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Closing Yield Gaps with GxExM and Precision Agriculture

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Abstract. *There are many challenges to be faced by agriculture if the global population of nine billion people projected for 2050 is to be fed and clothed, especially given the effects of changing climate. A focus on the interactions of genetics x environment x management (GxExM) offers potential for meeting the yield, and environment and economic sustainability goals that are integral to these challenges. The yield gap –defined as the difference between current farmer yields and potential yields offered by advances of genetics and breeding, addresses all factors affecting yields and also when these factors affect yield during the growing season. A fundamental tenet of precision agriculture is that the dominant factors affecting yield gap are different for each growing region, landscape or within-field location and that there are temporal considerations when addressing these factors. Precision agriculture is thus a way to close yield gaps using a GxExM approach. However, understanding and quantifying yield gaps through a GxExM approach requires transdisciplinary teams of agronomists, engineers, soil scientists, geneticists, plant pathologists, entomologists, weed scientists, and human nutritionists to comprehensively evaluate all factors limiting production. Precision agriculture with a broadened participation by these and other disciplines will enable greater* *synthesis and integration of new knowledge into production systems that can be implemented via precision farming. Further, aspirational production systems that include all we have learned about farming on the edge of the future, developed by transdisciplinary teams employing our best technology, may accelerate advances of agriculture to better meet the challenges of the future.*

Keywords. *Genetics, water management, nutrient management, photosynthetic efficiency, yield gap, climate change, intensification, soil degradation, crop simulation models, phenotyping, precision agriculture, decision support, sustainable agriculture, environment, soil biology, soil management.*

Introduction

There is an urgent need to accelerate the development, delivery and adoption of new technologies to meet the future global demand for food, feed, fiber and biofuels. Projections of demand for global food production by 2050 range from 60 to 110% above current levels (Tilman et al., 2011; Alexandratos and Bruinsma, 2012). Coincident with the increasing demand for agricultural production is a decrease of land for production, thus requiring intensification of production systems using practices that are sustainable. Changing climate is also affecting yields and the soil, water and air resources needed for agricultural production (Walthall et al., 2012). The largely evolutionary nature of agricultural research is insufficient to rapidly transform agriculture into a truly intensive, sustainable system with the ability to adapt to current and projected future environments. Clearly, a challenge to the agriculture community exists, there are no simple solutions, and there is an urgent need for different approaches to foster revolutionary (versus evolutionary) innovations.

G x E x M

The concept of the interaction of genetics by environment by management (G x E x M) as a foundation for moving forward to feed the future world was introduced by Hatfield and Walthall (2015). The rationale for a

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departure from the classic G x E interaction is to highlight the effects of climate variability on the environment factor and on opportunities for management to enhance performance of genetic resources.

Using this approach, Genetics is variety, breed or animal haplotype that are developed to offer potential for increased quantity and nutritional quality yields. Environment is a source of uncontrolled effects on agriculture, e.g., the weather. Management is what can be controlled by the producer, e.g,, fertilizer inputs. Yield, effects on the environment, and economic return are a result of the interaction of these factors. When problem solving in a production setting, identification of the dominant factors (G? E? M?) is undertaken, followed by the questions: What interactions are at work and what can be done to manage them?

How GxExM interactions translate to application is best explained when they are decoupled:

- G x E links animal/crop/variety/breed/haplotype development and choice with current environment, projected changes of environment, means and extremes of environment and abiotic and biotic stresses.
- G x M addresses what animal/crop/variety or breed or haplotype respond well to management practices such as soil management, water management, pest and pathogen management, timing of planting, cover crops, crop rotations, erosion and conservation management and fertilizer/nutrition management.
- E x M addresses what management practices work well under specific environments. Desired consequences of management interactions with environment include reduced emissions and runoff, leading to greater efficiency of inputs and reduced cost.

