Soil Ecosystem Services in Agricultural Systems Viewed Through a Provisioning Lens

Kenneth G. Cassman
Robert B. Daugherty  Professor of Agronomy
University of Nebraska—Lincoln

www.yieldgap.org
Backcasting Global Food Security

• What are the driving variables that will determine potential to achieve a food secure world in 2050 under a changing climate?
  • Slowing population growth to zero (9.5 billion plateau) by mid-century, then gradual decline
  • Rate of economic growth and impact on diets and energy use
  • Rate of increase in crop yields on existing crop land
  • Land-use change, especially the expansion of agriculture into carbon-rich and bio-diverse natural ecosystems
VIRTUOUS CYCLE OR SPIRAL OF DEGRADATION?
(per capita income of \(~\$5,000/yr\) required for zero population growth)
Research Priorities in Different Worlds

• World of plenty (the prevalent view in 2001)
  – Too much food, low commodity prices, reduced poverty and malnutrition
  – Focus on alternative uses of grain (ethanol, bio-plastics, higher end-use value.....) and policies that reduce crop production (land set-asides, multifunctional landscapes, organic agriculture......)

• World of scarcity
  – Too little food, high commodity prices, increased poverty and malnutrition
  – Increased yield and yield potential, ecological intensification, yield gap analysis.....

Estimating Future Food Demand

- Econometric models
  - Global computational equilibrium (partial equilibrium) models, such as IMPACT, GTAP
  - Based on assumptions about population and income growth rates, available land area suitable for cultivation, trajectories in crop yields (assumptions about investment in research and translation to yield)

- How do food demand estimates compare with reality since 2001?
  - UNDERESTIMATED BY A LARGE MARGIN
    - Projected economic growth rates in world’s most populous developing countries (e.g. China, India, Indonesia, Brazil, Russia, etc) were far too low
    - Overestimated crop yield growth rates and did not account for biophysical yield limits

Estimates of Future Food Supply

- Econometric models (previous slide)
- Biophysical estimates
  - Based on rough estimates of available land, water, and simulated crop yield potential, assuming global “optimal use and management” and generic crop simulation models
- How do food supply estimates compare with reality since 2001?
  
  OVERESTIMATED BY A LARGE MARGIN
  - Competition for land and water not accounted for
  - Land suitability for high-yield production not realistic

Historic versus projected U.S. maize yield trends

- Actual yield trends are decidedly linear
- Econometric models have primarily used exponential yield growth rates
- When linear rates have been used, they continue indefinitely without slowing


**SOLID LINE:**
linear regression (1965-2011)

\[ y = -220114 + 114 \times \]

\[ r^2 = 0.87 \ (P<0.01) \]
Global Cereal Yield Trends, 1965-2011
(tyranny of linear growth rates)

**Maize yield**
- slope = 65 kg ha\(^{-1}\) y\(^{-1}\)

**Rice yield**
- slope = 52 kg ha\(^{-1}\) y\(^{-1}\)

**Wheat yield**
- slope = 40 kg ha\(^{-1}\) y\(^{-1}\)

1965:
- maize: 2.8%
- rice: 2.9%
- wheat: 2.9%

2011:
- maize: 1.3%
- rice: 1.2%
- wheat: 1.4%

Source: FAOSTAT
Stagnating yields for RICE in Korea, Japan, and China; WHEAT in northwest Europe and India; MAIZE in China, and IRRIGATED MAIZE in the USA.

Cassman, 1999. PNAS, 96: 5952-5959

Grassini et al., 2011. FCR 120:142-152

Cassman et al., 2003, ARER 28: 315-358

Cassman et al., 2010, Handbook of Climate Change
Robust, statistical analysis of crop yield trends

Rice yield trends in selected countries

Wheat yield trends in selected countries

Maize yield trends in selected countries

Global analysis of crop yield trends

- Since 1965, yield trends of major cereal crops best-fit linear increase models in all countries
- No evidence of exponential rate of gain
- 31% of total global production of major cereal crops comes from countries in which rate of yield increase has markedly decreased or stagnated
- Rate of return on yield-enhancing research has fallen by 75% since 1965

Under the radar: 22nd Century “Agricultural Bomb”

Staple-crop area includes cereals, oilseed, pulses, sugar, root, fiber, and tuber crops.

