

High Yields, High Efficiencies, and High Environmental Standards: H^3 Pipe Dream?

Kenneth G. Cassman
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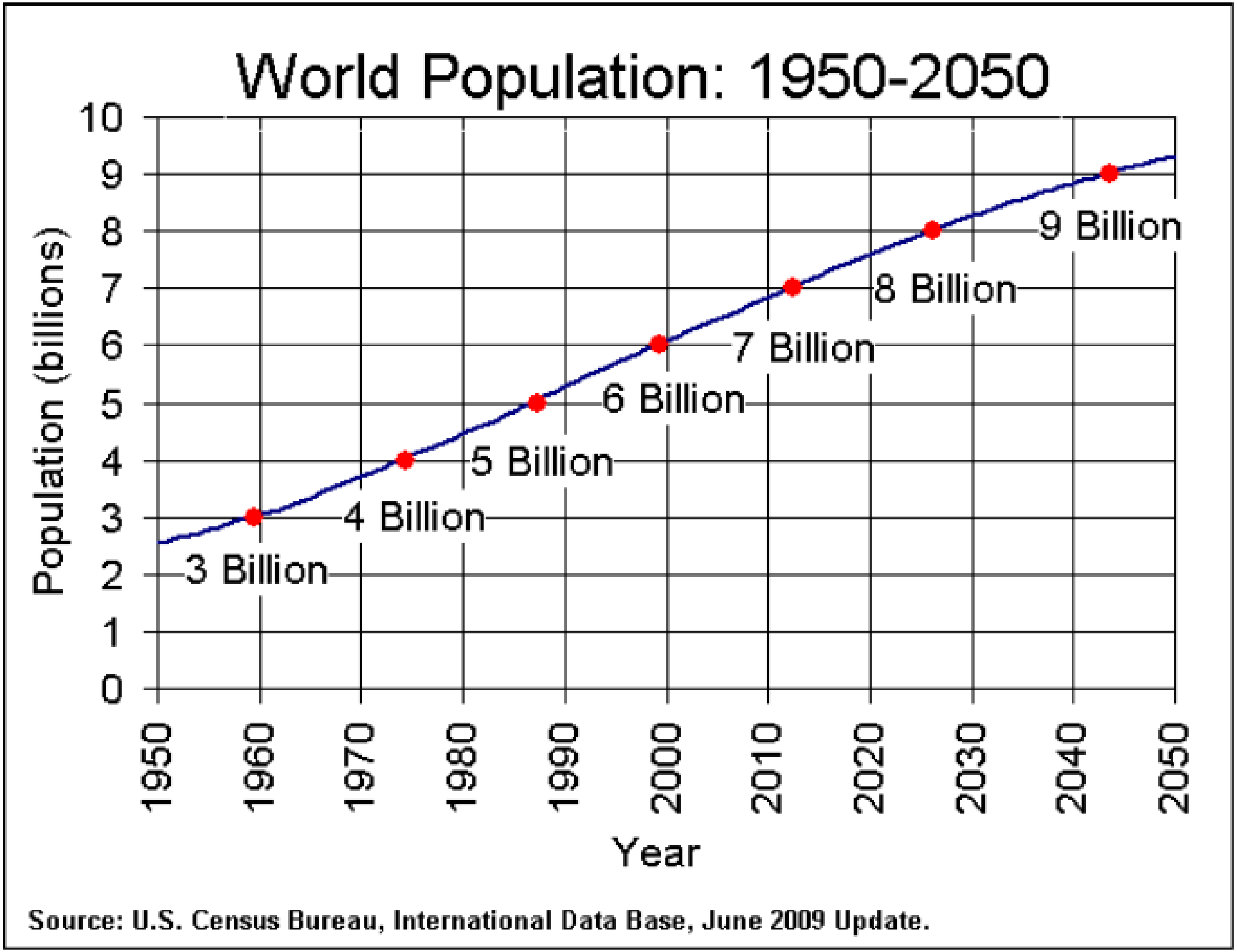
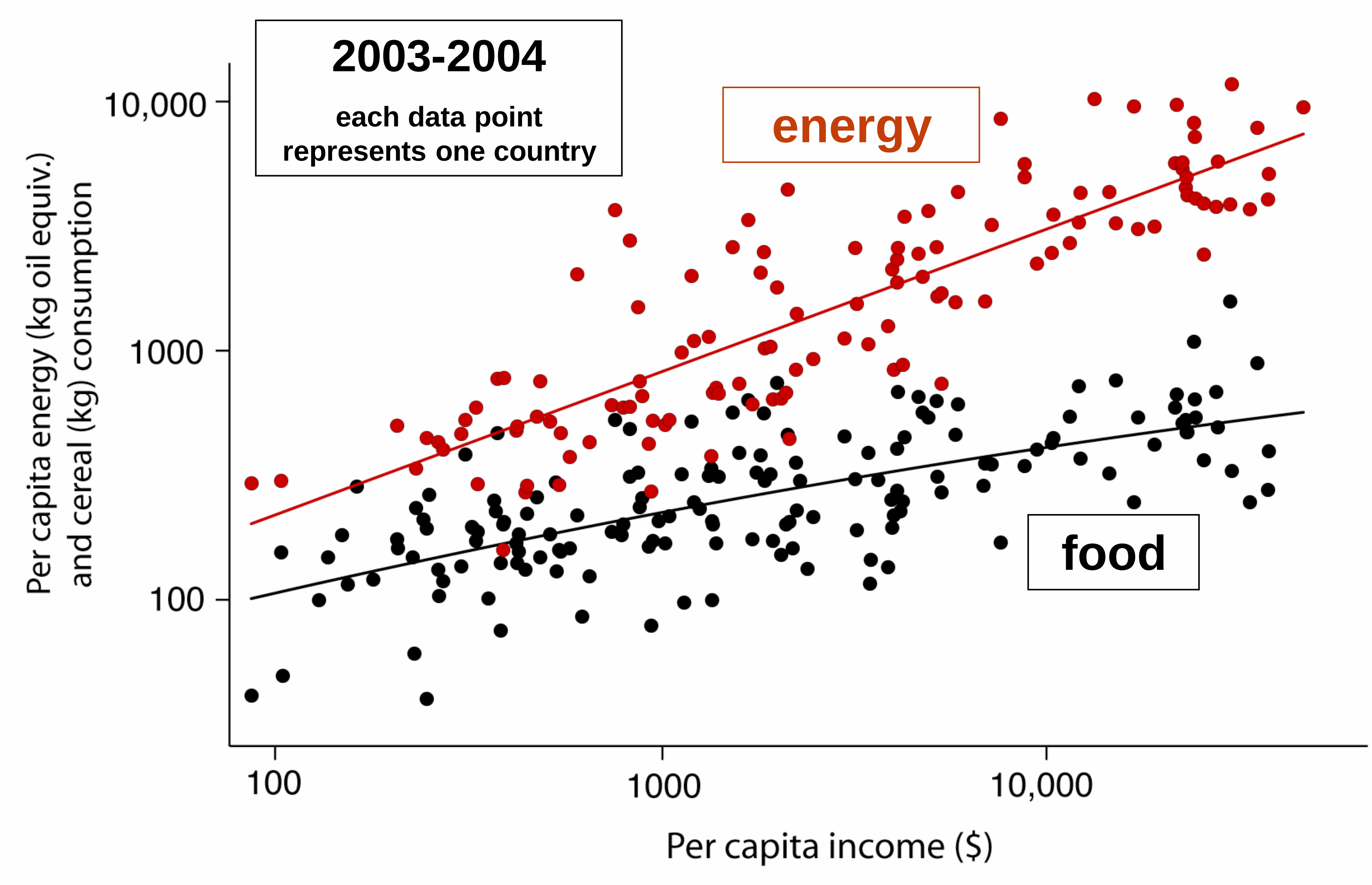
University of Nebraska Lincoln


World Population: 1950-2050
Population (billions)
10
9
8
7
6
5
4
3
2
1
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Year
3 Billion
4 Billion
5 Billion
6 Billion
7 Billion
8 Billion
9 Billion
Source: U.S. Census Bureau, International Data Base, June 2009 Update.

Brave New World Since 2005

- **Rapid, sustained economic growth in the most populous developing countries**
- **Rapid rise in petroleum prices**
- **Convergence of energy and agriculture**
- **Falling supply relative to demand for staple food prices**

Energy or Cereal Consumption versus Income by Country



Naylor et al., 2007. *Environment* 40: 30-43. Energy and income data from World Bank development indicators; cereal consumption data from FAOSTAT.

Biofuels compared to what in a world with changing climate?

Deep water petroleum? Oil sands? "Frac" natural gas? Coal? Nuclear Power?

Urban-industrial expansion onto prime farmland at the periphery of Kunming (+6 million), the capital of Yunnan Province, China,

Photo: K.G. Cassman

Clearing virgin rain forest in Brazil: powerful +feedback to GHG emissions

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- **Increased poverty and malnutrition**

Food insecurity: unsustainable crop production on marginal land by poor farm families without other options

Photo: K.G. Cassman


Photo: K.G. Cassman

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- Rapid, sustained economic growth in most populous developing countries
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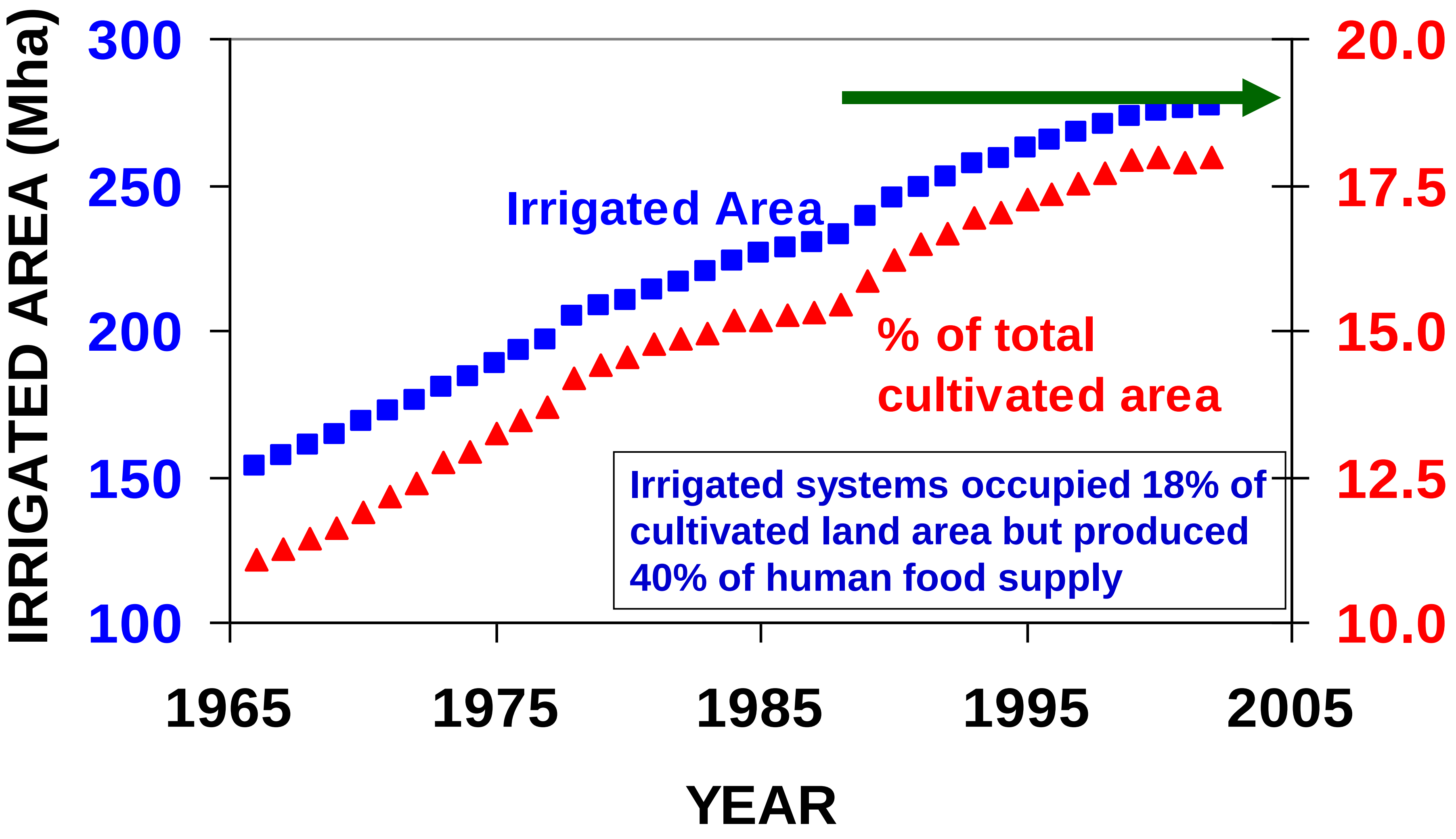
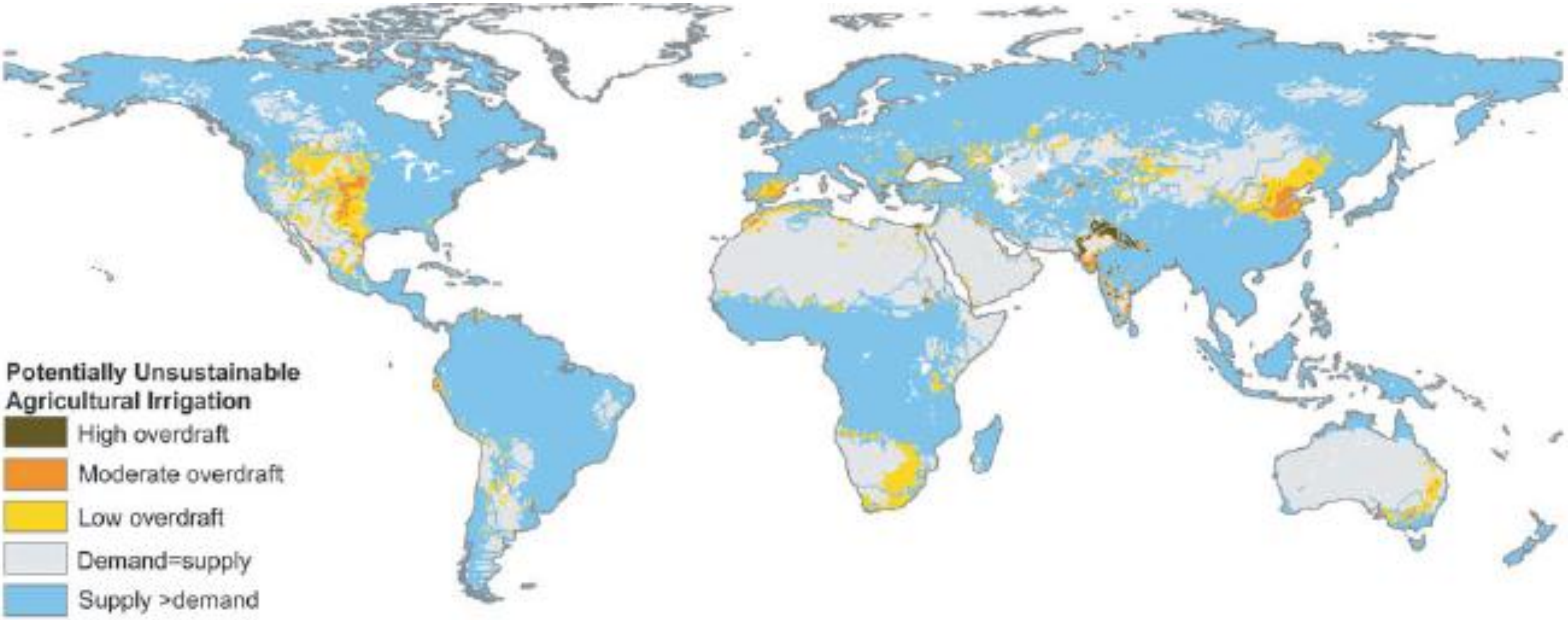
- Convergence of energy and agriculture
- Smaller supply, relative to demand, of staple food crops; steep rise in the price of these foods
- Increasing poverty and malnutrition
- **Limited supplies of good quality arable land and accessible fresh water**
- **Stagnating yields in some of the most productive cropping systems**
- **Increasing concerns about environment and climate change**

