High-yield Maize and Small Global Warming Intensity

Maximizing productivity per unit of arable land while reducing negative environmental impact is goal.

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Summary: *Addressing concerns about future food supply and climate change requires management practices that maximize productivity per unit of arable land while reducing negative environmental impact. On-farm data were evaluated to assess energy balance and greenhouse gas (GHG) emissions of irrigated maize in Nebraska that received large nitrogen (N) fertilizer (183 kg of N/ha^{-1}) and irrigation water inputs (272 mm or 2,720 m3 ha^{-1}). Although energy inputs were larger than those reported for US maize systems in previous studies, irrigated maize in central Nebraska achieved higher grain and net energy yields (13.2 Mg/ha^{-1} and 159 GJ/ha^{-1}, respectively) and lower GHG-emission intensity (231 kg of CO_2e/Mg^{-1} of grain). Large variation in energy inputs and GHG emissions across irrigated fields in the present study resulted from differences in applied irrigation water amount and imbalances between applied N inputs and crop N demand, indicating potential to further improve environmental performance through better management of these inputs. Observed variation in N-use efficiency, at any level of applied N inputs, suggests that an N-balance approach may be more appropriate for estimating soil N_2O emissions than the intergovernmental Panel on Climate Change approach based on a fixed proportion of applied N.*

High yield cropping systems require fossil-fuel inputs to substitute human and animal labor and to maximize the capture and conversion of solar radiation into crop biomass. Inputs to agricultural systems that require fossil fuel in their manufacturing process include fertilizer, seed, pesticides, and machinery. Fossil fuel also is required for application of inputs as well as field operations, irrigation pumping, and grain drying. Fossil-fuel inputs can be expressed in terms of their embodied energy, that is, the energy required for their synthesis, packaging, transport, and use in a crop production field. Because fossil fuel combustion results in GHG emissions, energy inputs also can be expressed in terms of global warming potential (GWP). Although GWP can be expressed per unit of crop production area, it also can be expressed per unit of grain yield (GWP intensity; GWPi), which recognizes the potential for indirect land use change and associated GWP from clearing of carbon-rich natural ecosystems for crop production.

Although it has been speculated that the efficiency with which applied inputs that result in increased yield can be greater in intensively managed high-yield cropping systems than in their low-input low-yield counterparts, because of optimization of growing conditions in the former, this hypothesis has not been evaluated in actual cropping systems where farmer's yields approach yield potential. The U.S. Corn Belt, including parts of the Great Plains in South Dakota, North Dakota, Nebraska, and Kansas, accounts for 33 percent of global maize production. Of total U.S. maize, approximately 13 percent is produced with irrigation on approximately 3.2 Mha with the majority grown in Nebraska. Energy-use efficiency of maize in the U.S. Corn Belt has increased steadily in recent decades as a result of (1) rising grain yield without increases in amounts of applied N fertilizer and applied irrigation, (2) widespread adoption of conservation tillage practices and center-pivot systems to replace less efficient gravity irrigation, and (3) increasing efficiency in manufacturing of agricultural inputs.

Field experiments on irrigated maize have shown that achieving high yields and high efficiencies, together with relatively low GWP, is possible when applied inputs are precisely managed in time and space, but the extent to which farmers can achieve precise management is not known. Likewise, there is a general notion that input-use efficiency of high-yield cropping systems is low, resulting in negative energy balances, high GWP, and degradation of soil and water quality. In part, such perceptions are based on previous studies that had several deficiencies, including:

- Obsolete embodied energy and GHG emissions factors for agricultural inputs

- Obsolete values for grain yield and actual crop management practices with regard to N fertilizer rates, irrigation, and tillage
- Use of metrics that do not weight energy inputs or GWP in relation to yield level
- Lack of clarity on methods used to estimate energy inputs or GHG emissions and system boundaries.

Hence, accurate and transparent estimates of on-farm energy balance and GWP for irrigated maize in the US Corn Belt are not available.

Management practices influence energy balance and GWP by amounts and efficiencies of applied inputs and yield level. Given concerns about the cost of energy and climate change, agriculture is challenged by the need to identify management systems that maximize productivity with high energy-use efficiency and low GWP. Addressing this challenge using a structured experimental approach, however, requires factorial experiments performed over many years at multiple locations. Because this approach is very costly and there are few opportunities for long-term funding to support such efforts, most research on energy balance and GWP of agricultural systems has relied on data from aggregate agricultural statistics or data gathered from a relatively small number of selected farms. An alternative is to use farmer-reported databases, collected over a large population of field-years, to perform direct analysis of on-farm energy balance and GWP, and to use the variation in management practices within these data to identify those that give high yields, high input use efficiencies, and low GWPi.