As the perspective of GxExM is communicated to producers it is readily accepted since GxExM mirrors how producers approach decision-making. The message from producers to the research community is clear: research and research results incorporating GxExM interactions are what producers want from agricultural research.

Yield Gap

Increased, intensified, sustainable production through GxExM begins with an assessment of where current farmer yields are relative to potential yield. Potential yield has been defined as "the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water not limiting; and with pests, diseases, weeds, and other stresses effectively controlled" (Evans and Fischer, 1999). Potential yield (Y_P) is a measure of the capacity of a crop to convert solar radiation into dry matter with no stress during the growth cycle. Cassman et al. (2003) and Lobell et al. (2009) advocate closing the yield gap, the difference between potential yield (Y_P) and farmer yield (Y_F), rather than seeking to increase Y_P. A yield gap approach addresses *all* factors affecting crop yields and also *when* these factors affect yield during the growing season. Fischer et al. (2014) proposed a more standardized method for yield comparisons and suggest that yield gap be expressed as a percentage of the Y_F as increased production will come from greater Y_F, rather than Y_P. They introduced the concept of attainable yield (Y_A) as a benchmark between Y_F and Y_P. Attainable yield was defined as the yield achieved by a producer under near-optimum weather and management inputs.

Lobell et al. (2009) summarized a comparison of Y_F with Y_P data of maize, rice, and wheat. Using a combination of simulation models and experimental observations to estimate Y_P, they found that the yield gap for maize ranged from 44 to 84%, for wheat 11 to 60%, and for rice 16 to 70%. Their observations suggest that much can be achieved by closing the yield gap for these crops: for rain fed crops, the average yield gap was close to 50% of the Y_P. They were not as optimistic for irrigated crops as observed yields, Y_F, were nearly 80% of Y_P and noted that increasing Y_P of irrigated crops is necessary for further yield gains (Lobell et al., 2009).

The assumption that Y_F will continue to increase at the same rate as the past 50 years is challenged by complicating factors. Brisson et al. (2010) analyzed trends of European wheat yields and showed that the lack of genetic improvements was not the cause of yield stagnation. Increased variability of climate during the growing season creating heat stress during grain-filling and water stress during stem elongation and tillering, were noted as significant factors. They attributed some of the yield stagnation to policy and economic changes which reduced the use of legumes in crop rotations and nitrogen fertilizer inputs. Analysis of farming in the tropics by Affholder et al. (2013) found that yield gaps between potential and non-limited-water yields were not due to global radiation, temperature, rainfall, or soil water holding capacity but rather due to poor soil fertility and weed infestation. Wang et al. (2014) noted that Y_F had already reached Y_P in the North China Plain and found that the Y_P was declining due to decreasing solar radiation and increasing air temperature.

Closing the Yield Gap through Precision Agriculture

Sinclair and Rufty (2012) suggest that nitrogen and water limit crop yield more than plant genetics, and therefore nitrogen and water should be considered the primary factors limiting yield. This points to a path to closing the yield gap via improving the capacity of each unit of land to support higher yields, i.e., land productivity. Increasing Y_F via improving the capacity of each unit of land to support higher yields is the foundation of precision agriculture.

Decision support is key for the use of precision agriculture to close yield gaps. Given the data that can be assembled about the capacity of a unit of land to support higher yields, several questions arise: 1) what data are needed? 2) what data are available? 3) how can data be used to make a decision? Using a GxExM approach expands the concepts and asks: What does a decision-support system incorporating GxExM look like? This question vastly expands precision agriculture research, requiring cross/trans disciplinary expertise – balanced with producer perspectives on what is possible/practical given the day-to-day realities of farming.

