0.59
Corn grain + residue, 20%	158.4	9.70	—	95.4	0.63

a. Partial factor productivity. All yields are on a dry matter basis. Corn grain and residue yields⁴⁶ (2004–2006) and conversion of grain to ethanol and ethanol energy density (21.1 MJ L⁻¹) were previously reported.⁴² Nitrogen rates for corn were previously reported²¹ and 20% residue removal is allocated N applied for 10% of above ground biomass. Switchgrass yields in NE were also previously reported,⁵⁴ and it is assumed that N will be applied at the recommended rate of 11 kg N Mg⁻¹ biomass yield.⁶⁶ Conversion yield for switchgrass and residue is 70 gal/ton based on Iogen technology from a DOE-funded facility (<http://www.energy.gov/news/4827.htm>). Grain sorghum yields⁴⁶ (2004–2006) and N application rates²¹ were for Nebraska. Sweet sorghum theoretical yield is based on field studies and estimated from 80% juice extracted and brix reading with the Simon cv. in 2008.⁷⁰ The corn plus residue system assumes additional N rate for the 20% of N removed.

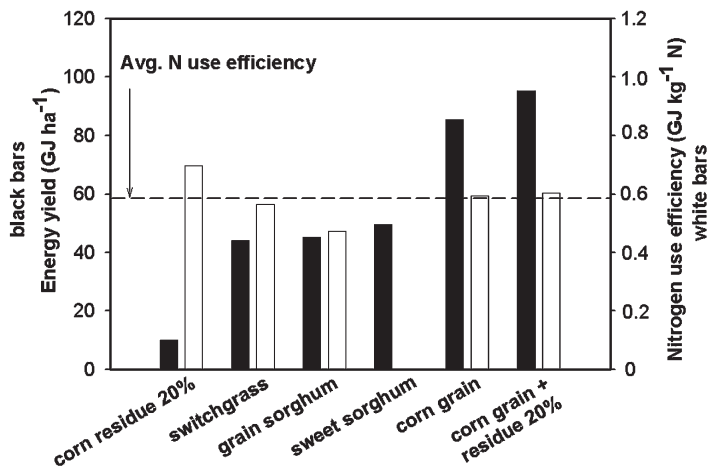


Figure 4. Bioenergy productivity versus nutrient use efficiency: ethanol gross energy yield (GJ ha⁻¹, black bars) and nitrogen use efficiency (GJ kg⁻¹ N applied, white bars) for selected cropping systems for ethanol production in Nebraska. Average N use efficiency (partial factor productivity) for the five systems reporting N application is shown with a dashed line.

4 Land Limitations and Global Agricultural Production

Pressure for increased agricultural production over the next 40 years will come from three sources: world population growth, per capita income growth, and demand for biofuels. Population growth alone is projected to require a one-third increase in crop production, and increased demand for livestock products, made possible by higher incomes, is expected to further increase the required production to approximately 50% above current levels by 2050 (Figure 5a). In addition, biofuel production will result in yet additional demands on agricultural resources. Yet, there is little potential for increasing the critical agricultural resources necessary to provide this additional biomass, making it crucial that more efficient production techniques be developed and adopted.