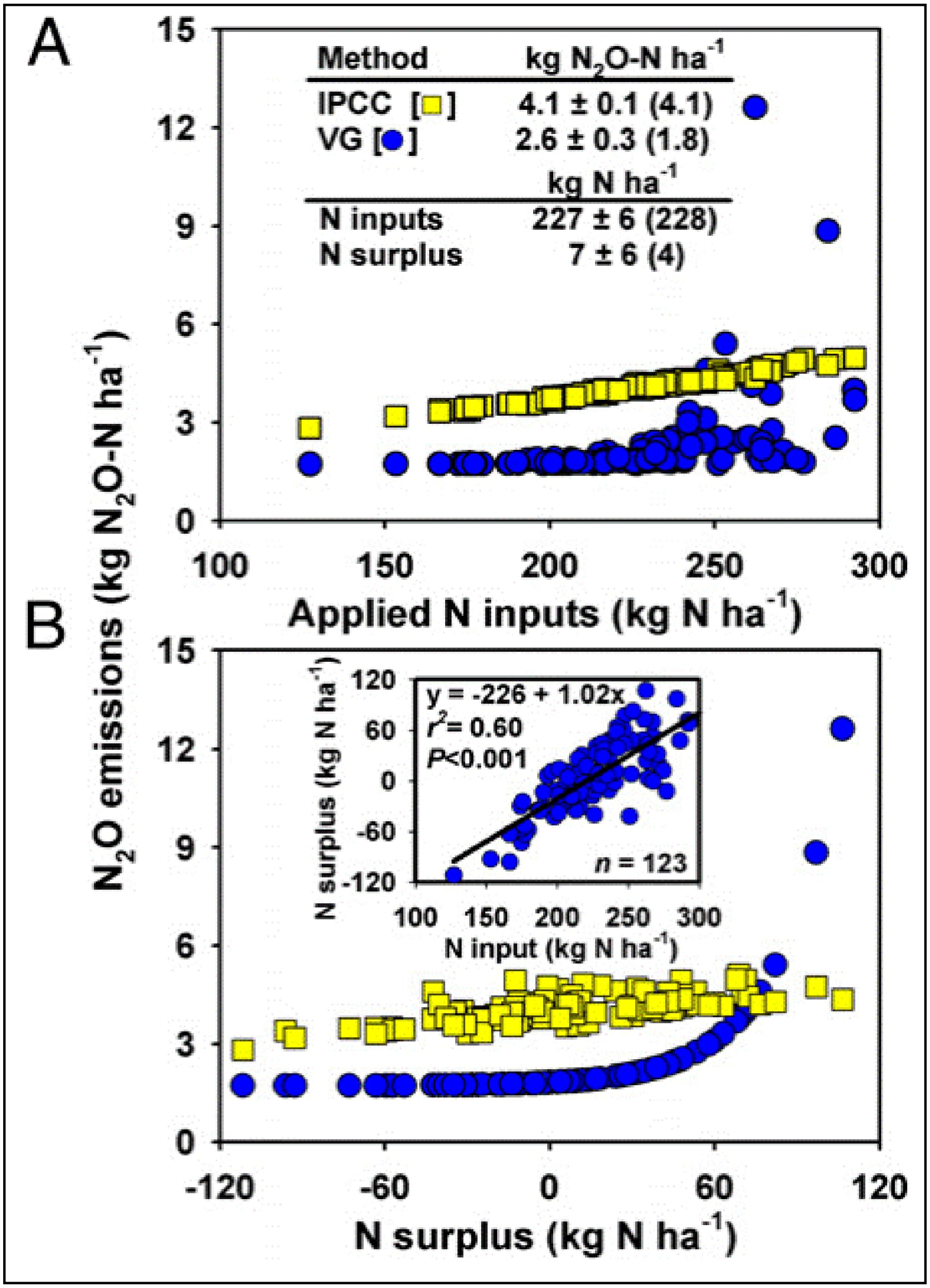

Figure 1: *Soil N2O emissions of irrigated maize against applied N inputs (A) and N surplus (B). Average (±SE) N2O emissions, N inputs, and N surplus (medians in parenthesis) are shown. B inset shows the relationship between N surplus and applied N inputs.*

