Improved spatial framework to better leverage research on the food-energy-water nexus

*Patricio Grassini [1, *], Kenneth G Cassman [1], Haishun S Yang [1], Sotirios Archontoulis [2], Mark Licht [2], Kendall R Lamkey [2], Ignacio A. Ciampitti [3], Jeffrey A. Coulter [4], Cameron Pittelkow [5], Sylvie M Broder [6], Jeffrey J. Volenec [6]*

[1] Department of Agronomy and Horticulture, University of Nebraska-Lincoln. [2] Department of Agronomy, Iowa State University. [3] Department of Agronomy, Kansas State University. [4] Department of Agronomy and Plant Genetics, University of Minnesota. [5] Department of Crop Science, University of Illinois at Urbana-Champaign.[6] Purdue University.

Meeting demand for food, feed, and fuel in a world with 9.6 billion people by 2050 without negative environmental impact is the greatest scientific challenge facing humanity. Current trajectories of crop production are insufficient and associated use of natural resources is unsustainable. We hypothesize that this challenge can only be met with current and emerging technologies if guided by proactive use of big data[1] and geospatial scaling approaches to ensure local to global relevance for setting research priorities and implementing agricultural systems responsive to real-time status of soils, crops, and markets. Despite the increasing volume of agricultural data that is becoming available, the spatial framework to make best use of these data is lacking. This white paper addresses this knowledge gap and provides a data-driven strategy for optimizing the productivity and sustainability of agricultural systems.

The fundamental challenge is to address crop productivity gains and environmental concerns concomitantly. Crop yield gains must accelerate (Cassman et al., 2003) and conversion of natural ecosystems to farmland must cease (Tilman et al. 2011). Such conversion accounts for about 15% of anthropogenic greenhouse gas (GHG) emissions (Burney et al., 2011; Vermeulen et al., 2012) and much of the global biodiversity loss (IUCN, 2014; Laurence et al., 2014). However, the rate of crop yield increase is slowing or stagnating in many of the world's most productive regions, which in turn has encouraged massive expansion of crop production area at the highest rate in all of human history (Grassini et al., 2013). Rising demand for food, livestock feed, and biofuels coupled with global climate change are also putting increasing pressure on freshwater resources (Falkenmark et al., 1998; Rosegrant et al., 2009). Similarly, there is increasing concern about the impact of modern farming practices practices on natural resources including water quantity and quality, wildlife and biodiversity, greenhouse gas emissions, and soil and air quality.

Given the diversity of environments where crop production takes place, it is inefficient to conduct studies dealing with the food-energy-water nexus without a robust framework to synthesize and upscale results to larger spatial scales while ensuring local relevance. We argue

---

* Corresponding author: pgrassini2@unl.edu (P. Grassini)

[1] **Big data for agriculture** includes good quality data on soil properties, long-term weather data with a daily time step, short- and medium-term weather forecasts, and crop management practices over the recent past and in the current cropping season, all with fine spatial resolution required for decision making at local to global scales.

that in addition to more ‘boots on the ground’ and “white-peg” field experiments, there is an urgent need for methods that allow appropriate scaling to larger spatial domains using frameworks specifically designed for their relevance and accuracy in predicting and evaluating performance of agricultural systems. For example, most studies to date dealing with food security, agriculture’s environmental footprint, and the impacts of climate change can be roughly grouped into two categories. One category includes an enormous and growing body of literature of studies focused on specific locations or small regions, which are not representative of larger spatial scales. A second category focuses on regional to global scales using a *top-down* approach largely based on a gridded spatial framework for data on climate, soils, and crop production (*Fig. 1, upper panels*). An example of such approach is the pSIMS platform that is highly used to simulate production and environmental outputs from cropping systems models such as DSSAT and APSIM (Elliot *et al.*, 2014). While useful to detect general global and regional trends, top-down approaches are not accurate at the granular spatial level at which agricultural decisions are made and results are difficult to validate (van Ittersum et al., 2013; Van Wart et al., 2013a; Grassini et al., 2015). In summary, existing frameworks are inadequate because they were not designed to explicitly assess the performance of agricultural systems across different spatial scales while ensuring local to global relevance.

A *‘bottom-up’* spatial framework has the inherent advantage of local to global relevance if the upscaling protocols are robust (*Fig. 1, bottom panels*). The costs of implementing a bottom-up approach, however, can be too expensive and time consuming if a large number of location-specific datasets are required to achieve adequate spatial coverage. Hence, an efficient method is needed for limiting the number of location-specific datasets through use of an effective method of spatial upscaling. Here the scientific challenge is to develop a bottom-up framework that identifies the minimum number of location-specific datasets required to achieve robust prediction of cropping system performance at regional, national, and global scales.