The scope of decision support is wider than support of yield goals. A concern of the effort to intensify production is the need for sustainable yields via practices that achieve the goals of sustainable agriculture. These goals were outlined by NRC (2010) and used to define sustainable agriculture: 1) meeting yield goals (interpreted here to mean quantity and nutritional quality of yields), 2) enhancing the environment, 3) maintaining economic viability of producers, and 4) enhancing the quality of life for rural populations and society as a whole. The benefits of precision agriculture when fully realized are increased yields, increased economic returns through greater efficiency of inputs, *and* environmental benefits from decreased losses of excess agrochemical inputs. Widening environmental goals to encompass other ecosystem services of the multifunctional landscape include soil health, watershed, pollinator health, biodiversity, etc. The GxExM approach can also be applied to these goals through its focus on efficiency made possible via precision agriculture.

The view of rural landscapes as multifunctional and the need for healthy soil as a foundation for sustainable intensification and resilience to the effects of changing climate, GxExM is also essential to farming for healthy soil. Soil biology, and the new generation of biotic fertilizers presents a promising frontier for advances of agriculture (Hatfield and Walthall, 2015). Management (M) of the health of soil biology for specific locations (E) is on the horizon with advances such as new approaches to managing crop nutrition (Delgado, 2016), and inoculants (Douds et al., 2016). With considerable research focused on improving soil health, including the promising role of soil biology, G x E x M may very well shift the widespread belief that increased agricultural production starts with GxE, to the perspective that increased agricultural production starts with interactions of M via precision technologies to enhance the soil E to make it possible via interactions to achieve the potential of G. –With G developed to respond to interactions with E and M.

A precision agriculture GxExM approach can also help accelerate the development of the next generation of crops simultaneously with the development of new production systems. Rapid phenotyping infrastructure currently being developed with its use of remote sensing, robotics, big data tools and planned capacity for improvements to crop models will greatly benefit from the inclusion of the where, when and how of precision agriculture spatial and temporal analysis. By including precision management in the rapid phenotyping experimental designs (what forms of fertilizer, irrigation management, tillage, planting strategies work best with specific varieties being tested at specific landscape and regional locations within the rapid phenotyping plots?), management options for closing yield gaps with the genetic resources being screened can be developed concurrently. Deployment of rapid phenotyping infrastructure under multiple environments (E) with concurrent selection of promising varieties (G) *and* management (M) practices, will enable development of crop model coefficient matrices that can account for genetic responses to environment and management practices. These coefficients will greatly advance the capabilities of crop models for decision support by producers and assessments of global production through projects such as the Agricultural Modelling Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2013).

The USDA-ARS has recently created the Long Term Agroecosystem Research Network (LTAR; Walbridge & Shafer, 2011). The purpose of the LTAR is to assess and enable sustainable intensification of production systems. The LTAR common (network-wide) experimental design seeks to measure the sustainability of existing local production systems as-practiced ("business as usual") and to develop and measure the sustainability of "aspirational" scenarios. The aspirational scenario is envisioned to be driven by advances of agricultural science and is especially exciting as plans for some include all of the latest technology, such as variable rate sampling (zone or smart sampling for nutrients), variable nutrient rates, and variable seeding rates across the landscape. The aspirational rotation is planned to be somewhat ahead of the curve; something that pulls out all of our best technology and is an embodiment of all that we have learned about farming on the edge of the future. Interactions of GxExM are at the heart of the aspirational scenario, implemented through precision agriculture technologies.

Conclusions

The concepts and practices of precision agriculture are key to closing yield gaps using a GxExM approach. However, understanding and quantifying yield gaps through a GxExM approach requires transdisciplinary teams of agronomists, engineers, soil scientists, geneticists, plant pathologists, entomologists, weed scientists, and human nutritionists to comprehensively evaluate all factors limiting production. Precision agriculture with a broadened participation by these and other disciplines will enable greater synthesis and integration of new knowledge of soil and plant interactions coupled with an understanding of the impact of increased climate variation. This will enable the development of options for producers to build intensified, sustainable production systems. Further, aspirational production systems build with solid foundations that exploit GxExM, including all we have learned about farming on the edge of the future, developed by transdisciplinary teams employing our best technology, and may accelerate advances of agriculture to better meet the challenges of the future.

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