The central hypothesis of this work is that it is possible for farmers to achieve a large positive energy balance with relatively low GWPi in high-input, high-yield maize systems. To test this hypothesis, farmer-reported data collected from the Tri-Basin Natural Resources District (NRD) in central Nebraska were used to:

- Quantify energy balance and GWP of irrigated maize
- Compare these parameters against previously published values for maize systems
- Identify and quantify the impact of energy-saving and GWP-reducing management tactics that could achieve these reductions without yield loss.

Overview

N_2O emissions. Separate estimates of soil N_2O emissions were calculated by following two methods:

- The "N-input-driven approach" developed by the Intergovernmental Panel on Climate Change (IPCC; ref 23)
- The "N-surplus-driven approach recently proposed by van Groenigen, et al.

The N input approach assumes that N_2O emissions represent a constant proportion of applied N inputs plus N in crop residues, which does not account for tremendous variability in the efficiency with which applied N is used by the crop across fields, crops, and regions.

In contrast, van Groenigen et al. provide strong evidence that N_2O emissions can be more accurately estimated from the magnitude of N surplus, which is defined as the difference between N inputs and crop N uptake.

In this study, applied N inputs were calculated as the sum of applied N fertilizer, N-NO_3- in applied irrigation water,

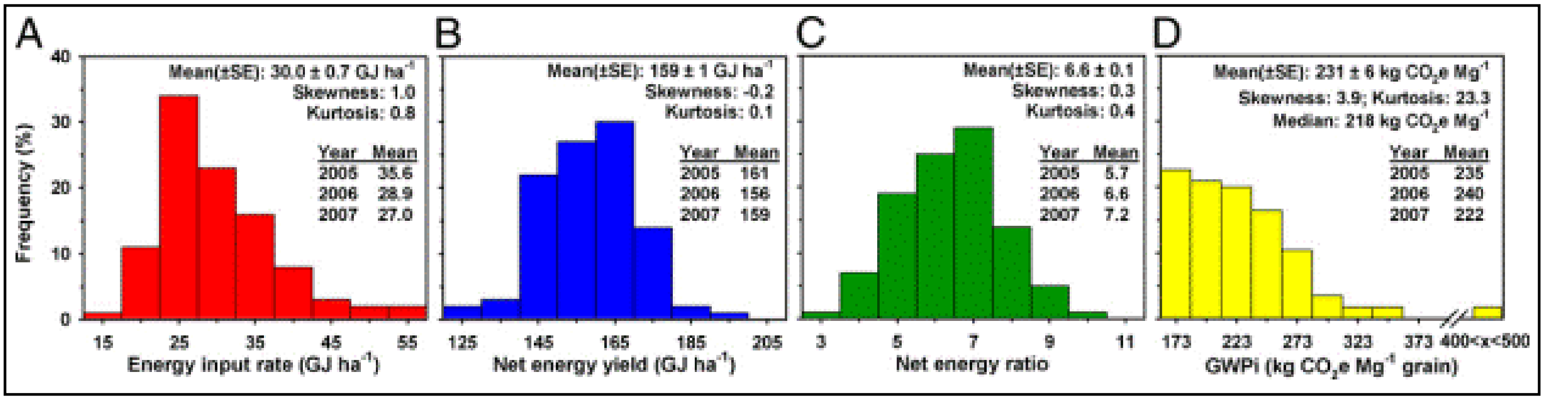

Figure 2: *Frequency distribution of fossil-fuel energy input (A), net energy yield (B), net energy ratio (C), and global warming potential intensity (GWPi)(D) based on data from 123 irrigated maize fields.*