Global Irrigated Area and as a % of Total Cultivated Land Area, 1966-2004

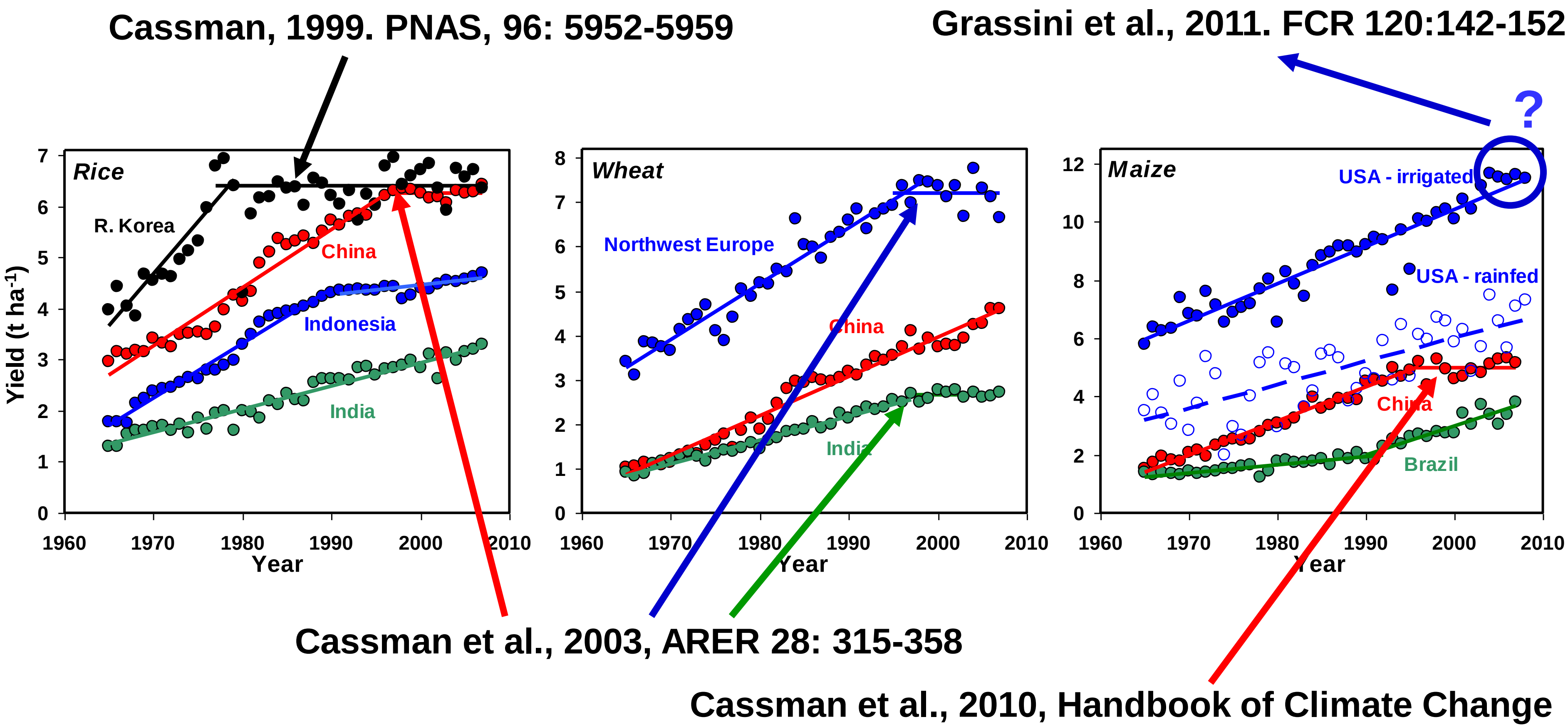


Decreasing water supply in all major irrigated areas



In an increasingly urban world, irrigated agriculture is more important than ever to provide "ballast" to global food supply

Also a concern are yield plateaus for several major crops. What are the causes? Korea and China for rice, wheat in northwest Europe and India, maize in China, and……..perhaps also for irrigated maize in the USA??



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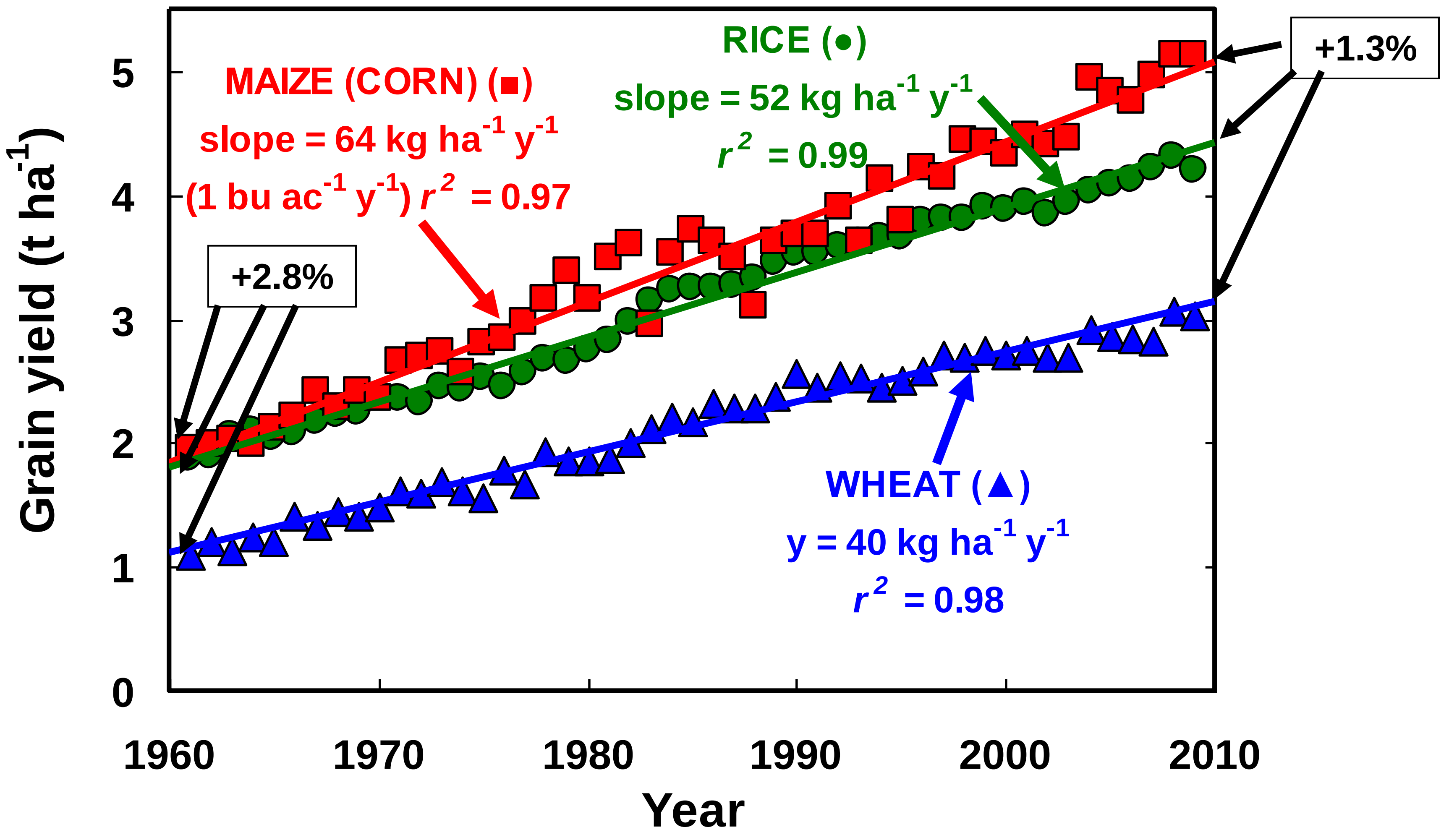
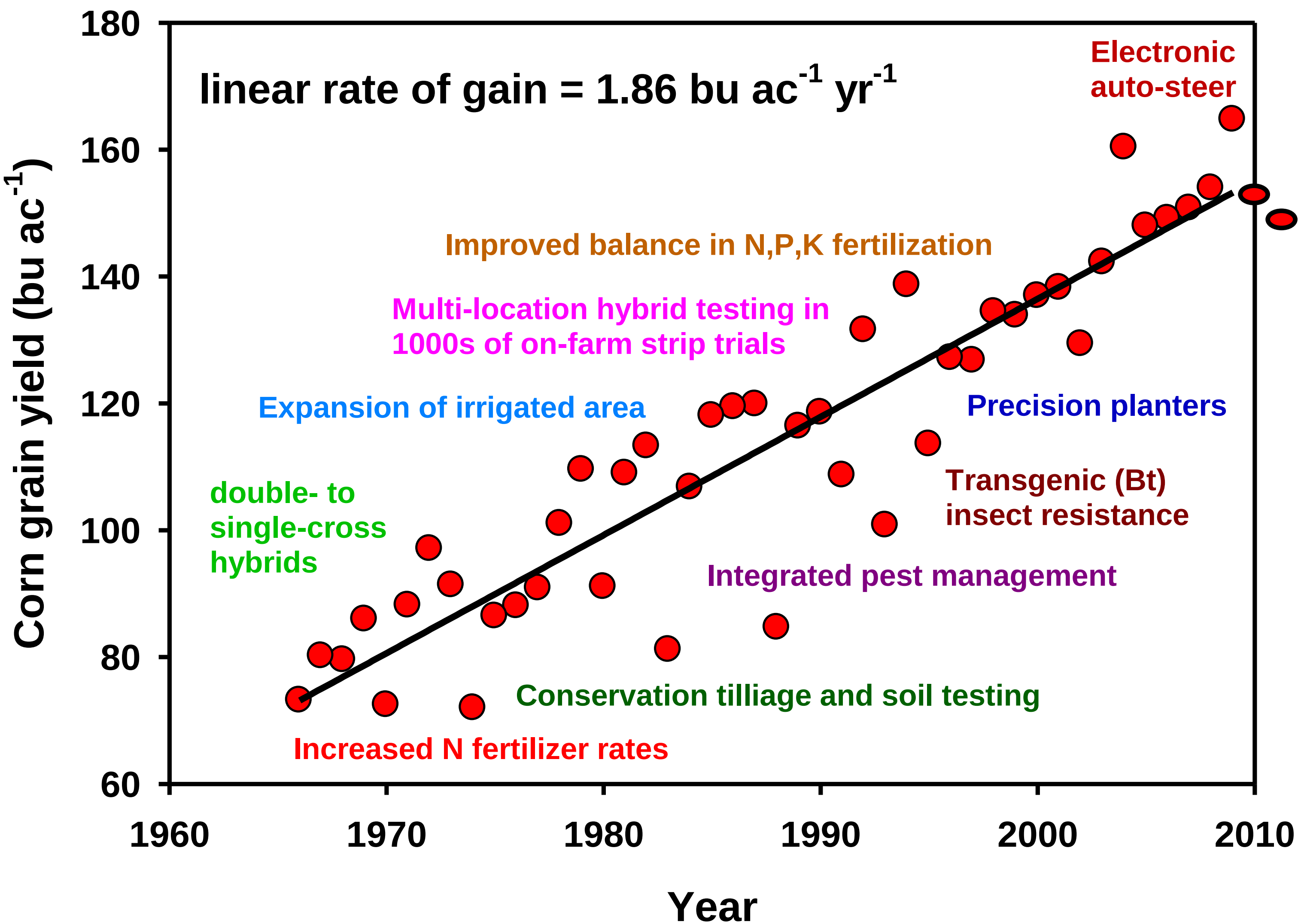
- Limited supplies of good quality arable land and accessible fresh water
- Stagnating yields in some of the most productive cropping systems
- Increasing concerns about environment and climate change
- These are likely to be LONG-TERM MEGATRENDS