The novel ‘bottom-up’ spatial framework developed for the Global Yield Gap Atlas (www.yieldgap.org) offers a complementary approach to top-down studies for research on the food--energy--water nexus. The approach is based on *measured* high quality weather, soil, and cropping system data. Briefly, a limited number of representative locations are selected to account for the greatest proportion of total regional or national production of the crop or cropping systems being evaluated (Van Wart et al., 2013b, c; Grassini et al 2015; van Bussel et al., 2015). Results derived for these locations are subsequently up-scaled to soil types and climate zones at national to regional and global spatial scales. This site selection and up-scaling process helps to limit the number of locations for which site-specific data on weather, soils, and cropping systems are required, which in turn facilitates the focus on quality of the underpinning data and helps ensure local to global relevance of the analysis. However, an inherent limitation using such approach is to leave out marginal or ‘frontier’ agricultural environments, which may not be relevant in terms of total food production but can be important relative to the environmental footprint and climate change. The challenge is, therefore, to design a bottom-up approach that can account for the majority of environments where crop production takes place so that it can be used to evaluate productivity and environmental performance of agricultural systems more generally, informing strategic investments in agriculture and policy decisions.

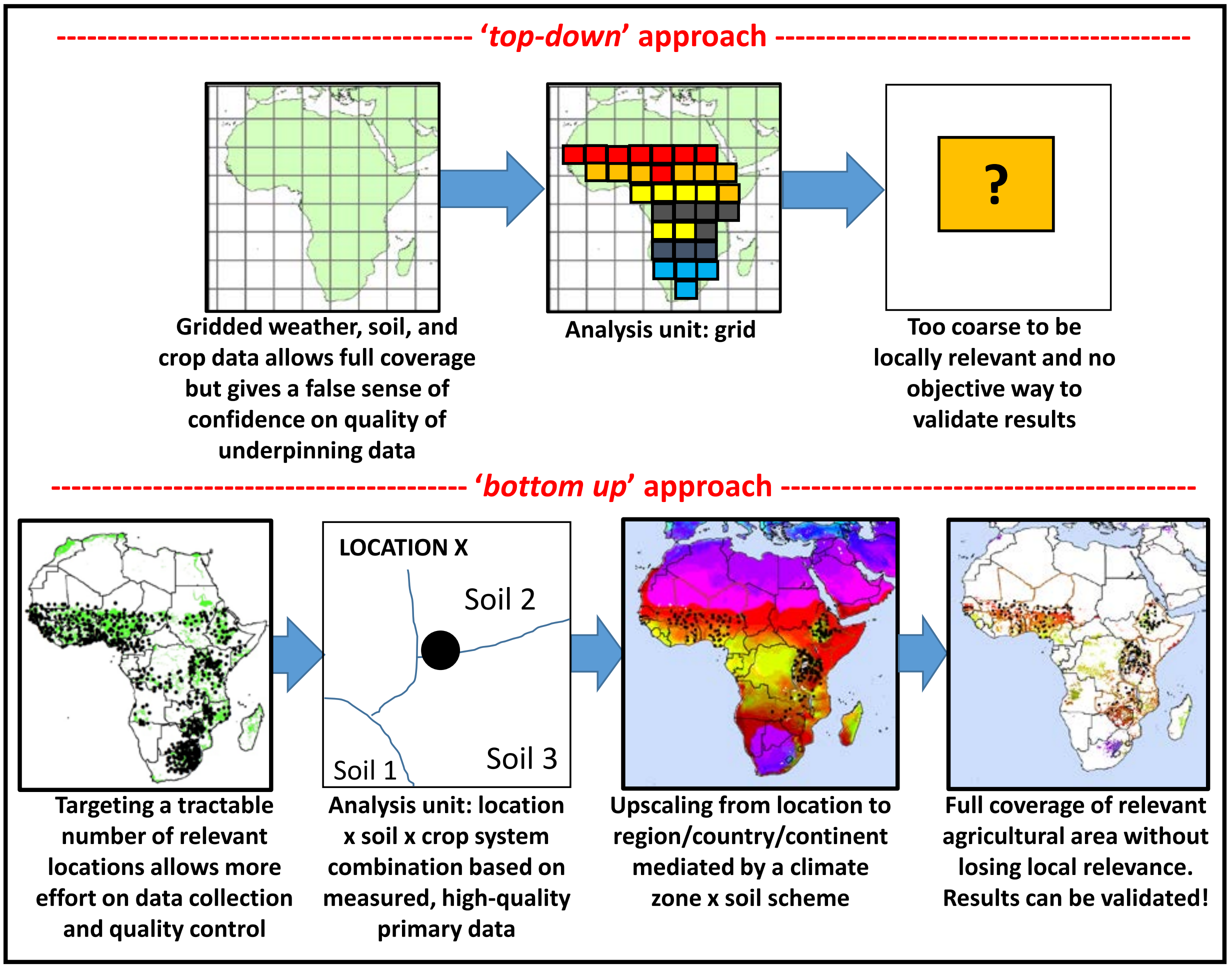

Fig. 1. *Hypothetical use of 'top down' and 'bottom up' approaches in Sub-Saharan Africa.*