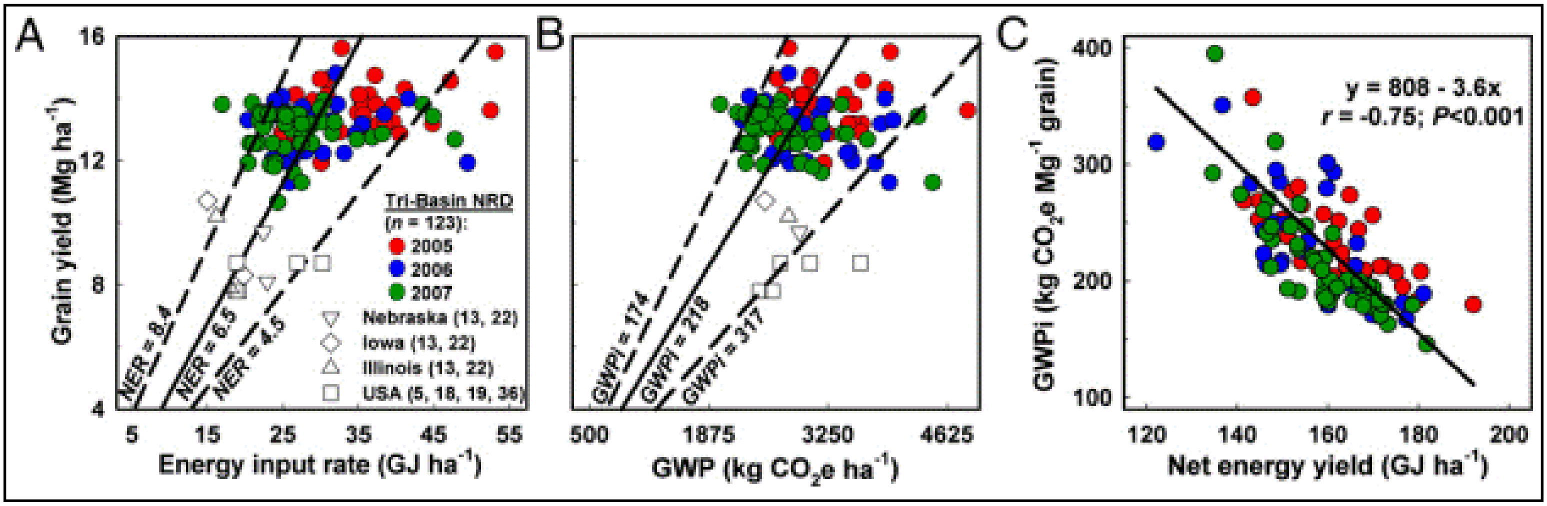

Figure 3: *Maize grain yield plotted against fossil-fuel energy inputs (A) and GWP (B). Lines indicate average 3-y median (solid line) and fifth and 95th percentiles (dashed line) for net NER and GWPi calculated for irrigated maize in Tri-Basin NRD. Relationship (C) between GWPi and net energy yield for irrigated maize in Tri-Basin NRD. De Oliveira MED, Vaughan BE, Rykiel EJ, Jr. (2005)*

and N in applied manure, which account for 81%, 15%, and 4%, respectively, of total N input.

With few exceptions, estimated N_2O emissions were consistently larger using the N-input approach across the range of N fertilizer rates applied to irrigated maize fields in the Tri-Basin NRD (Figure 1A).

In a small number of fields that received >225 kg of N/ha^{-1}, however, greater emissions were estimated by the N surplus approach. However, despite a high average rate of N fertilization, 76% of the fields had an N surplus <50 kg/ha-1 so that N_2O emissions by the N surplus method were smaller than emissions estimated with the N-input approach (Figure 1B). Large N surplus (>50 kg of N ha^{-1}) resulted from a combination of large N inputs and relatively low grain yields. Although there was a positive correlation between N surplus and the level of N input, large variation in N surplus was observed at any level of applied N input due to variation across fields and years in N use efficiency (NUE, kg of grain per kg applied N, also called partial factor productivity for N fertilizer; ref. 12) shown in Figure 1B, (Inset). Median values for direct N_2O emissions from irrigated maize in this study were 1.6 and 3.3 kg N_2O-N ha^{-1} when using the N-surplus and N-input approach, respectively. The N-surplus approach median value is similar to annual direct N_2O emissions of 1.9 kg N_2O-N/ha^{-1} measured in a well-managed irrigated continuous maize system in Nebraska that achieved grain yields similar to those in the Tri-Basin NRD.

The proposition that N losses from applied fertilizer tend to be small when the N supply is balanced by crop uptake is scientifically robust and supported by published data. Hence, reported GWP in the following sections was calculated based on N_2O emissions estimated by the N surplus approach unless stated otherwise.