Global Cereal Yield Trends, 1966-2009



THESE RATES OF INCREASE ARE NOT FAST ENOUGH TO MEET EXPECTED DEMAND ON EXISTING FARM LAND! source: FAOSTAT

USA Corn Yield Trends, 1966-2009
(and supporting science and technologies)



Modified from: Cassman et al. 2006. Convergence of energy and Agriculture. Council on Agriculture, Sci. Tech. Commentary QTA 2006-3. Ames, Iowa

Assuming a goal of no net expansion of current crop production area……

- **A ~60% increase in cereal* yields needed by 2050 (38 yr) = 1.54% yr^{-1} of current average yield**
- **Business as usual will not meet 2050 global demand for food, feed, fuel in without large expansion of crop area**
- **How much help from less meat and less post-harvest losses and food waste?**

***Cereals for food, feed, fuel, bio-industrials**

The Challenge is Clear

- Increase food supply +70% (cereals + 60%) on existing crop and pasture land
- Substantially decrease environmental footprint of agriculture
  - Protect water quality and conserve water for non-agriculture uses
  - Maintain or improve soil quality
  - Reduce greenhouse gas emissions
  - Protect wildlife and biodiversity
- Called “ecological intensification”

Four Stories About H^3 in Agriculture

- **Expansion of soybean production in Brazil (2005)**
- **Greenhouse gas emissions from corn-ethanol life cycle (2006-2009)**
- **Recent EPA report on Integrated Nitrogen Management**
- **Nebraska irrigated corn production**

Soybean Production and Expansion in Mato Grosso

B·r·a·z·i·l

Kenneth G. Cassman, Dept. of Agronomy, Univ. of Nebraska
In: Soybean Review, Fall 2005, NE Soybean Board

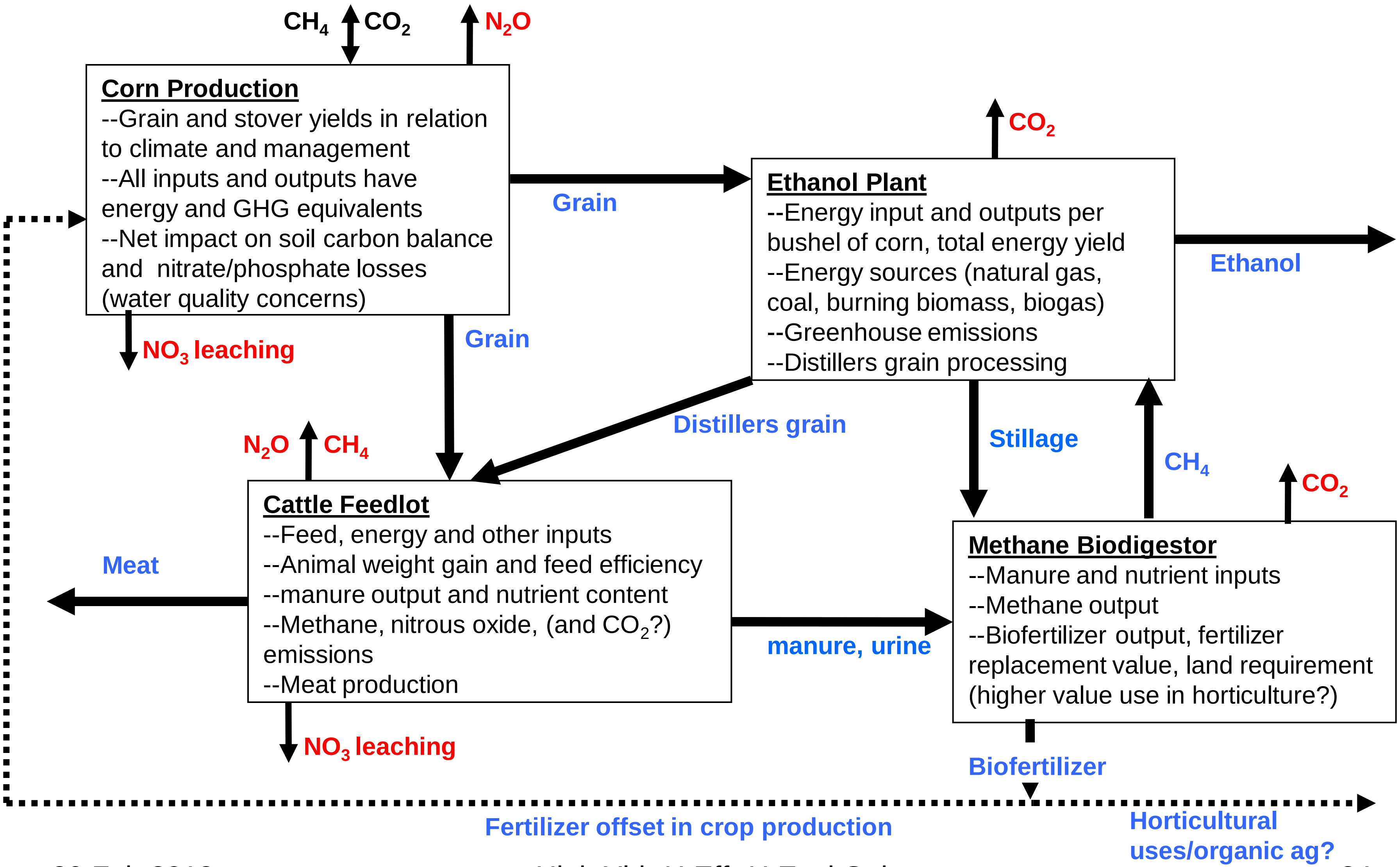
Brazilian vs USA Soybean Production

- **Brazilian soybean production costs are much lower than in the USA, but only because of lower fixed costs**
  - **Does not include cost of transport to markets, which are much higher in Brazil**
  - **Variable costs are much lower in USA due to better soils and much lower fertilizer inputs, disease and insect pressure**
- **Head-to-head environmental performance much better in USA**
  - **Global concerns about clearing of rain forest in Mato Grosso and elsewhere in Brazil for expansion of crop production**
  - **Large greenhouse gas emissions per ton of soybean production in Brazil due to large inputs and land clearing**

Biofuels Case Study: from good guy to villain in 2-years: 2005 to 2007

- **Benefits**
  - **Decreased reliance on imported petroleum**
  - **Net reduction in greenhouse gas (GHG) emissions**
  - **Rural jobs and economic development**
  - **Reduces cost of gasoline for consumers ($25-80B/yr)**
- **Negative impacts and concerns**
  - **Relies on subsidies**
  - **Net increase in GHG emissions and net energy loss (energy inputs > outputs)**
  - **Uses too much water, causes land use change**
  - **Major cause of rising food prices**

Life Cycle Assessment: Integrated Biofuel Biorefinery with Corn Grain as Feedstock



Purpose of LCFS

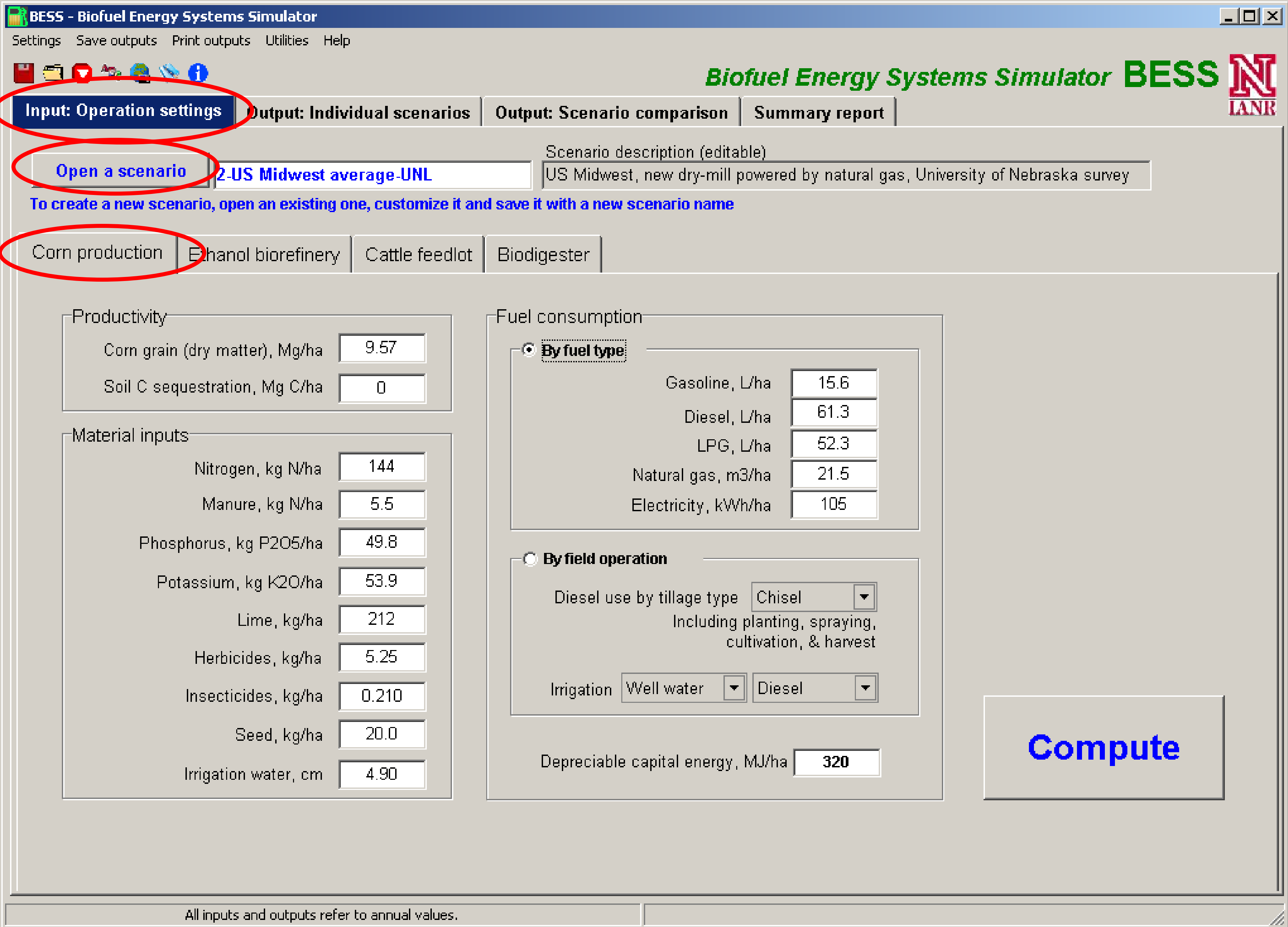
- **2007 Energy Independence and Security Act (EISA)**
  - **Help guide R&D prioritization & investment**
- **CA Low Carbon Fuel Standard**
  - **Achieve a 10% reduction in motor fuel GHG intensity by 2020**
- **Foster and reward the build-out of a “green” biofuel industry**
  - **GHG emissions trading, certification**

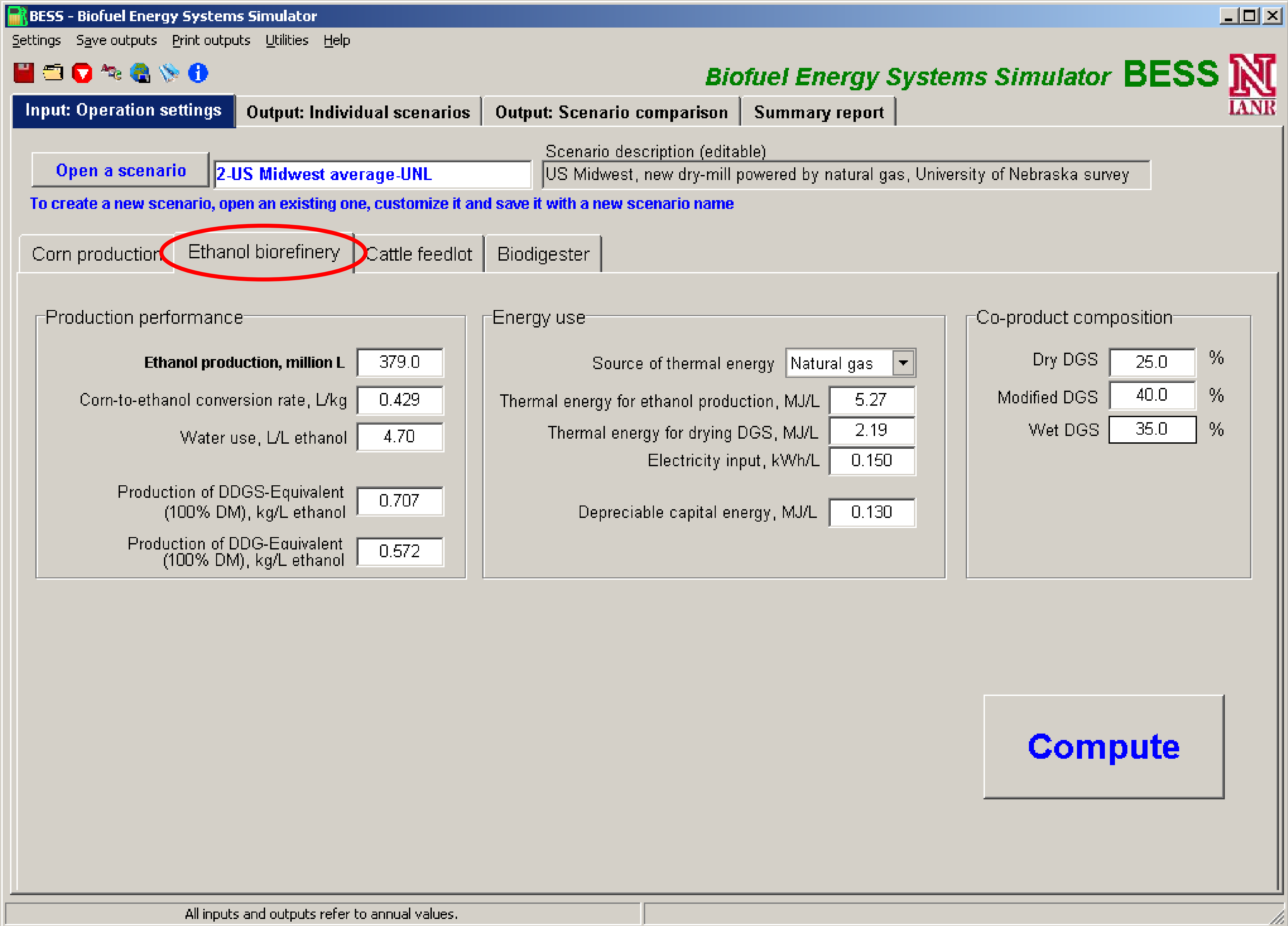
2007 EISA definition: Life Cycle GHG Emissions

''(H) LIFECYCLE GREENHOUSE GAS EMISSIONS.—The term 'lifecycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for their relative global warming potential.