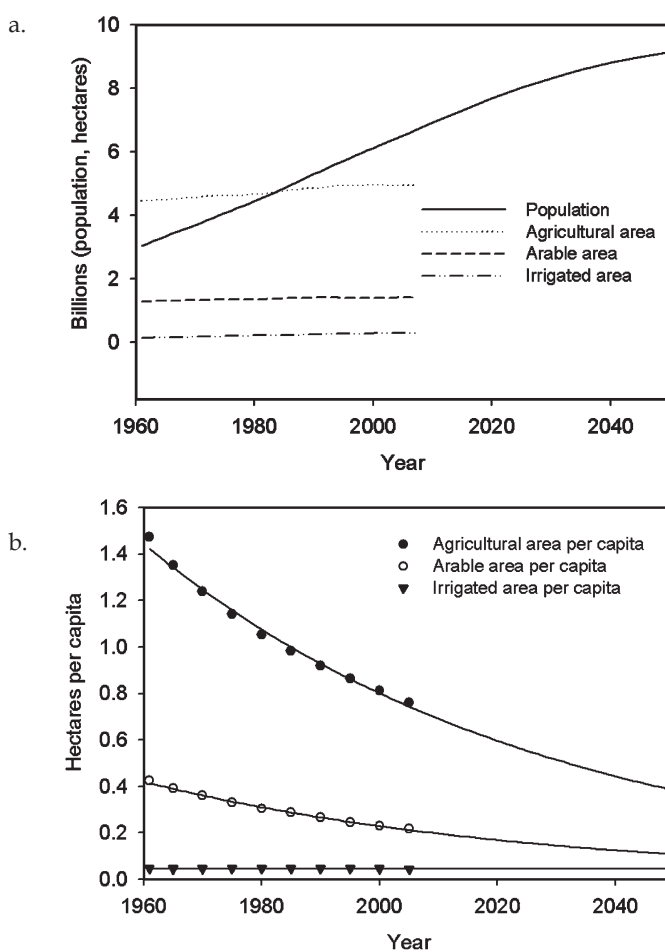


Figure 5. Trends and projections for global population and agriculture land resources (a) and agricultural area per capita (b). (From FAO [Food and Agriculture Organization of the United Nations], FAOSTAT; available at <http://faostat.fao.org> ; accessed November 24, 2009; UN [United Nations], *World Population Prospects: The 2008 Revision*; available at <http://esa.un.org/unpp> ; accessed November 24, 2009.)

Crops for biofuel production were grown on about 36 million hectares (Mha) around the globe, or 2.5% of the world's arable land in 2008.⁶⁰ Comparable figures for current biofuel area from another recent report are 41 Mha (2.8%).⁴⁸ Projections of future growth in land use for biofuel production are difficult to make, because of uncertainty about the relative prices of food and energy and uncertainty about policies that either encourage or discourage biofuel production. The UNEP⁶⁰ reports projections to 60–80 Mha, or even 166 Mha, by 2020, which are equivalent to 4%–11% of the current stock of arable land, or 1%–3% of total agricultural land.

Recent and potential increases of biofuel crops in Brazil and Indonesia are dramatic. Cropping area devoted to sugarcane in Brazil has increased from 7 to 9 Mha between 2007 and 2008, now constituting about 15% of the 60 Mha of arable land in Brazil.⁶⁰ This upward trend will continue, though the government intends to limit the expansion into sensitive ecosystems. Soybeans, also used in part for biodiesel, occupied about 23 Mha in 2005, and are expected to occupy the majority of an additional 60 Mha that will likely be converted from savannah to crop land. The Indonesian government intends that the current 6 Mha of oil palm be augmented by another 18–20 Mha,³³ with about two-thirds of this to be planted on land currently covered by rainforests.

It is clear that world agricultural land resources will not increase much, based on the experience of the last 10 years (Figure 5a). Of the approximately 5 Bha of total agricultural land, only about 1.4 Bha or 28%, is arable. Irrigated land has increased only about a half a percent per year, arable land less than 0.2% per year, while total agricultural land has actually declined.

Population has of course increased during this time, resulting in the very dramatic decreases in land per capita (Figure 5b). If the per capita land resource base continues to decline along the trend of the last 50 years, a great deal of pressure will be placed on agricultural research to achieve the kind of productivity improvement that will be needed.

Water is another critical component of the agricultural resource base, one that will more likely decline rather than increase with population. Irrigated land, as noted above, has increased very little over the past decade. Aquifers are being depleted, snowpack's and glaciers are declining, and climate change may reduce rainfall in many regions, while contributing to higher rainfall, and more extreme rainfall events in other areas.³⁵ It is clear that in the case of agricultural water, efficiency will have to increase if there is to be any chance of providing the needed production increases.

As opposed to land, global per capita consumption of fertilizer materials has increased over the last 50 years, though irregularly (Figure 6a). The increased fertilizer use over the past decade has helped make possible a slight per capita increase in agricultural production over the past two decades. With this increase in usage, worldwide average N efficiency has begun to decline, while phosphorus and potassium efficiencies have stabilized after realizing improvements over the previous 2 or 3 decades (Figure 6b). Figures reported here are measured in terms of fertilizer materials rather than in fertilizer elements; therefore, any change in the mix of materials over this period may slightly distort the trends in fertilizer elements.