Energy/emissions. Large energy inputs to irrigated maize in the study area were associated with high and stable grain yields (Table 1). Irrigated maize yield was 2.2-fold greater and much less variable across years than lower yielding less intensively managed rain-fed maize in the same region (mean rain-fed yield ± SE = 5.9±0.8 Mg/ha^{-1}; inter-annual coefficient of variation (CV) = 23%). Moreover, irrigated maize in the Tri-Basin NRD achieved, on average, 89% of its estimated yield potential as documented in a previous study. Although N fertilizer inputs were well above N rates reported in previous studies of energy balance and GWP in US maize systems, NUE achieved by irrigated maize products in the current study was much higher than previous published values (Table 1). Likewise, although total water supply was 41% greater with irrigation compared with rain-fed maize in the Tri-Basin NRD, water productivity of irrigated maize was 60% higher (14.0 vs. 8.8 kg/ha-mm^{-1}, respectively). Remarkably, conversion efficiency from solar radiation to total dry matter of 3.3%, estimated for irrigated maize in the Tri-Basin NRD, compares well with highest observed conversion efficiencies (range: 3.9 to 5.2%) for field-grown irrigated maize grown with optimal management practices.

Irrigated maize received relatively large fossil-fuel energy inputs (mean: 30.0 GJha^{-1}) and also achieved a large positive energy balance (average net energy yield [HEY]) and net energy ratio [NER] of 159 GJha^{-1} and 6.6 respectively) with substantial variation across site-years (Figure 2 A-C and Figure 3 A and C). The largest fossil fuel inputs came from embodied energy in N fertilizer and from fuel use for irrigation pumping, which represented 32 and 42% of total seed energy inputs, respectively (Table 1). Average energy inputs for irrigated maize production in the Tri-Basin NRD were much higher than previously reported energy inputs of US maize systems that were based mostly on rain-fed production (Figure 3A and Table 1). Hence, previous studies included little or no energy inputs associated with irrigation pumping and much less energy associated with N fertilizer because of lower fertilizer rates in rain-fed systems. Average NEY of irrigated maize in Tri-Basin NRD was the highest among published studies, whereas NER was equal to or higher than published values except for two of eleven cases.

Despite relatively large fossil-fuel energy inputs, irrigated maize exhibited low GWPi (Figure 2D). On average, CO_2, N_2O, and CH_4 emissions, expressed as CO_2 equivalents (CO_2e), accounted for 63%, 36%, and 1% of GWP in these irrigated maize fields (mean ± SE = 3,001 ± 67 kg of CO_2eha^{-1}). The largest impact on GWP came from soil N_2O emissions associated with applied N fertilizer (34%), fuel use for irrigation (29%), manufacture and transportation of N fertilizer (17%), and fuel use for grain drying and field operations (13%). Frequency distribution of GWPi deviated significantly from normality as a result of exponential increase in N_2O emissions at N surplus values >50 kg of N ha^{-1} (Figure 1B). Although GWP per unit area of irrigated maize in the Tri-Basin NRD was within the upper range of published values for maize systems, average GWP of 231 kg of CO_2e.Mg^{-1} of grain and GWP per unit energy input of 103 kg of CO_2eGJ^{-1} was the lowest among published values for US maize systems (Figure 3B and Table 1). Using the IPCC N-input approach to calculate N_2O emissions gave GWP and GWPi 28% higher values than based on N_2O emissions with the N-surplus method (Figure 1 and Table 1).

Table 1. Average 3-y (2005 - 2007) applied inputs (and percentage of total energy input), total fossil-fuel energy input, grain yield, and interannual coefficient of variation, fertilizer nitrogen-use efficiency, water productivity, and conversion efficiency from solar radiation into grain or total biomass based on data collected from 123 irrigated maize fields in Tri-Basin NRD.

Inputs	Rate (per ha)
N fertilizer, kg of N	183 (32%)
P fertilizer, kg of P_2O_5	43 (1%)
K fertilizer, kg of K_2O	11 (<1%)
Herbicides, kg of a.i.	2.4 (3%)
Insecticides, kg of a.i.	0.3 (<1%)
Seed, kg	25 (1%)
Machinery, MJ	464 (2%)
Fuel use for on-farm operations,* L	
Field operations	63 (9%)
Irrigation pumping**	324 (42%)
Grain drying	61 (9%)
Energy inputs, GJ.ha^{-1}	30
Grain yield, Mg.ha^{-1}	13.2 (CV = 3%)
NUE,*** kg of grain, kg^{-1} of N fertilizer	73
WP,**** kg of grain.mm^{-1} of water supply	14
PAR cpmversopm efficiency, ***** %	
Grain	1.4
Total dry matter	3.3

a.i., active ingredient; CV, coefficient of variation; NUE, fertilizer nitrogen-use efficiency; WP, water productivity.