Without more robust spatial frameworks, analyses of food security, climate and land use change, and environmental footprint will continue to rely on 'business-as-usual' top-down approaches, which cannot be validated and may provide biased assessments. Top-down approaches, in turn, may diminish the capacity for effective strategic planning and research prioritization to ensure future food security and conservation goals are met. Under the NSF Food-Energy-Water nexus program, we propose to develop a spatial framework that combines the strengths of top-down and bottom-up approaches to assess challenges related to the food-water-energy nexus at different scales (farm, watershed, state, and country). This framework will be designed to explicitly assess trade-offs and explore alternatives for sustainable food production through optimization. Our spatial framework will be based on four principles: (i) local and global relevance, (ii) representativeness of the range of environments where agriculture takes place, (iii) reliance on high quality measured weather, soil, and crop management data, and (iv) robust validation of results based on a combination of existing data and field experimentation. We propose to develop this spatial framework to benchmark metrics related to the water-food-energy nexus (e.g., productivity and energy, carbon, nitrogen, and water balances), explore trade-offs at different spatial levels, and identify pathways for increasing food production with reduced environmental footprints under current and future climate and production scenarios. Once developed, we propose to implement and validate this framework in the USA because of the availability of high quality data. With this novel approach, we believe our spatial framework will have the potential to become the most widely used tool to benchmark and optimize sustainability of crop production systems.

References

Burney J, Davis S J, DB Lobell, 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Natl Acad. Sci. USA 107, 12052–12057.

Cassman KG, Dobermann A, Walters DT, Yang H, 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28: 315-358.

Elliott J, Kelly D, Chryssanthacopoulosc J, Glotter M, Jhunjhnuwala K, Best N, Wilde M, Foster I, 2014. The parallel system for integrating impact models and sectors (pSIMS). Env. Modeling & Software 62: 509-516

Falkenmark M, Lundqvist J, Klohn W, Postel S, Wallace J, Shuval H, Seckler D, Rockström J, 1998. Water scarcity as a key factor behind global food insecurity: round table discussion. Ambio 27, 148–154.

Grassini P, Van Bussel LGJ, Van Wart J, Wolf J, Claessens L, Yang H, Boogaard H, de Groot H, Van Ittersum MK, Cassman KG, 2015. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crops Res. 177, 49-63.

Grassini P, Eskridge K, Cassman KG, 2014. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nature Communications 4: 2918.

IUCN 2014. The IUCN Red List of Threatened Species. Version 2014.3. <http://www.iucnredlist.org>. Downloaded on 1 February 2015.

Laurance WF, Sayer J, Cassman KG, 2014. Agricultural expansion and its impact on tropical nature. Trends in Ecol. Evol. 29:107-116.

Rosegrant MW, Ringler C, Zhu T, 2009. Water for agriculture: maintaining food security under growing scarcity. Annu. Rev. Environ. Resour. 34, 205–222.

Tilman D, Balzer C, Hill J, Befort B, 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences (PNAS) 108:20260-20264.

van Bussel LGJ, Grassini P, Van Wart J, Wolf J, Claessens L, Yang H, Boogaard H, de Groot H, Saito K, Cassman KG, Van Ittersum MK, 2015. From field to atlas: Upscaling of location-specific yield gap estimates. Field Crops Res. 177, 98-108

van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. 2013. Yield gap analysis with local to global relevance – a review. Field Crops Res. 143:4-17

Van Wart J, Grassini P, Cassman KG, 2013a. Impact of derived global weather data on simulated crop yields. Global Change Biology 19:3822-3834.

Van Wart J, Van Bussel LGJ, Wolf J, Licker R, Grassini P, Nelson A, Boogaard H, Gerber J, Mueller ND, Claessens L, Cassman KG, Van Ittersum MK. 2013b. Reviewing the use of agro-climatic zones to upscale simulated crop yield potential. Field Crops Res. 143, 44-55

Van Wart, J, Kersebaum KC, Peng S, Milner M, Cassman KG. 2013c. A protocol for estimating crop yield potential at regional to national scales. Field Crops Res. 143, 34–43.

Vermeulen SJ, Campbell BM, Ingram JSI, 2012. Climate change and food systems. Annu. Rev. Environ. Resource 37, 195–222.