Biofuel Energy Systems Simulator (BESS) [available at: www.bess.unl.edu]

- **Most up to date estimates for direct-effect GHG emissions for corn ethanol based on best current science and input from all key disciplines (engineers, agronomists, soil scientists, animal nutritionists, industry professionals)**
- **User-friendly, completely transparent, and well documented**
- **Default scenarios based on regional-scale data, but can also be used for certification of an individual ethanol plant, its associated corn supply and co-product use**
- **Can be used for estimating carbon-offset credits for emissions trading with an individual ethanol plant as the aggregator**
- **If GREET can be consistent with BESS for corn-ethanol GHG emissions estimates, then BESS can be used for compliance and certification**


BESS - Biofuel Energy Systems Simulator
Settings
Save outputs
Print outputs
Utilities
Help
Biofuel Energy Systems Simulator BESS
LANR
Input: Operation settings
Output: Individual scenarios
Output: Scenario comparison
Summary report
Open a scenario
2-US Midwest average-UNL
Scenario description (editable)
US Midwest, new dry-mill powered by natural gas, University of Nebraska survey
To create a new scenario, open an existing one, customize it and save it with a new scenario name
Corn production
Ethanol biorefinery
Cattle feedlot
Biodigester
Productivity
Corn grain (dry matter), Mg/ha 9.57
Soil C sequestration, Mg C/ha 0
Material inputs
Nitrogen, kg N/ha 144
Manure, kg N/ha 5.5
Phosphorus, kg P2O5/ha 49.8
Potassium, kg K2O/ha 53.9
Lime, kg/ha 212
Herbicides, kg/ha 5.25
Insecticides, kg/ha 0.210
Seed, kg/ha 20.0
Irrigation water, cm 4.90
Fuel consumption
By fuel type
Gasoline, L/ha 15.6
Diesel, L/ha 61.3
LPG, L/ha 52.3
Natural gas, m3/ha 21.5
Electricity, kWh/ha 105
By field operation
Diesel use by tillage type
Chisel
Including planting, spraying, cultivation, & harvest
Irrigation
Well water
Diesel
Depreciable capital energy, MJ/ha 320
Compute
All inputs and outputs refer to annual values.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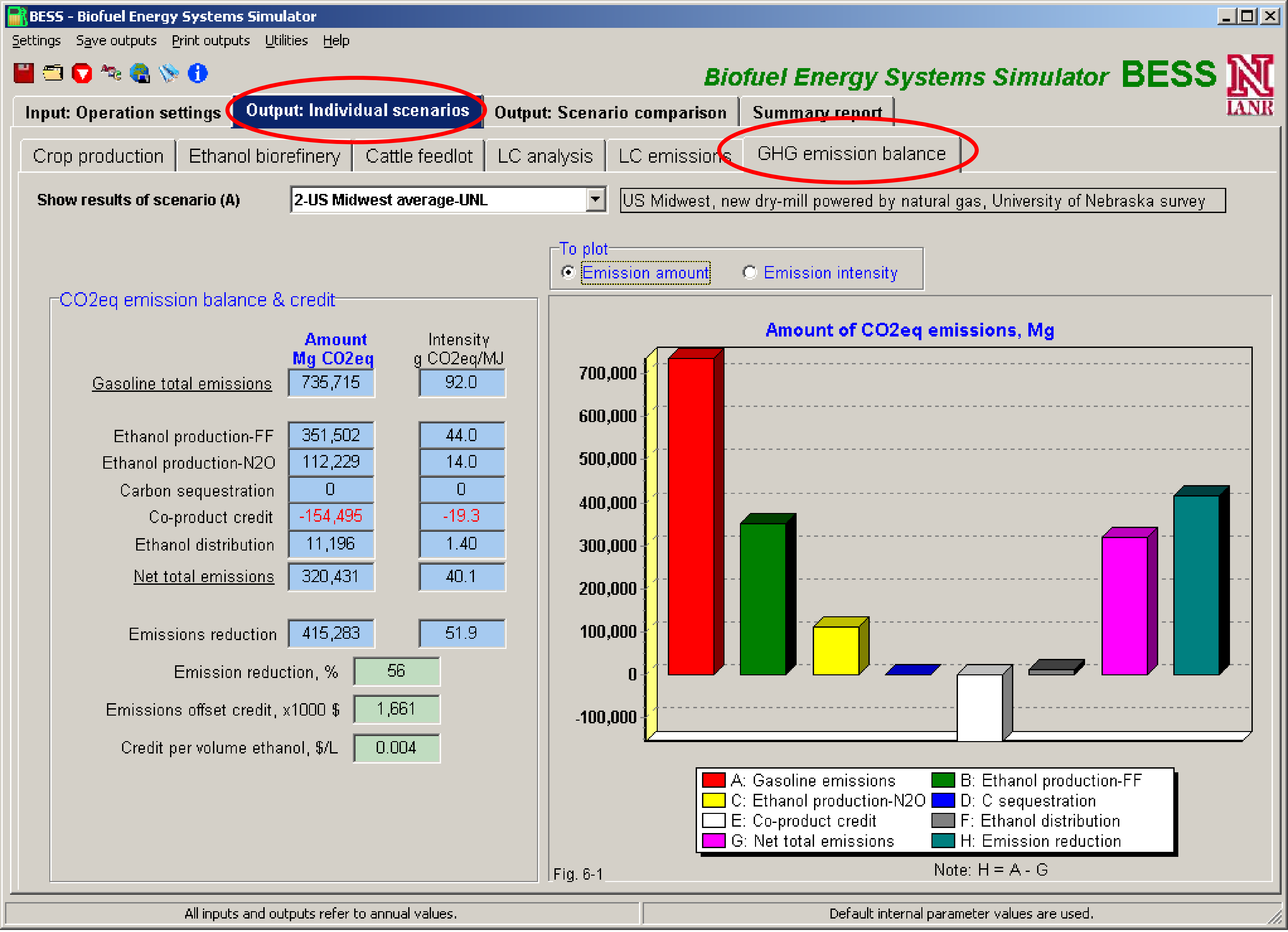
Corn production
Ethanol biorefinery
Cattle feedlot
Biodigester
Production performance
Ethanol production, million L
379.0
Corn-to-ethanol conversion rate, L/kg
0.429
Water use, L/L ethanol
4.70
Production of DDGS-Equivalent (100% DM), kg/L ethanol
0.707
Production of DDG-Equivalent (100% DM), kg/L ethanol
0.572
Energy use
Source of thermal energy
Natural gas
Thermal energy for ethanol production, MJ/L
5.27
Thermal energy for drying DGS, MJ/L
2.19
Electricity input, kWh/L
0.150
Depreciable capital energy, MJ/L
0.130
Co-product composition
Dry DGS
25.0
%
Modified DGS
40.0
%
Wet DGS
35.0
%
Compute
All inputs and outputs refer to annual values.


BESS - Biofuel Energy Systems Simulator
Settings
Save outputs
Print outputs
Utilities
Help
Biofuel Energy Systems Simulator BESS
Input: Operation settings
Output: Individual scenarios
Output: Scenario comparison
Summary report
Crop production
Ethanol biorefinery
Cattle feedlot
LC analysis
LC emissions
GHG emission balance
Show results of scenario (A)
2-US Midwest average-UNL
US Midwest, new dry-mill powered by natural gas, University of Nebraska survey
To plot
Emission amount
Emission intensity
CO2eq emission balance & credit
Amount Mg CO2eq
Intensity g CO2eq/MJ
Gasoline total emissions 735,715 92.0
Ethanol production-FF 351,502 44.0
Ethanol production-N2O 112,229 14.0
Carbon sequestration 0 0
Co-product credit -154,495 -19.3
Ethanol distribution 11,196 1.40
Net total emissions 320,431 40.1
Emissions reduction 415,283 51.9
Emission reduction, % 56
Emissions offset credit, x1000 $ 1,661
Credit per volume ethanol, $/L 0.004
Amount of CO2eq emissions, Mg
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
-100,000
A: Gasoline emissions
B: Ethanol production-FF
C: Ethanol production-N2O
D: C sequestration
E: Co-product credit
F: Ethanol distribution
G: Net total emissions
H: Emission reduction
Fig. 6-1
Note: H = A - G
All inputs and outputs refer to annual values.
Default internal parameter values are used.

Conclusions from BESS analysis

- Corn-ethanol systems are not accurately evaluated as an aggregate, due to differences in *biorefinery designs*, *energy sources*, and *crop production practices*
- Based on state records and new surveys, natural gas powered dry mills (88% of the industry) can reduce GHG emissions by 48-59% compared to gasoline on average, which is a 2-3 fold greater reduction than reported in previous studies
- Crop production represents 42-51% of life-cycle GHG emissions for typical USA corn-ethanol systems; *needs accurate assessment*
- Co-product credits offset 26-38% of life-cycle GHGs
- Accurate GHG analysis is essential for enabling ethanol producers to meet the 20% GHG emissions reduction relative to gasoline for the *EISA* of 2007, and will be critical for state-level LCFS

Published in 2009: Liska AJ, Yang HS, Bremer VR, Klopfenstein TJ, Walters DT, Erickson GE, Cassman KG. Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol. J. Industrial Ecol. 13:58-74

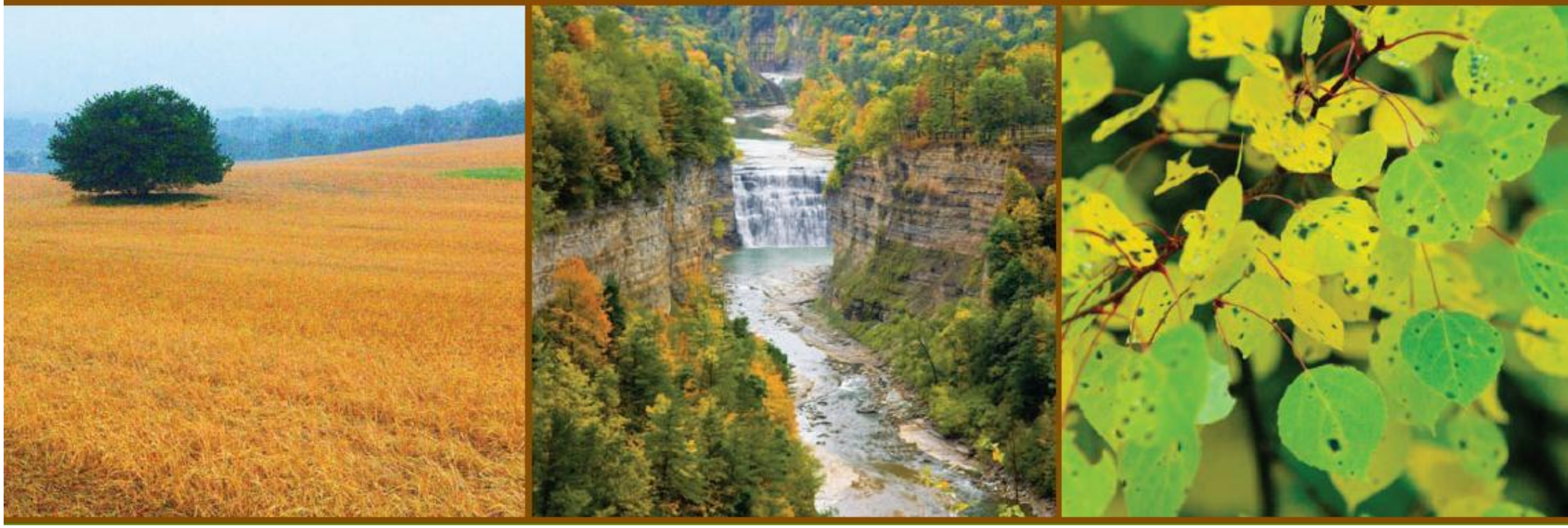
Most sensitive input parameters on GHG emissions [as well as on net energy yield]

1. *Crop yield: Mg per hectare* **or bushels per acre: tremendous scope for improvement**
2. *Conversion yield: liters ethanol per lb grain: little scope for improvement*
3. *Conversion thermal energy inputs: MJ per L: little scope for improvement*
4. *Reduced drying of distillers grains (i.e. use more for local livestock or dairy production)*
5. *Increased N fertilizer use efficiency in corn production*

Released: October, 2011

Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options

A REPORT OF THE EPA SCIENCE ADVISORY BOARD



Objectives

- Identify and analyze from a scientific perspective the problems Nr presents in the environment and the links among them;
- Evaluate the contribution an integrated nitrogen management strategy could make to environmental protection;
- Identify additional risk management options for EPA's consideration; and
- Make recommendations to EPA concerning improvements in nitrogen research to support risk reduction.

Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options

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FINDINGS:

- In the United States, human activities across multiple sources currently introduce more than five times the Nr into the environment than natural processes. The largest U.S. sources of new Nr entering the U.S. environment include: the creation and use of synthetic fertilizers, Nr created by legumes, and the combustion of fossil fuels.
- Much of the Nr used to ensure a plentiful supply of food, fiber and biofuel is released to the environment, as is the Nr formed during fossil fuel combustion.
- The introduction of human created Nr into the environment degrades air and water quality, which can cause harmful algae blooms, hypoxia, fish kills, loss of drinking water potability, loss of biodiversity, forest declines, and human health problems resulting in losses of billions of dollars per year.
- Multiple strategies and actions exist to more effectively minimize the inputs of Nr to the environment and maximize nitrogen use efficiency.

Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options

A REPORT OF THE EPA SCIENCE ADVISORY BOARD

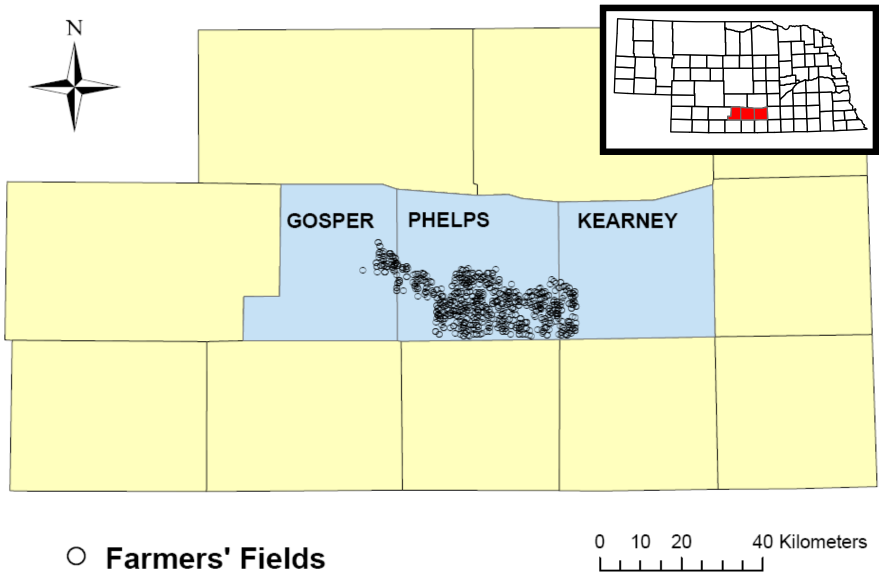
Recommendations

- Because reactive nitrogen (Nr) flows through multiple ecosystems (land, surface and groundwater, estuaries) and in many different forms (NH4, NO3, N2O), new institutional structures are needed for effective control and management
- Requires integrated management that recognizes complex tradeoffs, are cost-effective, and identifies key intervention points
- EPA Intra-agency task force recommended to: (i) better quantify Nr impacts on ecosystems, human health, climate change, (ii) monitoring needs to support informed policies, (iii) identify most efficient and cost-effective ways to reduce Nr volumes and negative Nr impacts on environment, HH, CC.
- Inter-agency task force needed (EPA, USDA, DOE, NSF, DOT, etc) to *coordinate "all of government" efforts*

Take Home on EPA Nr Study

- Nr in form of commercial fertilizer is critical to ensure global food security
- There is too much reactive N in the global environment, and it causes degradation of water quality, biodiversity, and has health concerns
- Majority of Nr in the environment comes from agriculture
- Recommends increased monitoring to identify best mitigation interventions

On-farm analysis: maize fields in the Tri-Basin NRD



--- Data from 3 years (2005, 2006, and 2007)
--- 777 field-year data identified with 100% irrigated maize

34° Partly Cloudy
Weather Closings

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Tri-Basin data - with both water use and crop production figures - offered UNL crop and irrigation efficiency researchers everything they needed

Story Discussion Image (2)

Pivot

Photo by: Lori Potter, Hub file

University of Nebraska-Lincoln researchers are using the 2005-2007 crop and water use reports farmers in Gosper, Phelps and Kearney counties submitted to the Holdrege-based Tri-Basin Natural Resources District to study practices and variables affecting the goal of growing more bushels of corn with the same or less irrigation water. A presentation about the study is on the agenda for the Feb. 4 Holdrege Water Conference.

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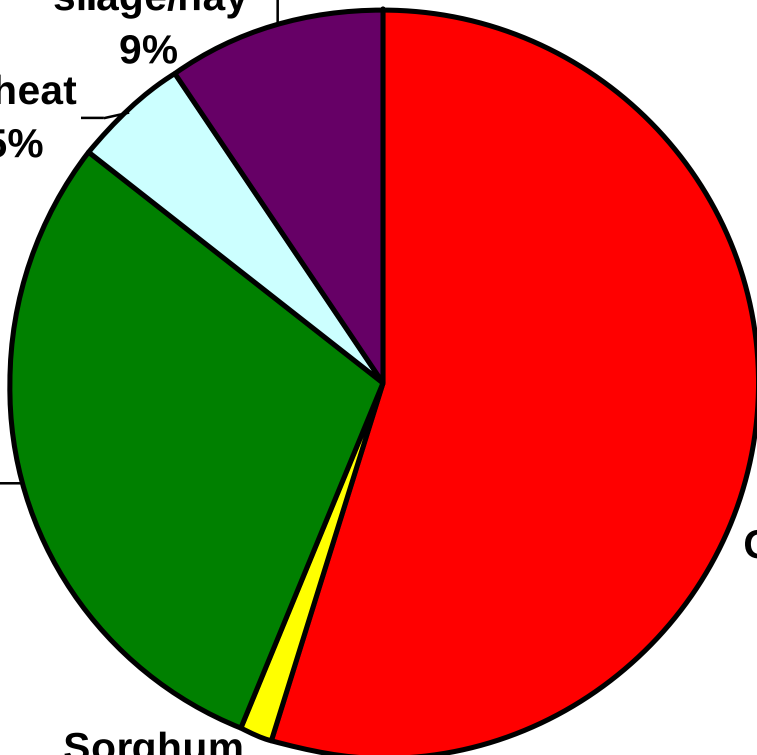
Water, Energy and Agriculture Initiative WEAI

20 Feb 2012

Land allocation and average yields in Tri-Basin NRD
(2000-2008, USDA-NASS)

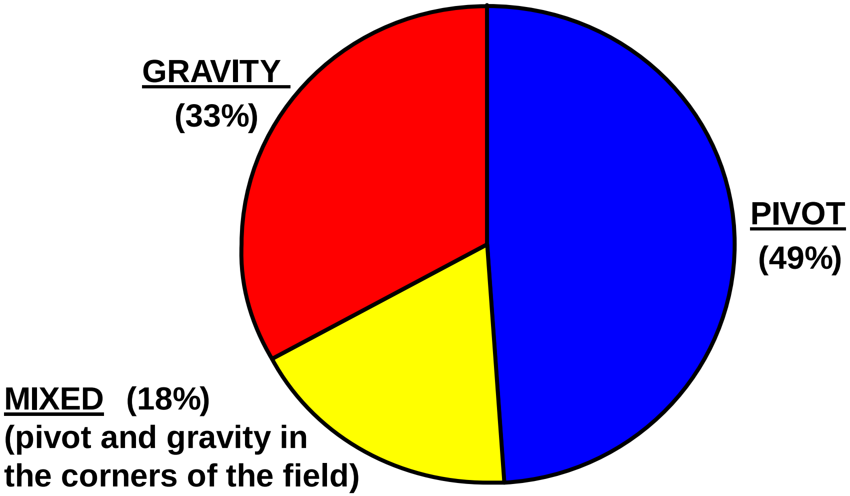


Crop	*Yield (bu ac^{-1})**
Corn	180.0
Soybean	56.1
Wheat	46.5
Sorghum	73.7

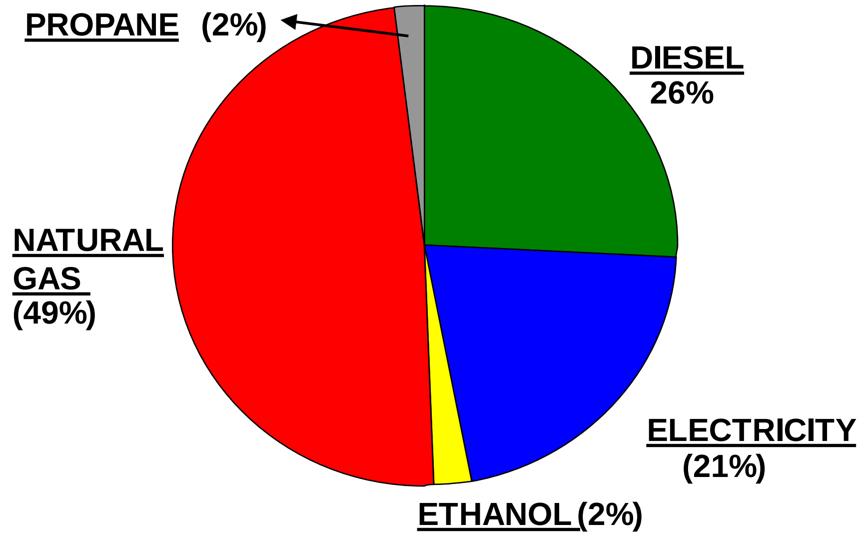
* Includes both rainfed and irrigated crops

Tri-Basin NRD: irrigation system, rotation, and tillage

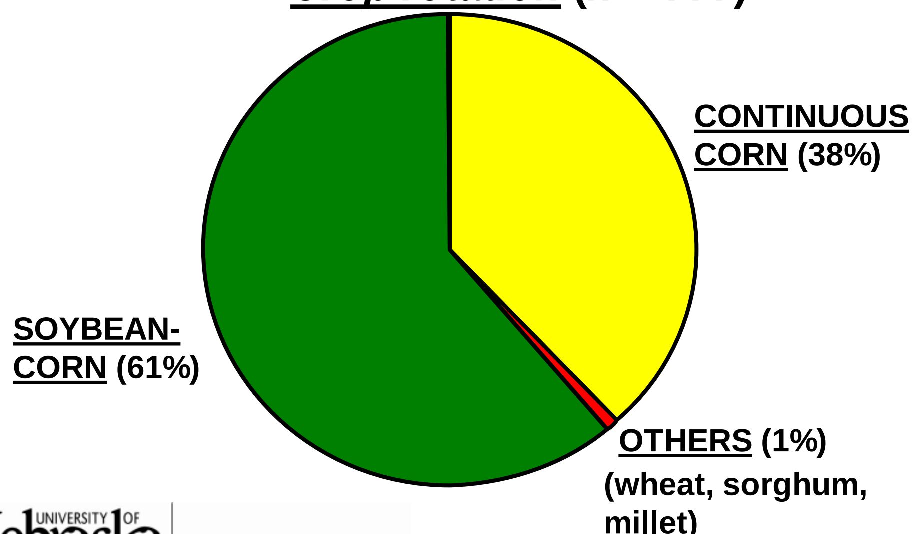
Irrigation system **(*n* = 777)**



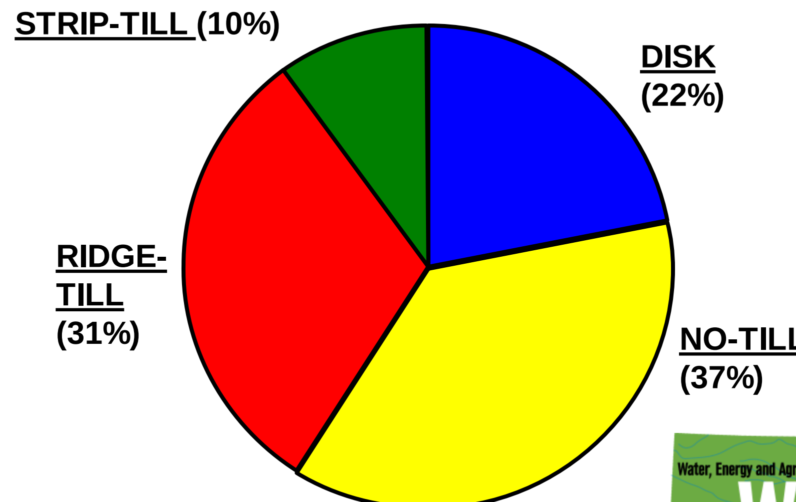
Energy source for irrigation **(*n* = 777)**