**Expressed as diesel equivalents (S3).*

***Average 3-y (2005-2007) annual applied irrigation amount was 272 mm.*

****Ratio of grain yield to applied N fertilizer.*

*****Ratio of grain yield to total water supply. Total water supply includes plant available soil water at planting and in-season rainfall plus applied irrigation water.*

****** Ratio of embodied energy in grain or total dry matter to total incident photosynthetically active solar radiation (PAR) from sowing-to-maturity.*

Management impact. Energy balance and GWP were calculated for irrigated maize and different combinations of irrigation systems, tillage method, and crop rotation based on actual reported values in the Tri-Basin NRD dataset (Figure 4). Energy inputs in fields under pivot irrigation and some form of reduced tillage (no-till, ridge-till, or strip-till, which are also called conservation tillage methods) were lower than in fields under surface irrigation and conventional disk tillage, respectively, mostly because of energy savings from irrigation. Applied irrigation was 41% and 20% less in fields under pivot irrigation and reduced tillage, respectively, compared with their counterparts under surface irrigation and conventional tillage. Apparent advantage of fewer tillage operations was partially counterbalanced by extra fuel use for other field operations such as herbicide application. Although applied N was 21 kg of N.ha^{-1} less in maize-soybean rotations than under continuous maize, the associated rotation benefit on energy saving was not significant ($P = 0.90$) and small compared with the energy savings achieved with pivot irrigation or reduced tillage.

Of interest was the observation that management systems with the highest grain yield (NER, and NEY) also had the lowest GWPi (i.e., pivot irrigation under soybean maize rotation and reduced-till). Differences in NEY due to crop rotation x tillage interactions were explained by variations in grain yield (Figure 4). Whereas crop rotation had no detectable impact on NEY in conventional-tilled fields, NEY of maize after soybeans was 7% higher than maize after maize in fields in which reduced tillage was practiced. On the average, NER was 23% and 5% higher in fields under pivot and reduced tillage than under surface irrigation and conventional tillage, respectively. GWPi was 7% and 14% smaller on fields in a maize-soybean rotation as well as fields under pivot irrigation (respectively), compared with their counterparts under continuous maize and surface irrigation.

Reducing emissions. A large decrease in GHG emissions per hectare of crop production would result from converting

