Ecological Intensification of Maize-Based Cropping Systems

By Kenneth G. Cassman

Ecological intensification (EI) is the process of improving both yields and environmental performance of crop production with a focus on precise management of all production factors and maintenance or improvement of soil quality.

Innovation and adoption of EI practices will be facilitated by use of "big data" that farmers themselves generate, coupled with a robust spatial framework to identify cohort fields that respond similarly to these innovations.

Maize and soybean research plots at IPNI Global Maize Project site in Mato Grosso, Brazil.

The terms ecological intensification (EI) and sustainable intensification (SI) were first coined in the late 1990s (Cassman et al., 1999; Pretty, 1997). A unifying objective supporting each of these concepts is the need to increase crop yields per unit land, time, and consumable resources used in food production. Whereas EI was originally seen as essential to achieve the dual goals of meeting projected food demand on existing farm land while minimizing negative impacts on environmental quality and conserving natural resources, SI was originally concerned mostly with "regenerative", low input agricultural options as the means to reduce negative impacts of agriculture on ecosystem services. Since then, general understanding of SI has come closer to that of EI in terms of the underpinning objective of producing enough food to supply a climax human population of 9.5 to 11 billion people without degrading the environment or exhausting the natural resource base upon which agriculture depends. The primary difference between the two is that SI includes economic and social dimensions of sustainability whereas EI focuses on biophysical aspects.

Why is Ecological Intensification Important for Maize Systems?

Ecological intensification is especially relevant for addressing global concerns about conservation of biodiversity and mitigating climate change because conversion of natural ecosystems to farmland has devastating impact on both (Burney et al., 2010; Laurance et al., 2014). For example, since 2002 crop production area has been increasing at the fastest pace in all of human history in response to rapid growth in demand for livestock products, grain, and oilseed crops. During the 2002 to 2014 period, harvested crop area increased by more than 13 million (M) ha annually (32 M Ac/yr), and increased production of maize and soybean accounted for 52% of this total (**Figure 1**). Because projected demand for maize and soybean in coming decades is not expected to slow, the explicit goal of accelerating yield gains in maize and soybean on existing farmland is an essential component of efforts towards wildlife conservation and climate change mitigation.

But if accelerating yield gains leads to amplification of negative environmental impact, beyond current levels that already are of concern, the path to food security is not sustainable. Therefore, progress towards EI requires simultaneous improvements in *both* yields and environmental performance. In most cases the productivity and environmental dimensions cannot be investigated separately because few "trade-off free" options exist. There are many management options that can increase crop yields while also resulting in greater negative environmental impact, and many that can reduce environmental impact with a yield penalty. For example, converting from

Abbreviations and notes: N = nitrogen.

conventional tillage to no-till often results in substantial reduction in erosion and improved soil quality. In wetter regions of the U.S. Corn Belt, however, no-till makes it more difficult to achieve timely sowing and gives less uniform plant stands that reduce crop yields and decrease yield stability.

How to Achieve Ecological Intensification

The original vision of EI identified three key elements: (1) closing the exploitable yield gap, (2) improving soil quality, and (3) precision agriculture (Cassman, 1999). The *exploitable* yield gap for a given field or region is defined as the difference between the current yield level and 75 to 85% of the yield potential (either rain-fed or irrigated) for that field or region as can be simulated with a well validated crop model (van Ittersum et al., 2013). Variation in the exploitable *ceiling yield* (i.e., 75 to 85% of the yield potential) reflects the degree of risk associated with use of additional inputs needed to move yields up the response curve beyond 75% of the potential yield, and the ratio of commodity price to input costs (Lobell et al., 2009). For crops in which ripening grain is located at the top of the canopy with high center of gravity, such as rice and wheat, applying sufficient N to achieve 85% of yield potential can often result in lodging and reduced grain yields and quality. For these crops, the exploitable ceiling yield may be at the lower end of the 75 to 85% range. In contrast, maize ears are located in the middle of the stalk and have relatively low center of gravity, which means less susceptibility to lodging and the exploitable yield ceiling is likely closer to 85% as suggested by a recent study based on famer-reported data (Grassini et al., 2011a). Other risks typically associated with management that seeks to push yields to the high end of the exploitable ceiling yield range include greater disease and insect pressure that occurs in lush canopies.