Crop rotation **(*n* = 777)**



Tillage system **(*n* = 123)**



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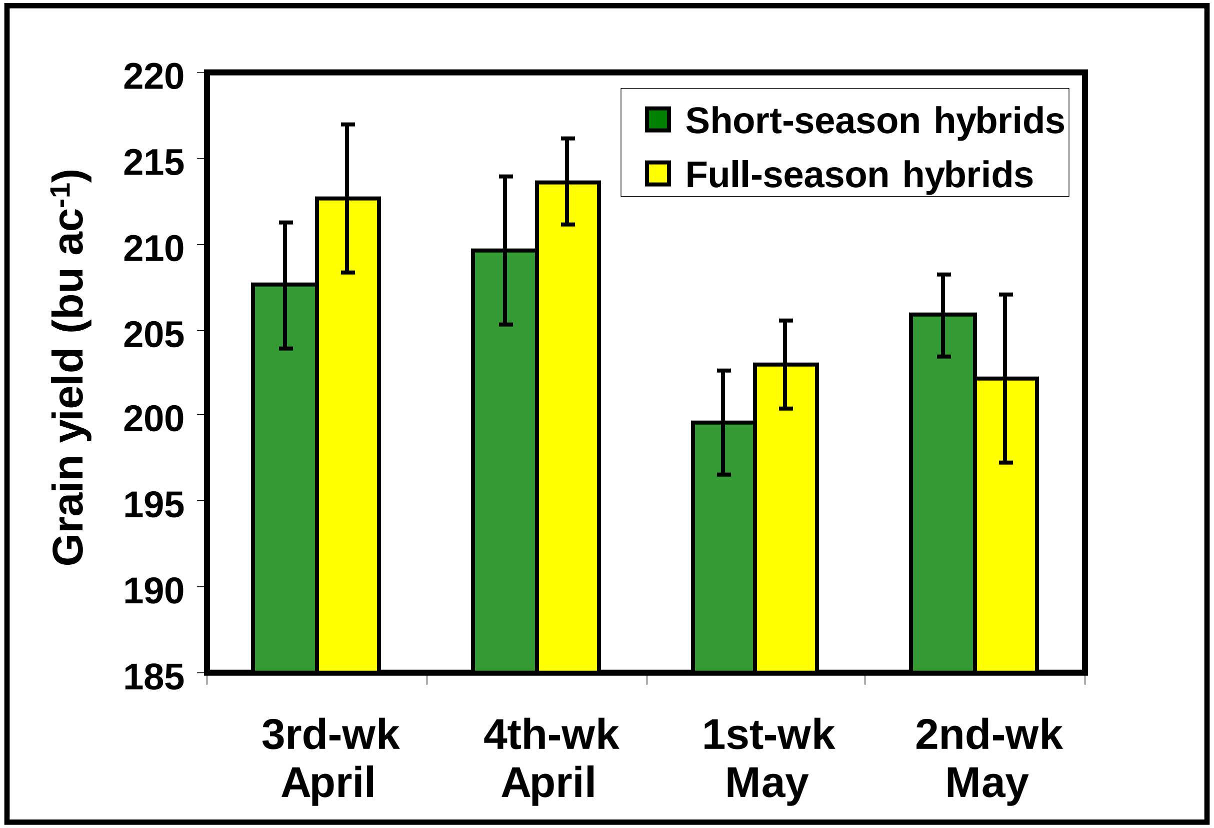
Grain yield: effects of hybrid maturity x sowing date

**** Based on management data collected from 123 fields in the Tri-Basin NRD during 2005-2007 seasons.***
***** Data were aggregated into two hybrid maturity categories [short- (106-112 days) and full-season (113-118 days)] and four sowing date 7-day intervals. Vertical bars indicate ±SE of the mean***

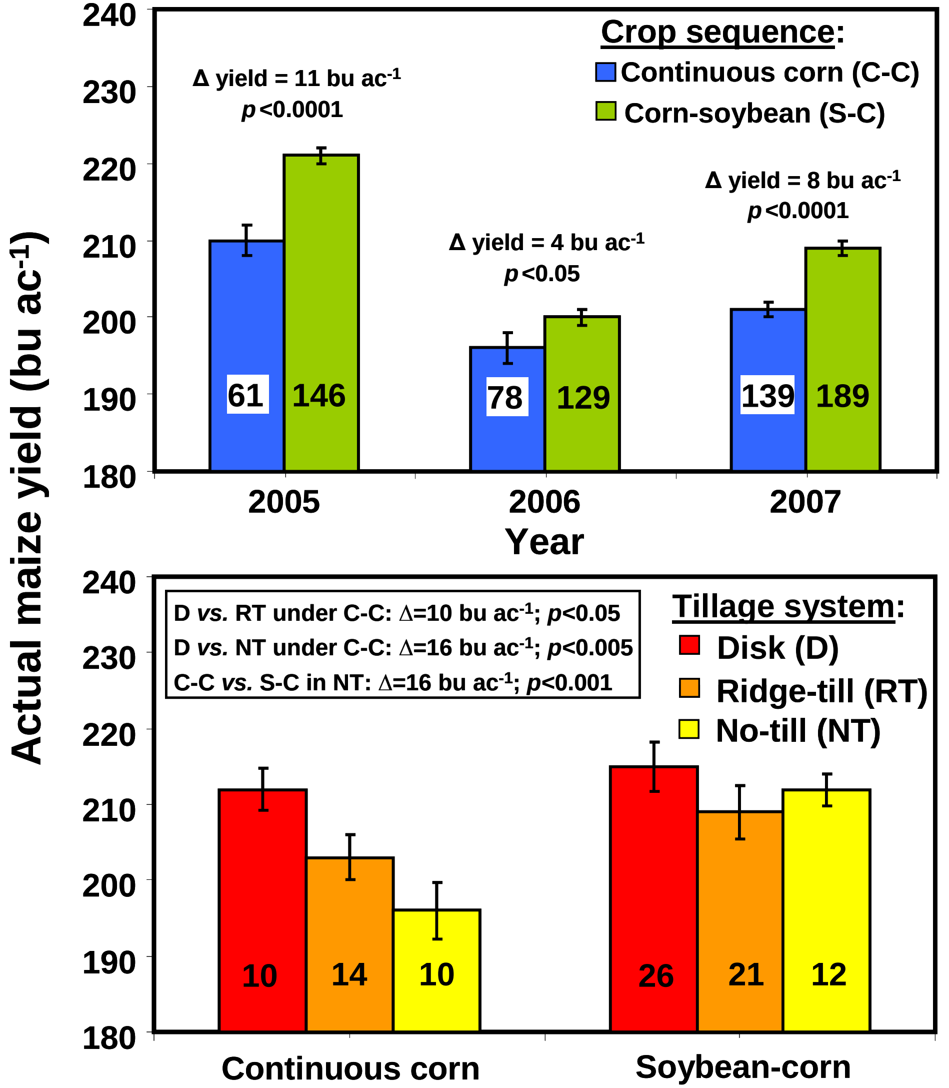


Modified from Grassini *et al.* (2010): *Field Crops Res.*

Planting date and hybrid maturity effects were significant at *p*=0.05 and 0.07, respectively.

Effect of previous crop and tillage

* number of observations is indicated inside bars; ** vertical bars indicate ±SE of the mean; *** in the second figure, data were pooled across years. Selected t-test comparisons are shown.



Yield advantage of soybean/corn rotation over continuous corn was consistent across years, but..,,,,,,,,,,,,

Large yield advantage in cont. corn but little benefit when corn follows soybean (Tillage x previous crop interaction significant)

Grassini *et al.* (2011): *Field Crops Res.*

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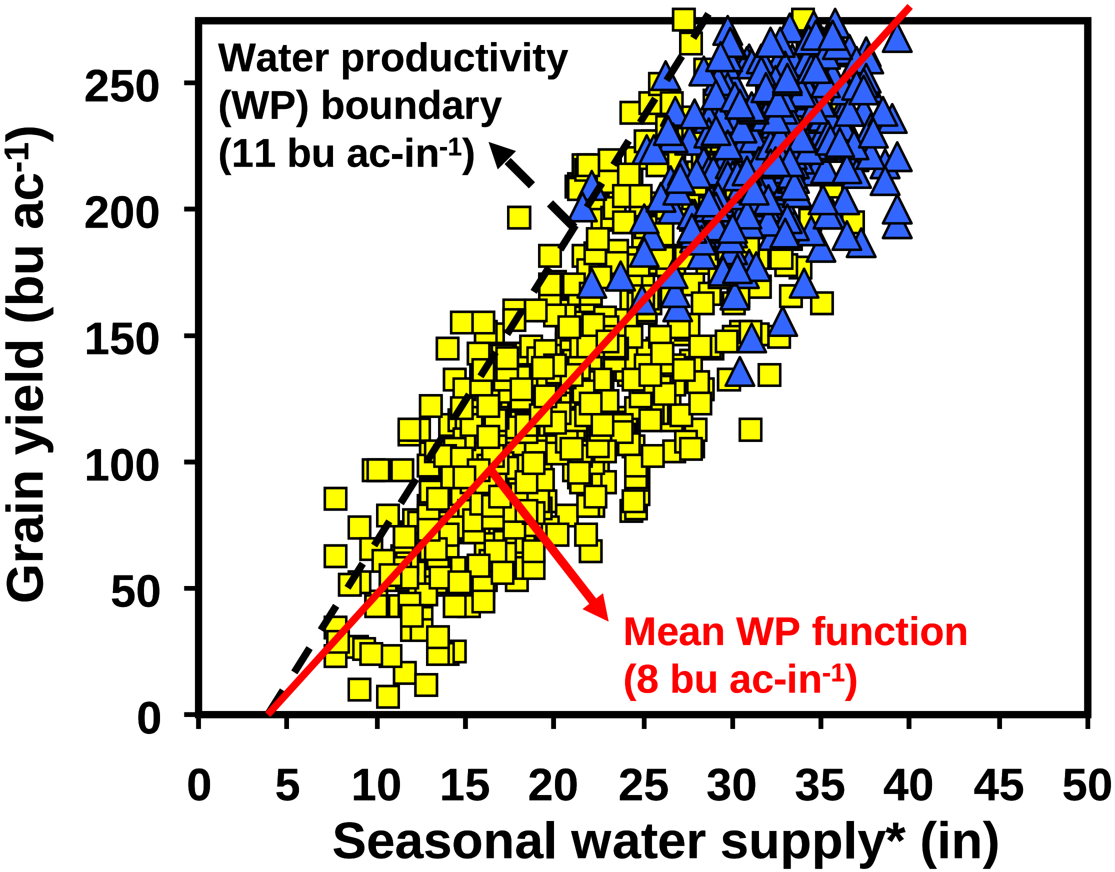
Simulated corn yield / water supply relationship



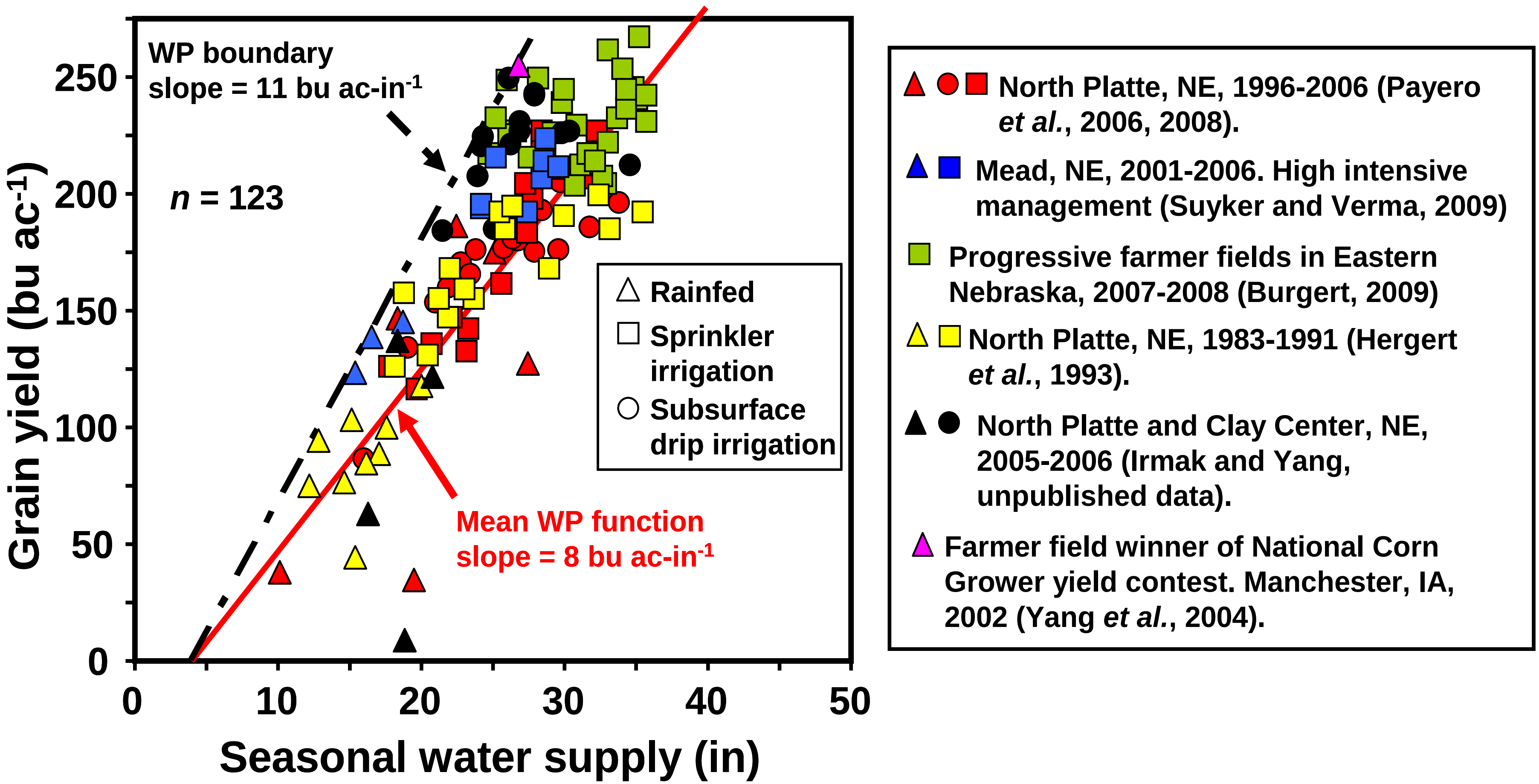
Yields were simulated over 20-y for 18 locations in the Western Corn-Belt using Hybrid-Maize model (Yang et al., 2004). Crops assumed to grow under optimal conditions (no nutrient deficiencies and no incidence of pests, diseases, and weeds). Model inputs based on actual sowing date, plant population, weather data, and soil properties for each of the 18 locations.