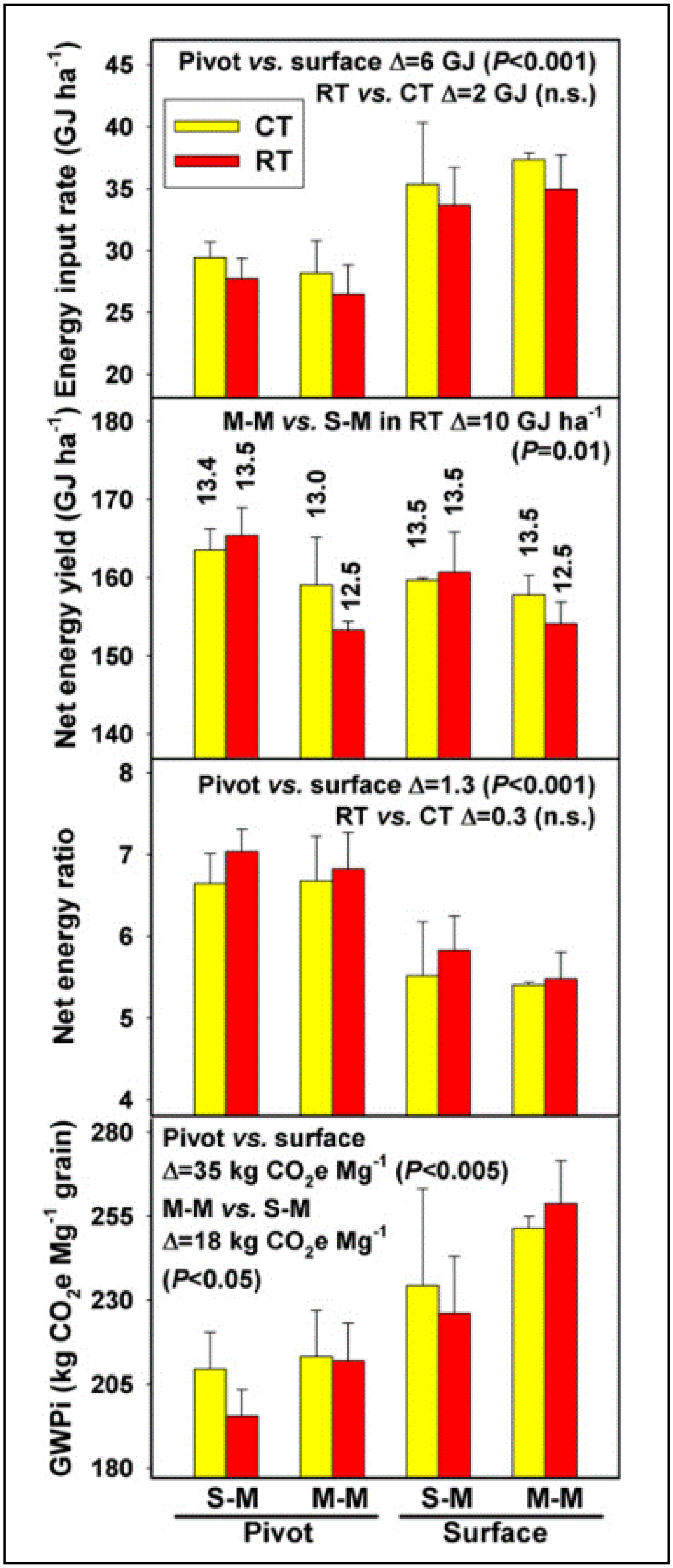

Figure 4. *Average (±SE) energy input rate, net energy yield, net energy ratio, and GWPi of irrigated maize under different combinations of irrigation system (pivot, surface), crop rotation (maize after maize [M-M] or maize after soybeans [S-M]), and tillage method (conventional [CT]; reduced till [RT]). Maize grain yields (Mg. ha^{-1}) are shown above bars in Middle Upper. All values are 3-y (2005-2007) means. Differences (△) and t test significance for selected comparisons between factor levels are shown (n.s., not significant).*

current irrigated cropland into dryland agriculture. However, the option has an unavoidable tradeoff of a 55% reduction in grain yield and much greater year-to-year yield variability as shown by comparison of yields and yield variability of rain-fed and irrigated maize in the Tri-Basin NRD. Assuming elimination of irrigated maize production, the amount of additional maize area (in addition to all existing maize land area in Tri-Basin NRD) to replace this lost production would depend on yield level in the new production area. For example, based on current average rain-fed yields, replacement would require 124,170 ha in Nebraska, 90,517 ha in Iowa, or 276,722 ha in Brazil. Additional land requirements, GHG emissions from land use change, and GHG emissions from crop production on this newly converted land would offset apparent benefits of expanding low-input/low- yield rain-fed maize at the expense of irrigated maize in the Tri-Basin NRD.

Given concerns about land use, the most promising avenue to reduce GHG emissions, without significant impact on productivity, appears to be through improvements in input use efficiency of current irrigated maize systems. Among irrigated maize fields in the Tri-Basin NRD, lack of correlation between irrigated yields and energy input or GWP in all years and three- and four-fold greater variation in energy inputs and GWP than observed variation in grain yield (Figure 3, A and B) suggests substantial scope to improve energy balance and to reduce GWP of irrigated maize without affecting productivity. Differences in both applied irrigation and magnitude of N surplus explained 57% of the variation in GWP. Therefore, achieving greater NUE and water productivity through better management of applied N and irrigation water would be a most effective way for increasing energy yield and reducing GHG emissions. Analysis of farmer's data indicated that values of NER and GWP higher and lower than 6.5 and 218 kg of CO_2eMg^{-1} of grain, respectively, can be set as reasonable energetic and environmental targets for irrigated maize (Figure 3 A and B).