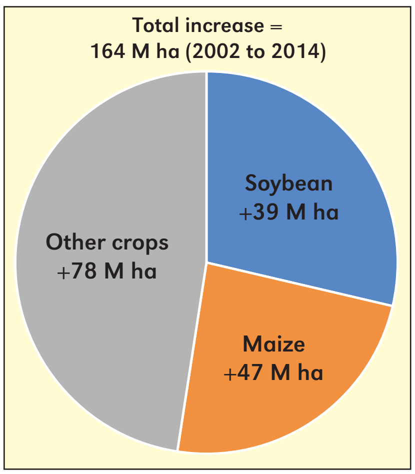

Figure 1. Global increase in harvested staple food crop area from 2002 to 2014, including cereals, oilseed, pulses, root, and tuber crops in million hectares (M ha). Source: FAOSTAT http://www.fao.org/faostat/en/#data/QC

Improving soil quality is the second cornerstone of ecological intensification. For this purpose, soil quality is defined by those soil properties that have greatest impact on crop yields and input use efficiencies. These include soil chemical properties that determine nutrient supply capacity, stimulate or constrain root growth and plant health; biological properties that govern microbial and faunal populations that decompose crop residues and organic matter to release N, P, and S, suppress pathogens and insect pests, fix atmospheric N_2, and symbionts that help acquire P and other nutrients; physical properties that govern aeration, water infiltration rate and storage capacity, root extension, and rooting depth.

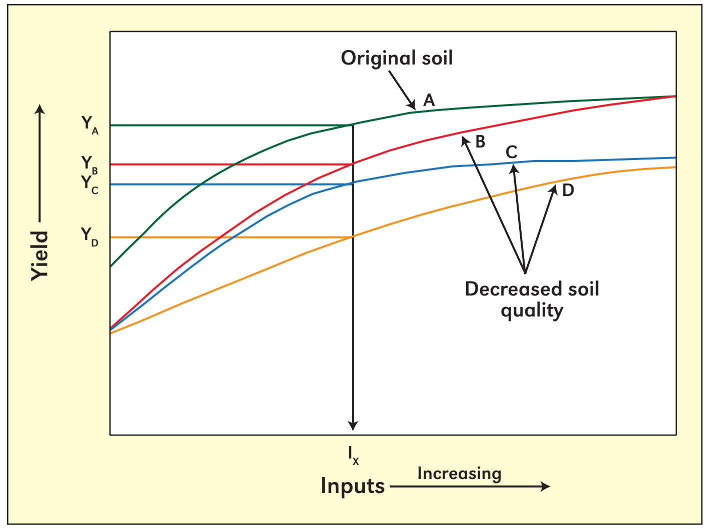

Figure 2. Conceptual framework illustrating the relationship between crop yields and input requirements as influenced by soil quality. A decrease in soil quality from an initial state (curve A) can result in the need for greater inputs of energy, nutrients, water, seed, and pest control measures to achieve the same yield. The slope and asymptote of the shifted response (shown by curves B, C, and D) depend on the type of soil degradation and result in reduced input use efficiency, yield potential, or both. (Cassman, 1999).

An underpinning assumption is that a change in soil quality affects the relationship between yield and input requirements (**Figure 2**). A reduction in soil quality means that increased external inputs are needed to overcome this degradation. Conversely, an increase in soil quality reduces input requirements and thus increases input use efficiency. For example, a management system that leads to an increase in soil organic matter can also bring greater N supply from mineralization and a smaller requirement for applied N, thus increasing the yield per unit of applied N. Likewise, a reduction in soil organic matter can lead to greater requirements for applied N per unit of yield.

Precision agriculture, in a broad sense, is the third cornerstone. In large commercial production fields, it involves variable-rate, or zone management of inputs such as seed, fertilizer, lime, irrigation, and pesticides. In small fields typical of crop production in many developing countries of Africa and Asia, it involves field-specific management with a focus on precise timing and quantities of applied inputs on a field by field basis rather than by routine, blanket recommendations across a district or county.