***Available soil water (0-5 ft) at planting + planting-to-maturity rainfall + applied irrigation**

Grassini *et al.* (2011): *Field Crops Res.*

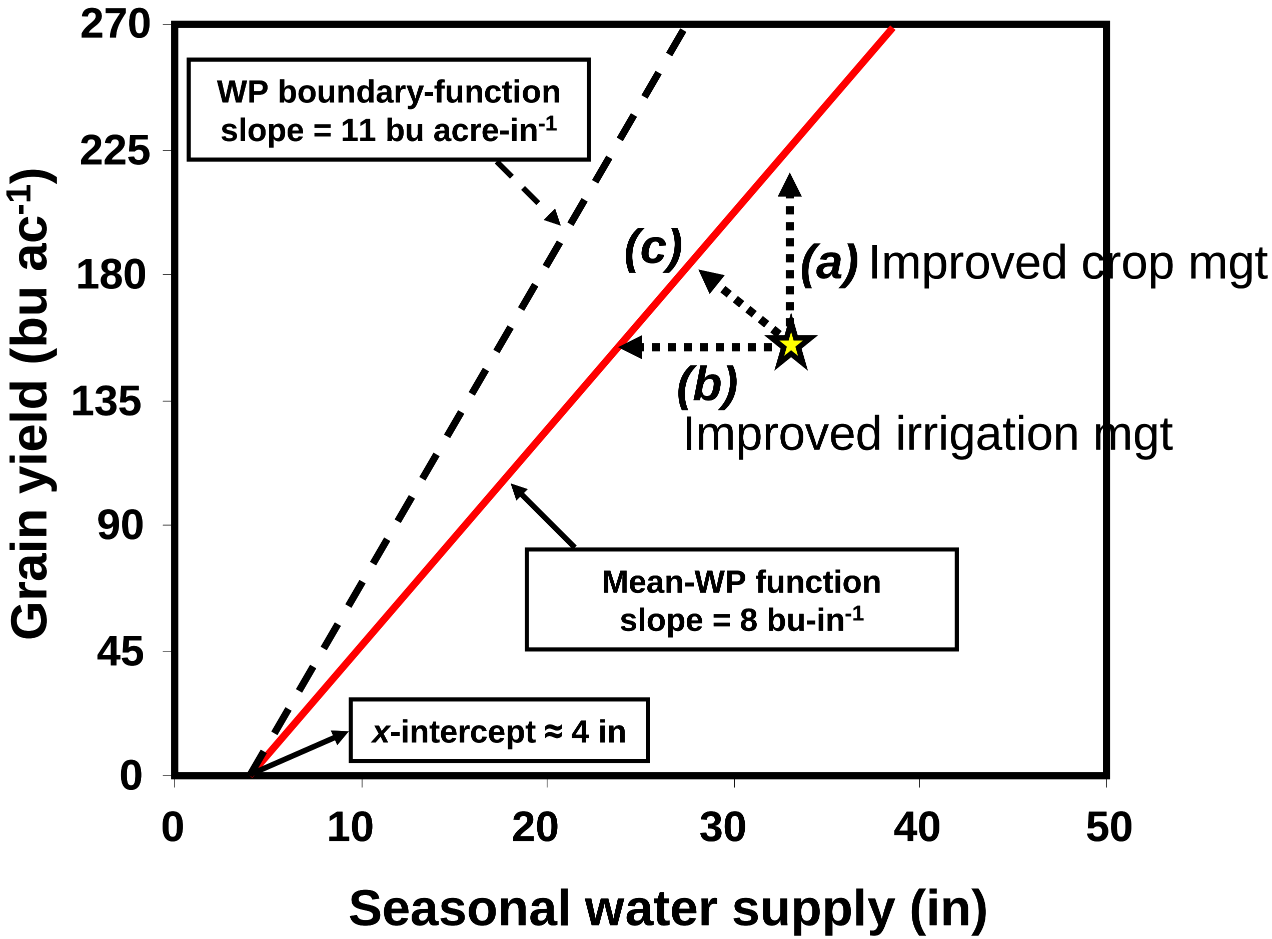
Reported grain yield** / water supply data collected in the Western Corn-Belt by UNL researchers

** Crop grown under near-optimal management practices



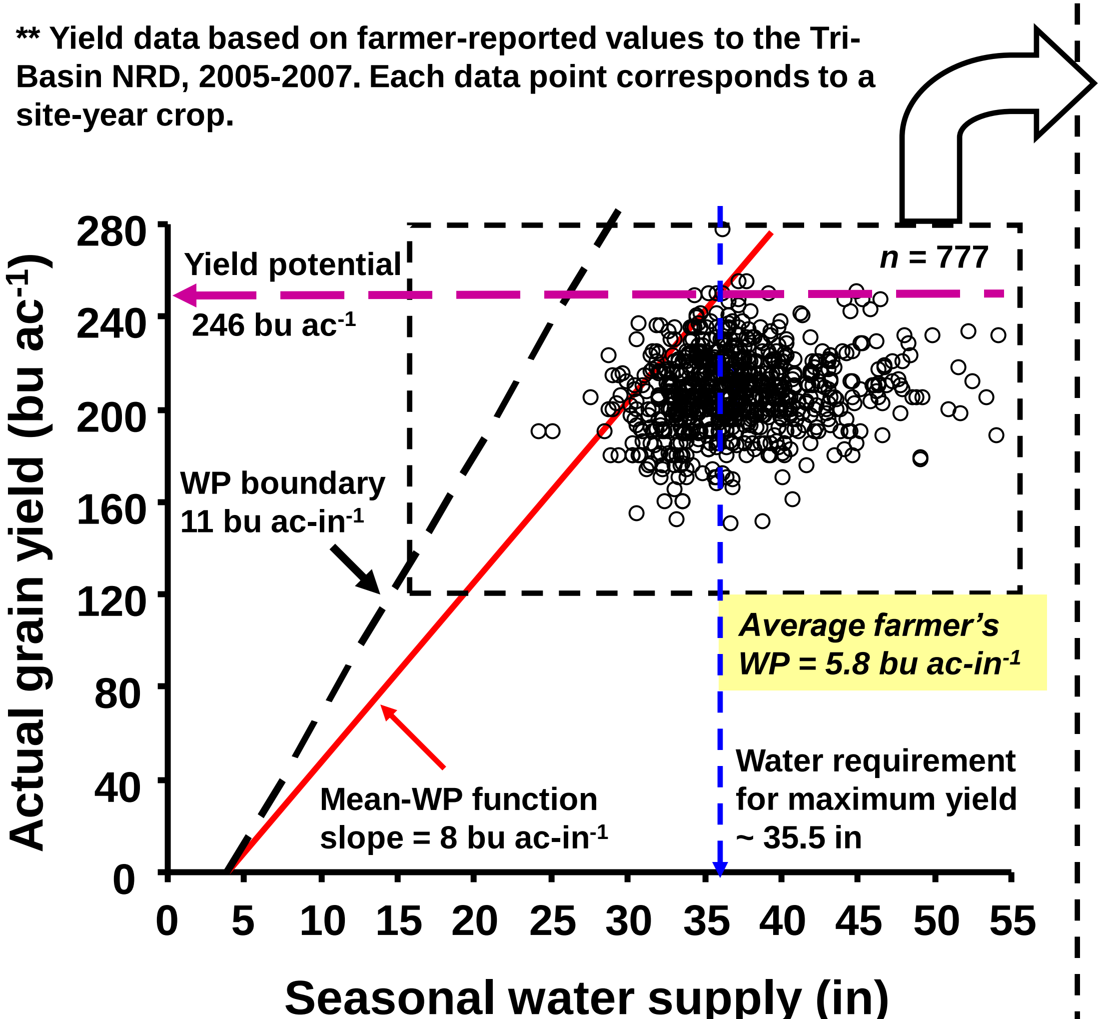
Grassini *et al.* (2011): *Field Crops Res.*

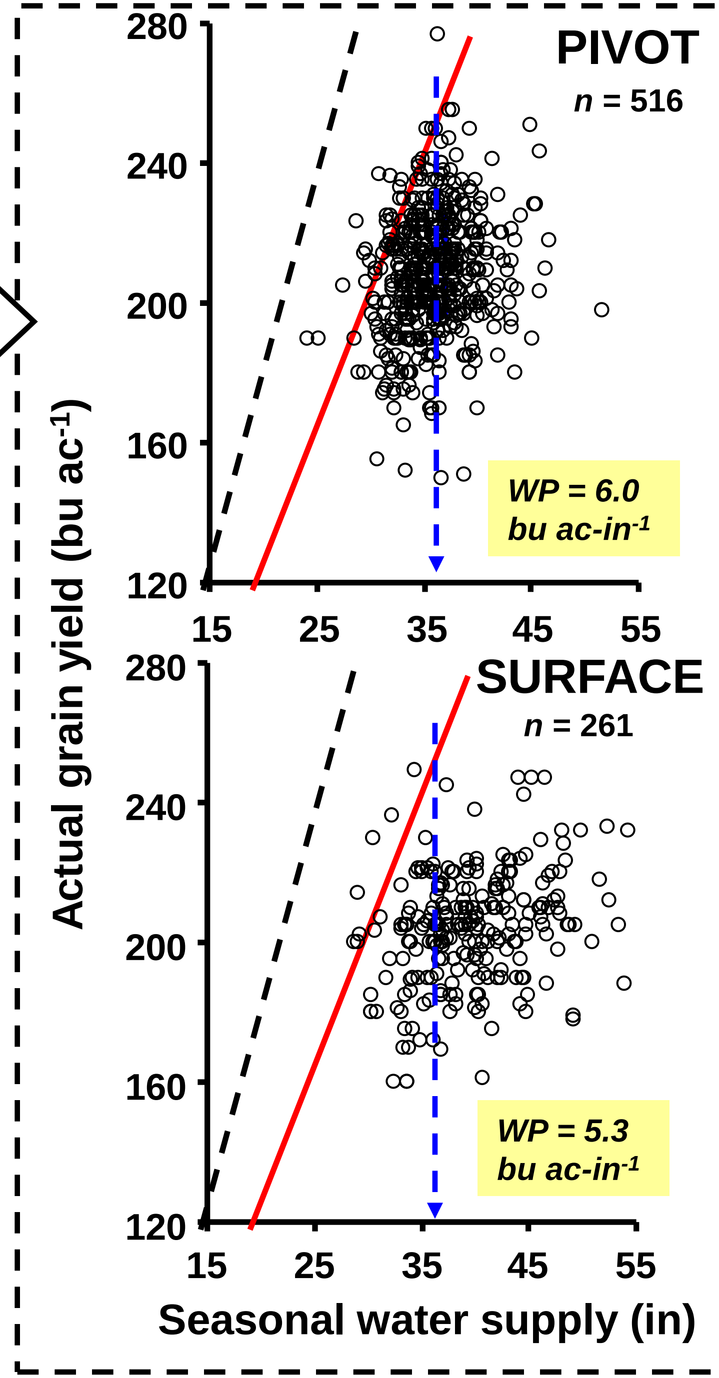
Analytical framework to benchmark and analyze water productivity in farmers' fields



On-farm water productivity at the Tri-Basin NRD

** Yield data based on farmer-reported values to the Tri-Basin NRD, 2005-2007. Each data point corresponds to a site-year crop.