In fact, achieving high yield with large energy inputs and high input use efficiency resulted in a strong negative correlation between GWPi and NEY (Figure 3C). This finding is consistent with results from a previous life cycle assessment for maize-enhanced systems. There is, however, an important distinction between analyses based on Tri-Basin NRD irrigated maize data and previously published data. In the present study, HEY and GWPi were calculated based on (1) maize yield and input data collected during a recent 3-year time interval (2005 to 2007) across a large number of farmer fields, (2) the most recent embodied energy values for inputs to estimate energy balance and GHG emissions, and (3) the N-surplus approach to estimate soil N_2O emissions. In contrast, previous studies relied on national or statewide aggregated yield and applied input statistics and the IPCC-N input approach to estimate soil N_2O emissions. Also, the embodied-energy and GHG-emission values for specific inputs were not consistent across these previous studies and in some cases the values used are now obsolete and/or unrepresentative compared with current crop management practices and manufacturing efficiencies.

The impact from adoption of best management practices, compared with current average management, on energy use and GWP was evaluated for irrigated maize in the Tri-Basin NRD (Table 2). Best management practices included use of low-pressure pivot irrigation, improved irrigation pump performance rating (PPR), use of electrical power for irrigation water pumping rather than diesel or natural gas, fine-tuning of irrigation timing, and better N fertilizer management. Taken together, adoption of these management practices would result in a 25% and 21% reduction in energy

Table 2. Potential impact of adoption of best management practices on energy use and global warming potential in irrigated maize in Tri-Basin NRD.

Scenario	Total energy* GJ	Total GWP,* Mg of CO_2e
Actual baseline**	28,758	2,745
Potential***	22,018	2,180
Difference****	-6.741 (-25%)	-566 (-21%)

*See **Materials and Methods** for details on calculation of energy use and GWP under each scenario.*

**Values are per 1,000 ha of irrigated maize in Tri-Basin NRD.*

***Based on actual frequency of fields under each type of irrigation system, tillage method, crop rotation, and source of energy for irrigation pumping.*

****Based on full adoption of improved plant performance rating (90%), use of electrical power for irrigation water pumping, pivot irrigation, limited irrigation, and optimal N management in current irrigated maize land area that is not already under these management practices.*

***** Absolute and relative (in parentheses) difference in energy use and GWP under the potential scenario compared with actual baseline.*

use and GWP, respectively, with very little reduction in crop yield (4% reduction under limited irrigation). It is noteworthy that the greatest opportunity to reduce GHG emissions appears to be from fine-tuning N management practices aiming to reduce N surplus rather than reducing average N fertilizer rate. This proposition follows from the fact that, although many fields required higher or lower N fertilizer rates to achieve a zero N surplus (Figure 1), the estimated average N rate for optimal N management is similar to the current average fertilizer N rate (178 vs. 183 kg of N ha^{-1}, respectively).

Summing up

Increased demand for food and fuel with limited reserves of arable land will require further intensification of existing cropping systems. At issue is whether it is possible to achieve an ecological intensification that gives both high yields and reduced environmental burden. Results from our study clearly document that high yield and high input-use efficiencies, together with low GWP, are not conflicting goals in well-managed commercial-scale production fields. Although energy inputs and GWP per unit of land area were much greater in irrigated production compared with published values based mostly on rain-fed maize production, associated NEY and GWPi of irrigated systems were substantially greater and lower respectively. Hence, advantages of lower-input, lower-yielding maize systems vanish when metrics are scaled by grain yield or net energy output. For this reason, assessments of energy efficiency and GWP metrics are most relevant when corrected for yield rather than on a land-area basis.

Our results also showed large discrepancies between two methods for estimating N_2O emissions from applied N inputs. Because the current standard IPCC N-input method does not account for large variation in NUE observed across farmers' fields, due to differences in yield level and competence in fertilizer management, estimated N_2O emissions in high-yield, high NUE irrigated maize fields in the Tri-Basin NRD were much higher by using the IPCC input method than by estimating by the N-surplus approach. Hence, the IPCC method to estimate N_2O emissions based on a fixed proportion of applied N inputs is likely to over-estimate N losses from well-managed, high-yield, high-input systems such as irrigated maize in Nebraska. Moreover, the N input approach cannot support incentives for investment in technologies to reduce N losses and thereby achieve better N balance without sacrificing yield.

In a broad context, irrigated maize production in Nebraska can be taken as a benchmark for other current and future irrigated cropping systems because it achieves remarkably high and stable grain yields, high efficiencies in use of solar radiation, N, and water, plus has a large positive energy balance and low GWPi.

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