Source: FAOSTAT
Brave New World Since 2005

• Rapid, sustained economic growth in most populous developing countries
• Rapid rise in energy demand and petroleum prices
• Convergence of energy and agriculture
• Smaller supply, relative to demand, of staple food crops; increased price volatility
• Slowing progress in reducing poverty and malnutrition
• Limited supplies of good quality arable land and fresh water to support high-yield agriculture
• Stagnating yields in some of the most productive cropping systems (no biotech panaceas)
• Increasing concerns about environment and climate change

• These are likely to be LONG-TERM MEGATRENDS, which means we are in a race against time to achieve global food security
The Challenge is Clear: Race against time

• 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” (also called “sustainable” intensification)
The Challenge is Clear: Race against time

• Increase food supply +70% (cereals +60%) on existing crop and pasture land

• What about reducing post-harvest losses and waste, or changing human diets?
  – Chris Barrett, Ag Economist, Cornell Univ.: Reducing food waste and changing diets to reduce food demand are ASPIRATIONS not components of a viable food security strategy

• Clear food supply target is essential to inform policies and to effectively focus investments in agricultural research and development, climate change, and land use
Issues Viewed Through a Food Security Lens

- Answers to questions about how future agriculture should look, and policies to get there, depend on scale at which the question is asked: local versus regional, national or global food security
  - Organic agriculture vs conventional
  - GMOs (recombinant DNA technology)
  - “Localvore” vs liberalized global trade
  - Cropping system diversity in terms of crop species and crop germplasm
  - Large-scale confined feeding livestock operations versus grassfed grazing systems
Staple-crop area includes cereals, oilseed, pulses, sugar, root, fiber, and tuber crops.

Source: FAOSTAT

Year

Crop harvested area (Mha)

Staple crops area

1965-1982
slope = 1.6 Mha y⁻¹

1982-2002
slope = 9.8 Mha y⁻¹

2002-2011
slope = 3.9 Mha y⁻¹

Rice + wheat + maize area

1965-1980
slope = 5.3 Mha y⁻¹

1982-2002
slope = 5.9 Mha y⁻¹

2003-2011
slope = 3.9 Mha y⁻¹

82% due to M, R, W, Soy

Under the radar: 22nd Century “Agricultural Bomb”
Ecosystem services that soils can provide

- **Provisioning of food**
  - Physical matrix for plant support and to absorb and supply water
  - Nutrient supply and buffering
  - Suppressive to diseases and insect pests
- **Conservation of water quality and filtering of pollutants**
- **Flood control**
- **Mitigation of climate change**
- **Habitat for bio-diversity, which influences biodiversity of terrestrial plant communities supported by soil**
Why research on soil environmental services?

- Basic research
  - For its own sake
  - As component of natural ecosystems
- Mission-oriented applied research
  - Component of restoration ecology (remediation, reconstitution, renewal)
  - To guide land-use decisions
    - To improve performance of agricultural systems (ecological intensification for global food security)
Research on soil ecosystem services (ES) that support the quest for ecological intensification

• Provides an opportunity to move beyond “descriptive” to “functional” soil biology/ecology, where the function is to support substantially higher yields while also reducing yield variability and improving other ecosystem services

• Key questions
  – Which soil properties support increased yields and yield stability?
  – What are the critical thresholds for these properties?
  – Of these, which also provide other beneficial ecosystem services? Thresholds for these?
Research on soil ecosystem services (ES) that support the quest for ecological intensification

• Key hypothesis
  Soil properties that support increased yields and yield stability also provide other beneficial ecosystem services

• Converse, are there biological, chemical, or physical soil properties that, if improved for crop production, do not also contribute to biodiversity, climate change mitigation/adaptation, flood control, water quality, etc.?
Long-term field experiment with wheat, Pendleton, Oregon: 1932-1966

Soils of California’s San Joaquin Valley:
Sedimentary origin on west side and granitic origin on east side
Severe potassium deficiency on cotton
Biotite mica

\[ \text{Clay < } 2 \times 10^{-6} \text{ m} \]

\[ \text{Silt } 2 - 20 \times 10^{-6} \text{ m} \]

Vermiculite

Hydrous mica

Hydrobiotite
SOIL K POOLS

20,000

K IN UNWEATHERED MINERALS
[MICAS, FELDSPARS]

2,000

SLOWLY AVAILABLE K⁺
[FIXED IN SECONDARY MINERALS]

200

AVAILABLE K⁺
[EXCHANGEABLE ON CLAY SURFACES]

<5

SOIL SOLUTION K⁺
SEED COTTON YIELD (lb/ac)

WATER SOLUBLE K, 0-16 in (ppm K)

- 'GC510' (●)
  \[ y = 3250(1 - 1.67e^{-2.25x}) \]
  \[ r^2 = 0.73 \]

- 'SJ2' (○)
  \[ y = 3450(1 - 1.24e^{-1.21x}) \]
  \[ r^2 = 0.67 \]
Influence of mobile humic acids (MHA) on solution-phase and ammonium-extractable K+ in a Grangeville soil after K addition

6-yr on-farm study
• Four levels of applied K fertilizer first 3 yrs, with or without barely cover crop
• Residual K fertilizer benefit measured in next 3 yrs, with and without manure (K input equalized)
Residual K benefit from K fertilizer applications from 1984-1987 in long-term field study on a Grangeville soil in the San Joaquin Valley

\[
(M): \quad Y = -6.6 + 0.98X, \quad r^2 = 0.92 \\
(IF): \quad Y = 6.7 + 0.75X, \quad r^2 = 0.87
\]
Ecosystem services “Counter-intuitivities” in agriculture