It appears that quantities of land and water allocated to crop production will not increase much in the future, whereas crop nutrients and energy inputs will

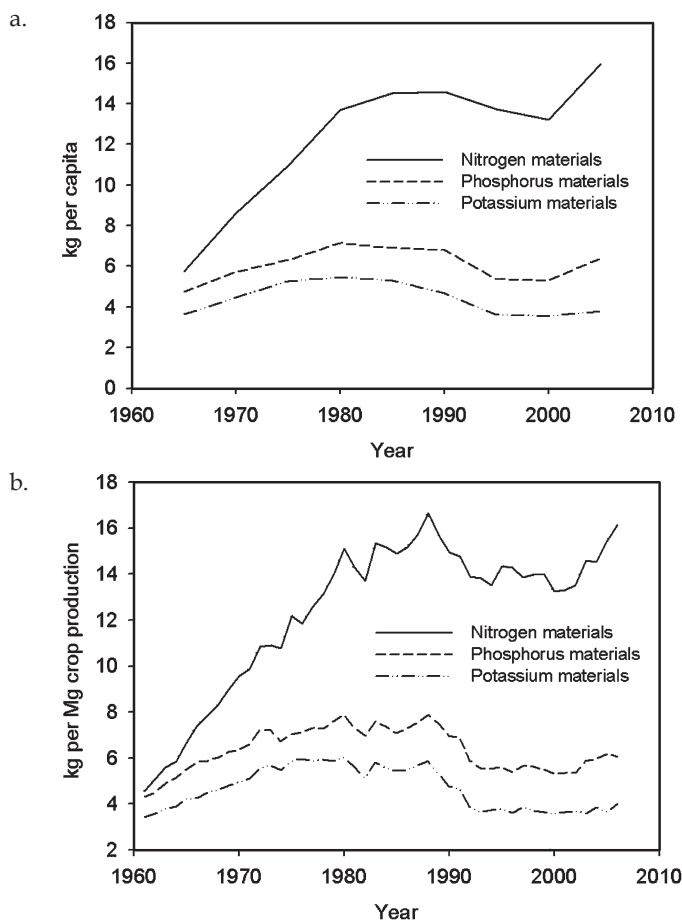


Figure 6. Global fertilizer materials consumption per capita (a) and fertilizer materials per ton of crop production (b) derived from References 22 & 59. (From FAO [Food and Agriculture Organization of the United Nations], FAOSTAT; available at <http://faostat.fao.org>; accessed November 24, 2009; UN [United Nations], *World Population Prospects: The 2008 Revision*; available at <http://esa.un.org/unpp>; accessed November 24, 2009.)

be more elastic in supply. But increases in land, energy inputs, and nutrients will entail increases in GHG emissions, making it critical that the required increase in output be achieved with maximum possible efficiency of input use.

Land use change is a significant source of GHG emissions and a driver of climate change, being responsible for approximately 20% of global anthropogenic GHG emissions in the 1990s.³¹ These emissions result from the burning of forest and savanna biomass when those lands are converted to cultivated crop production, and from loss of soil carbon stocks when the land is cultivated. It is therefore likely that climate change policies will provide further barriers to the expansion of arable land, adding another source of urgency for improving efficiencies in crop production.⁴¹ Similarly, the GHG emissions related to fertilizer use, mentioned above, may lead to higher costs of nutrients or restrictions on the use of nutrients, adding incentives for generating improved efficiencies in nutrient use.

5 Conclusions

Multiple lines of evidence point to a global oil economy that is increasing unstable, which has broad consequences for economic growth, international military activity, and the future costs of agricultural production. Energy and climate issues are stimulating the production of biofuels from agricultural products which has numerous implications for nutrient use. Climate change has multiple potentially serious impacts on agriculture as well. Growing demand for agricultural products, in conjunction with volatile weather and more costly cropping inputs will lead to greater pressure in the future to increase yields, while minimizing nutrient inputs. These trends will provide significant incentive to heavily invest in better management of nutrient applications in the future and to develop the science necessary to keep improving nutrient use efficiency while meeting new demands on agricultural production from both biofuels and population growth.

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