Grassini *et al.* (2010): *Field Crops Res.*

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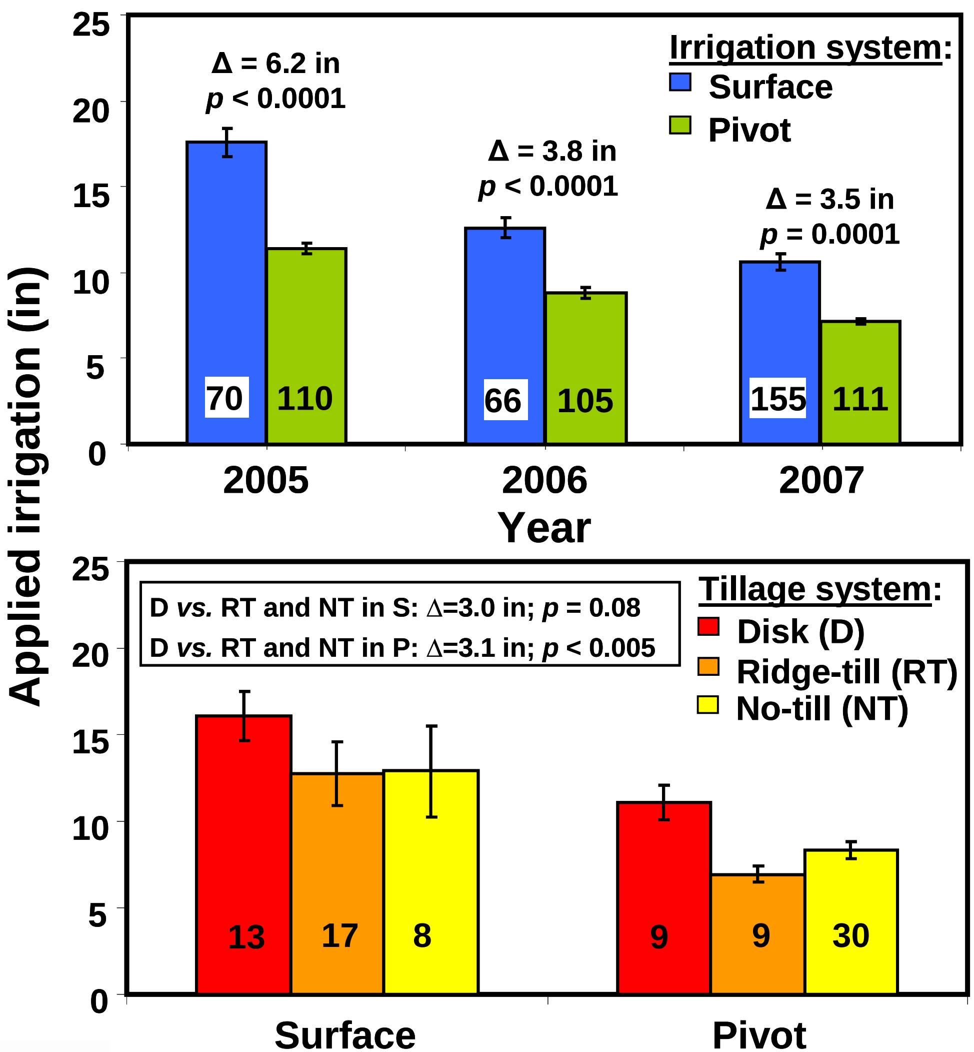
Effect of irrigation system and tillage

*** number of observations is indicated inside bars; ** vertical bars indicate ±SE of the mean; *** in the second figure, data were pooled across years. Selected t-test comparisons are shown.**



Applied irrigation was higher (-4.5”) in gravity than in pivot systems in all years No yield difference!

Applied irrigation under ridge- and no-till was lower than under disk (-3.0”)

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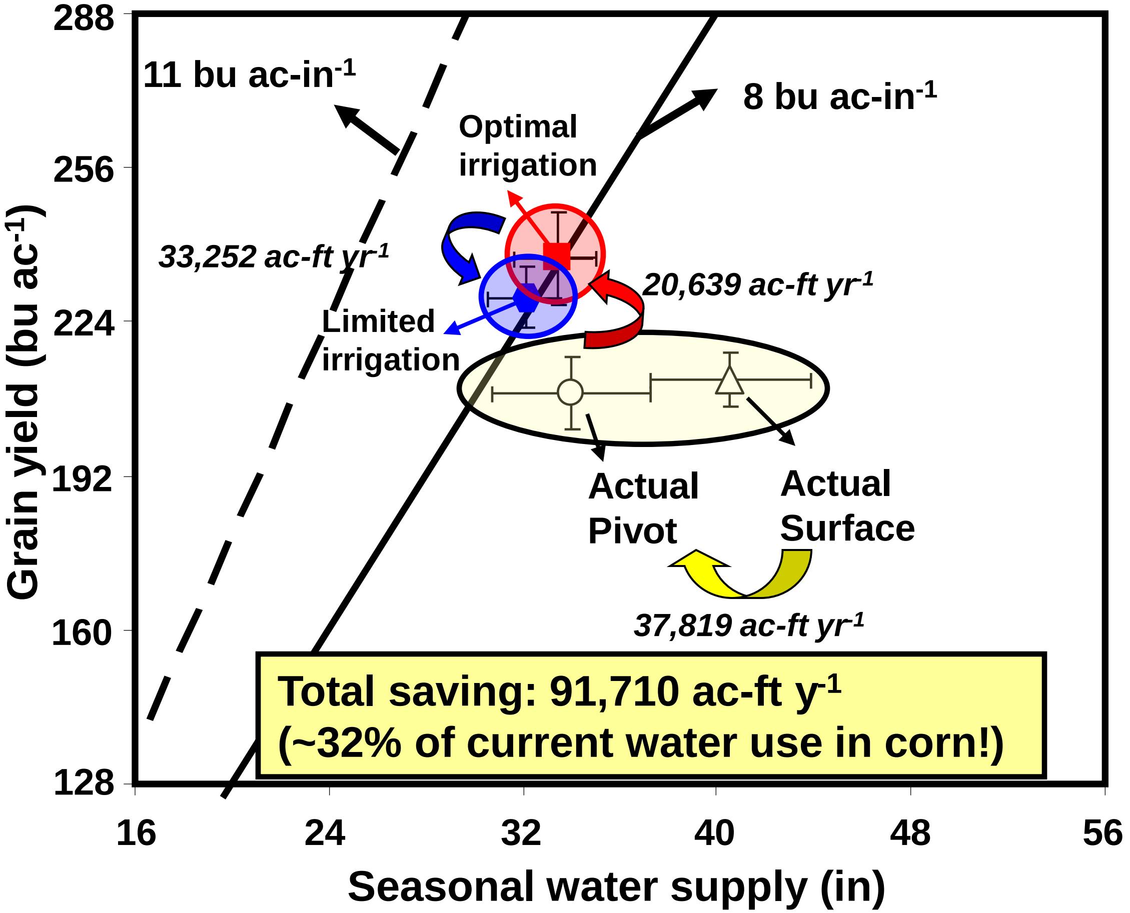
Modified from Grassini *et al.* (2011): *Field Crops Res.*

Water, Energy and Agriculture Initiative WEAI

Opportunities to increase WP and save irrigation water through optimization of the irrigation management

Each point is the average of 3 years (2005-2007); circles indicate the approximate distribution of each category. Vertical and horizontal bars indicate ± SD of the mean.



Reported yield and actual water supply under pivot (○) and gravity (Δ) irrigation systems.

■ Simulated yield under fully-irrigated conditions (irrigation based on ET_O and phenology)

● Simulated yield under limited-irrigation management (75% of fully-irrigation except during the interval around silking when the crop was fully-irrigated)

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Modified from Grassini *et al.* (2011): *Field Crops Res.*

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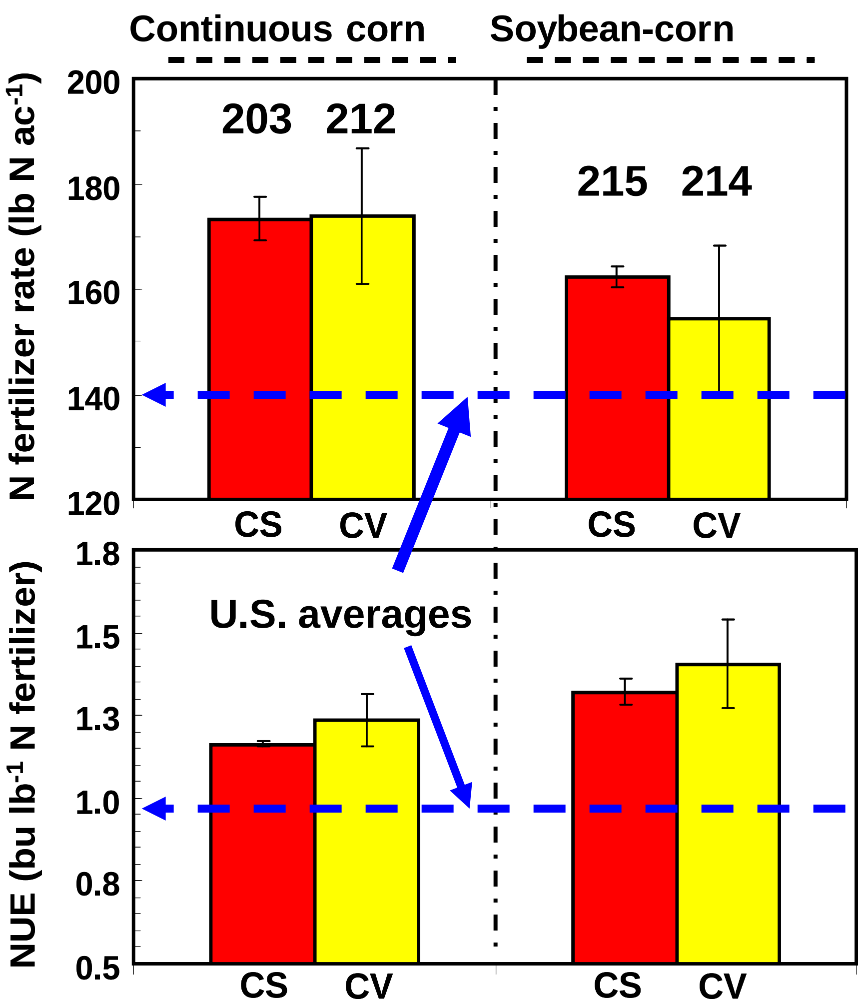
Corn yield, rate of N fertilizer, and nitrogen use efficiency (NUE)*

***** Based on management data collected from 123 fields in the Tri-Basin NRD during 2005-2007 seasons. Values above bars indicate average corn grain yield (bu ac^{-1}) for each rotation x tillage combination***



Tillage system:

- Conservation (CS): strip-, ridge-, and no-till
- Conventional (CT): disk

- **Although N rate is above U.S. average, yields and NUE are higher especially under soybean-corn rotation due to higher yields and lower N rate than continuous corn.**
- **No difference in N fertilizer rate under continuous corn with CS or CV tillage; under soybean-corn rotation, N fertilizer tended to be higher under CS than CV.**
- **NUE tended to be higher under conventional tillage due to (i) higher yields at the same N rate under continuous corn and (ii) same yield with lower N rate under soybean-corn rotation.**

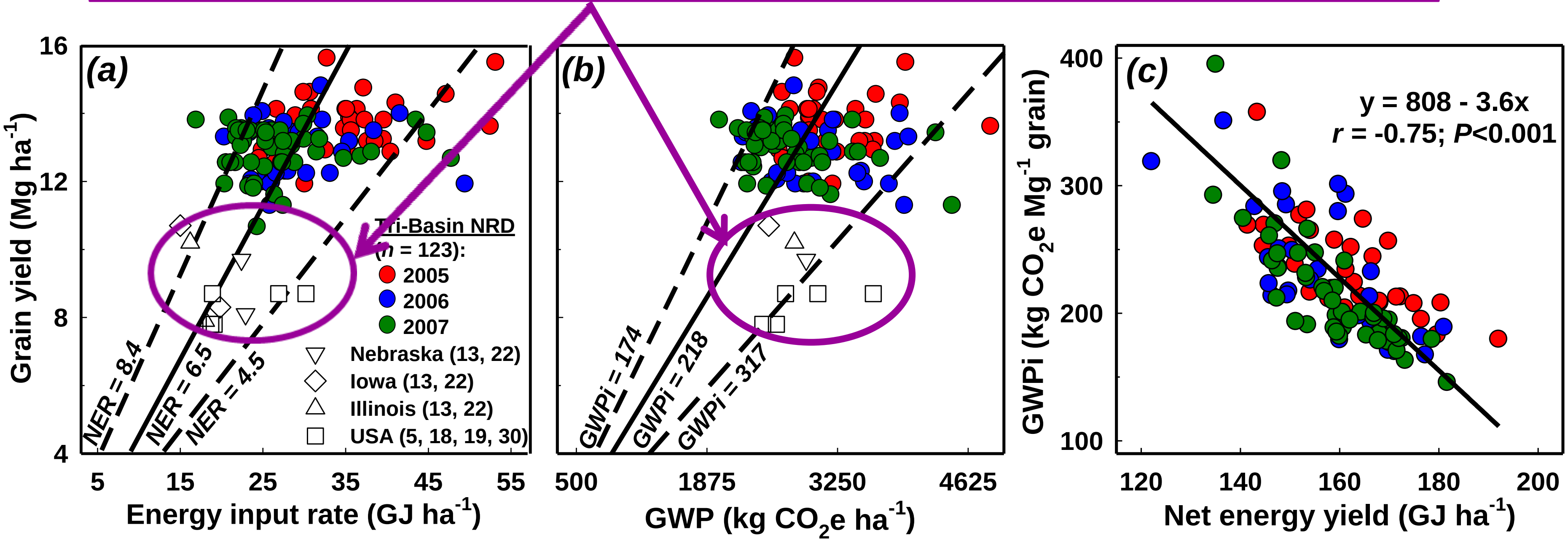
Modified from Grassini *et al.* (2010): *Field Crops Res.*

High-yield maize with large net energy yield and small global warming intensity

Patricio Grassini and Kenneth G. Cassman, Univ. of Nebraska

Proceedings of the National Academy of Science (Jan. 2012)

Estimates from previous studies mostly on rainfed corn production



Take home from Environmental Assessment of Irrigated Corn in Nebraska

- **Although NE irrigated corn high levels of N fertilizer, water, and energy input, compared to rainfed corn it has:**
  - **Greater N fertilizer efficiency**
  - **Greater net energy yield**
  - **Smaller global warming potential intensity**
- **Good news for modern, science-based agriculture**
  - **Goals of high yield, high input efficiency, large energy yield, and minimal GHG emissions are complementary**
  - **Significant potential to further improve environmental performance of high-yield systems**

Conclusions

- **Conventional agriculture is continually behind the curve and on the defensive in relation to environmental concerns and standards**
  - **Agenda and metrics are established by those who know little about agriculture or care about its fate**
  - **"Crisis mode " in response to bad science, but negative perceptions never seem to be overturned**
  - **Increased monitoring of environmental performance is going to happen, driven by the food industry and public perceptions about impact of agriculture on the environment**
  - **Ironically, high-yield, science-based agriculture is actually quite good and getting better in terms of fertilizer, water, energy efficiency, and CC mitigation**
- **There is a tremendous opportunity to set the environmental agenda if fertilizer, seed, and ag equipment companies provide leadership**

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