• Diversity is essential for stability?
  – Continuous double-crop rice systems in Asia
  – Continuous high-yield maize systems in the USA
  – Wheat-fallow systems worldwide

• High N fertilizer rates and irrigated agriculture are bad for the environment?
  – N uptake efficiency and water productivity higher in many irrigated systems compared to lower-yielding, lower input rainfed systems

• Organic matter is a good proxy for soil quality
  – Not for irrigated lowland rice systems in Asia
Contest-winning maize field in SE Nebraska that produced 18.5 t/ha grain. Management included:

- Continuous maize under rainfed conditions (18.5 t residue/ha-yr returned to soil)
- Higher than average plant population and N fertilizer rate, but NUE was much higher than US average
- Early planting, longer-maturing hybrid
Contest-winning maize field in Iowa, 1997. Yield = 18 t/ha
Contest-winning farmers appear to create a large volume of high quality soil, which provides a conducive environment for root growth, extension, and function:

- Nutrient supply
- Water holding capacity
- Disease and insect pest suppressive
- Beneficial microbes?

But, we have poor knowledge of critical thresholds for these factors
Soil in contest winning maize field in Iowa, 1997

Do such soils also provide other environmental services?
On-farm analysis: maize fields in the Tri-Basin NRD

--- FARMER REPORTED DATA
--- 3 years of data (2005, 2006, and 2007)
--- 777 field-year data identified with 100% irrigated maize

13 August 2013
N Fertilizer Efficiency Conf
Grain yield, energy yield and efficiency, and greenhouse gas (GHG) emissions from maize production in Nebraska

<table>
<thead>
<tr>
<th>Crop-system variable</th>
<th>Rainfed</th>
<th>Irrigated</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain yield (t ha(^{-1}))</td>
<td>5.9 (CV = 23%)</td>
<td>13.2 (CV = 3%)</td>
<td>+124%</td>
</tr>
<tr>
<td>Energy input (GJ ha(^{-1}))</td>
<td>10.8</td>
<td>30.0</td>
<td>+178%</td>
</tr>
<tr>
<td>Net energy yield (grain energy minus fossil-fuel energy)</td>
<td>74</td>
<td>159</td>
<td>+115%</td>
</tr>
<tr>
<td>N fertilizer efficiency (kg grain kg(^{-1}) N)</td>
<td>54</td>
<td>71</td>
<td>+32</td>
</tr>
<tr>
<td>Water productivity (kg ha(^{-1})mm(^{-1}))</td>
<td>8.8</td>
<td>14.0</td>
<td>+59</td>
</tr>
<tr>
<td>GHG intensity (kg CO(_2)e t(^{-1}))(^{\dagger})</td>
<td>388</td>
<td>231</td>
<td>-40%</td>
</tr>
</tbody>
</table>

\(^{\dagger}\) Relative to rainfed maize values. Based on data from 2005-2007.

\(^{\dagger}\) Includes emissions of CO\(_2\), N\(_2\)O, and CH\(_4\) adjusted for CO\(_2\) warming equivalent. N\(_2\)O estimated by the N-surplus method of Van Groenigen et al. (2010).

\(^{\dagger}\) GHG emissions per metric ton of grain production
Take home from Environmental Assessment of Irrigated Corn in Nebraska

• Compared to rainfed corn, NE irrigated corn receives much larger inputs of N fertilizer, water, and energy, but irrigated corn has:
  – Greater N fertilizer and water use 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
Raison d’etre for soil ES research in agriculture

- Benchmarks
- Thresholds
- Metrics (transparent, robust, reproducible, low-cost, scientifically defendable)
  - Requires simplification on the far side of complexity
  - Requires good science and appropriate context for the system in question
  - In many cases, establishing thresholds requires tradeoffs between productivity and ES
What are most appropriate metrics for quantifying progress towards EI?

- N use efficiency versus N productivity (also called partial factor productivity)
- Water use efficiency vs water productivity
- GHG emissions per acre or GHG emissions intensity
- Soil quality (yield without applied nutrients)

Why benchmark and monitor performance?

- To get higher prices for environmental performance
- To quantify impact from improved management
- To comply with regulations
Summary and Conclusions

- It will be impossible to achieve global food security without an improvement in soil quality as related to soil’s provisioning function.
- Improving production-enhancing soil properties is likely to also enhance capacity to provide other ecosystem services.
- Lack of quantitative understanding of relationships between key soil properties and crop performance in terms of yield, nutrient and water input requirements, and pest protection costs makes it difficult to estimate costs and benefits from management practices that improve soil quality.
- We need thresholds, metrics, and monitoring of soil properties governing ES within food security context.