Metrics for Measuring Progress Towards Ecological Intensification

The conceptual framework of **Figure 2** leads to a focus on yield and input use efficiencies as the basis for monitoring progress towards EI. Thus, for any point in time, the goal is to move average yields up while also improving the ratio of outputs to inputs for nutrients, water, and energy. Some have criticized this focus as being too narrow for two reasons. The first argues that a focus on yield and output/input ratios does not give enough emphasis to the "*ecological*" dimensions of EI with the goal of better leveraging internal resources, as opposed to use of purchased inputs of external origin, through attention to management of microbial, floral, or faunal components of the agroecosystem. At the end of the day, however, such systems must also be shown to result in higher yields and greater input use efficiency or they would not meet the definition of EI. *Indeed, EI is agnostic with regard to farming methods and approaches to achieve the dual goals of increasing yields while decreasing negative environmental impact so long as the approach is also economically viable and socially acceptable.*

A second concern with the conceptual framework of **Figure 2** is that a focus on soil properties influencing crop performance is too myopic and ignores other important ecosystem services that soils provide, such as: (1) habitat for an enormous host of biota including bacteria, fungi, protozoa, nematodes, worms, insects, arachnids, and such, (2) water storage to capture rainfall and reduce runoff and flooding, (3) pollutant filtering and detoxification to protect water quality, and (4) regulation of atmospheric composition through release, capture, or retention of carbon dioxide, methane, and nitrous oxides—each a powerful greenhouse gas. However, it is difficult to conceive of a soil property, that if improved for its capacity to contribute to higher yield and input use efficiency, would not also maintain or improve each of these four ecosystem services. Hence a focus on yield and input use efficiencies as the metrics for monitoring progress towards EI is not likely to result in unintentional degradation of the broader array of ecosystem services that soils provide.

The Path Forward

At issue is how to accelerate innovation and adoption of technologies and cropping systems that support EI of maize-based systems. For the high-yield, large-scale, mechanized systems of the U.S., Brazil, and Argentina, the challenge is how to efficiently identify the suite of management practices that perform best under the location-specific conditions of a given field or zone within a field. The number of production factors that must be considered is large, including variety or hybrid, seeding rate, sowing date, tillage method, nutrient quantities-formulation-amounts-placement-timing, weed, insect pest, and disease control measures, use of organic nutrients, lime, and other soil amendments, and crop rotation. The sad fact is that conventional, replicated field experiments are a poor vehicle for evaluating and fine-tuning multiple, interacting factors because of the time and cost requirements of such work. For example, to identify the most appropriate seeding rate, N fertilizer amount and timing, and tillage method for maize in a specific region would require a multi-factor experimental design, with at least four replications of each treatment at each location, and four to six locations over several years. And the results of such a study would be biased by the other management factors selected as the "background" management approach (e.g., sowing date, pest control, variety or hybrid used, crop rotation, and cover crop options).

Given this complexity, there is growing excitement for use of "big data", which includes high spatial resolution data for long-term historical daily climate records coupled with real-time data on current and short-term weather forecasts, yield records and immediate soil and plant status with regard to water and nutrient status, and plant health. To be effective however, big data needs a robust analytical framework to sift through all the noise and identify the driving variables and best combination of practices for a given situation on a particular field.

Unfortunately, to date, I am not aware of successful use of a big data approach to foster EI *at scale*. In contrast, smaller steps towards use of a big data approach show substantial promise. One example from Nebraska used farmer-reported data, from hundreds of pivot-irrigated maize fields, on yield, sowing date, irrigation amount, hybrid maturity, tillage method, crop rotation, and N fertilizer rate to identify the optimal combination of management factors for highest yield, water, and N fertilizer use efficiencies (Grassini et al., 2011a,b).

Also needed is a robust spatial framework for identifying the "*technology extrapolation domain*" (TED) for a given field to facilitate use of results from field studies and farmer-reported data across landscapes with variable soils and climate. A TED is defined as a region in which soil type and climate are of sufficient uniformity that a specific technology, management practice, or cropping system would behave similarly within that zone. The Global Yield Gap Atlas (www.yieldgap.org) has developed such a spatial framework based on the most sensitive variables governing rain-fed crop performance: temperature regime, water balance, and water holding capacity in the rootable soil depth, which is largely determined by soil texture and depth to which roots can grow without physical or chemical impediments (van Wart et al., 2013; Grassini et al., 2017).

By unlocking the power of big data and use of a robust spatial framework to accelerate technology innovation and adoption, I have every confidence it will be possible to meet expected maize demand, and expected demand for other food crops for that matter, without a large expansion of crop production area or degrading environmental quality. But it will require a ruthless focus of research and development investments funded by both the public and private sectors on the dual EI objectives of higher yields and reduction of negative environmental impact. BC

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