Spatial frameworks to support agronomic innovation

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What works in one field might not work in another close by due to differences in soil properties and slope or in other regions with similar soil type but with a different climate, cropping system, or both. Photo by Hannah Dorn.

U.S. crop producers are faced with increasing challenges to maintain productivity growth and profit while also addressing environmental concerns about nutrient losses and climate change. Because progressive producers must optimize a large number of strategic and tactical crop and soil management decisions, conventional, replicated field experiment designs with two or three management treatment factors are not up to the task. It is therefore important to utilize crop performance evaluation methods that more efficiently identify those management factors with greatest impact on yield and input requirements, and their interactions with other management practices, across the wide range of soil and climates that comprise our major crop-producing regions.

Abbreviations:

GDD   growing degree-days;

PAWHC   plant-available water-holding capacity in the rootable soil depth;

RDE   research, development, and extension;

TED   technology extrapolation domain.

Two planters sow canola in a research plot in Montana. While continued investment in agronomic research, development, and extension is necessary, it is not sufficient because the efficiency of that investment must also improve in delivering new technologies and farming approaches that are adopted at scale. One of the barriers to improved efficiency is the highly variable response that can be expected from adoption of a new technology given the wide range of climates, soils, and farming systems. Photo by Kyle Reedy.

U.S. agriculture has enjoyed a remarkable 70-year period of innovation and productivity growth since the end of WWII that was driven by public- and private-sector investments in research, development, and extension (RDE) (Figure 1). Maintaining its current global leadership position in productivity growth and environmental stewardship will require continued investment to ensure the rate of innovation does not slow. However, current crop yields are steadily rising towards their genetic yield potential ceiling, which shrinks the exploitable yield gap. This makes it harder to eke out further yield gains while also holding down additional production costs and labor requirements associated with adoption of new productivity-enhancing technologies. Thus, while continued investment in agronomic RDE is necessary, it is not

sufficient because the efficiency of that investment must also improve in delivering new technologies and farming approaches that are adopted at scale.
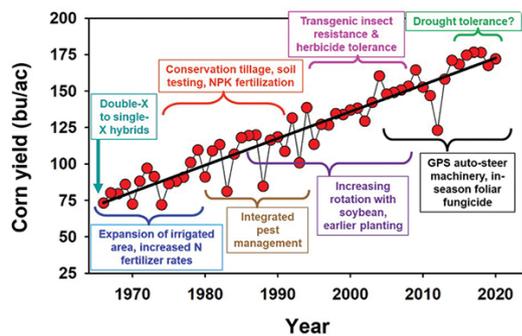

Figure 1, *Corn yield trends in the USA from 1966–2020 and the technological innovations that contributed to this steady yield advance. Rate of gain is 1.8 bu/year (r2 = 0.94).*

One of the barriers to improved RDE efficiency is the highly variable response that can be expected from adoption of a new technology given the wide range of climates, soils, and farming systems that comprise U.S. agriculture. What works in one field might not work in another close by due to differences in soil properties and slope or in other regions with similar soil type but with a different climate, cropping system, or both. Likewise, a grower must make 10–20 or more strategic and tactical decisions about crop and soil management to produce each crop, and the manner in which one practice is implemented affects the performance of most others. The challenge is how to optimize crop rotation, tillage method, inclusion of a cover crop (or not), cultivar, sowing date, seeding rate, and numerous nutrient, weed, insect pest, and disease management options for each field and subfield management zones across this enormous range of environments.

Analytical Spatial Frameworks to Support Crop Management Decisions

Analytical spatial frameworks are designed to increase the efficiency and cost effectiveness of field research based on evaluation of crop performance by organizing data on soil properties and climate to better assess the influence of cropping systems, soils, and climate on response to new technologies and farming approaches. Here we employ a "broad sense" view of new technologies and approaches to include those

that require strategic or tactical decisions. Strategic decisions are generally made before planting and sometimes require investment in new equipment and software; they include decisions about crop rotation, hybrid and cultivar selection, seed treatments, use of a cover crop, and tillage method. Tactical decisions are made during the growing season and can most often be implemented with existing equipment and expertise; they include timing and amount of nutrient inputs, pest management operations, and in irrigated systems, the timing and amount of water applications.

Strategic management decisions depend in large part on "state" variables that provide insight about how a dynamic system is expected to perform. In agroecosystems, state variables include climate and soil properties governing root growth, water, and nutrient supply. While there are large year-to-year differences in weather, long-term average temperature regime and water balance (defined as the difference between rainfall and evapotranspiration) are useful for distinguishing different climatic zones within the range of temperature and moisture regimes most relevant for rainfed crop production. Hence, strategic management decisions are based on the most likely growing environment, which in turn, is best characterized by long-term average temperature and water balance regimes. In contrast, tactical decisions require "real-time," in-season daily weather data and short-term weather forecasts to help assess current crop growth status and the expected future rate of crop development, timing of upcoming management operations, and yield level.

Technology Extrapolation Domains

The technology extrapolation domain (TED) framework is an analytical spatial framework explicitly developed to better estimate yield gaps of major food crops under rainfed conditions at a local to global scale (www.yieldgap.org). Each TED is a spatial unit with a unique combination of climate and soil properties that largely govern crop response to management practices (broad sense) without irrigation. The four properties are: (i) annual total growing degree–days (GDD), which largely determines the length of the growing season; (ii) aridity index, which largely defines the degree of water limitation in rainfed cropping systems; (iii) annual temperature seasonality, which differentiates between temperate and tropical climates; and (iv) plant–available water–holding capacity in the rootable soil depth (PAWHC), which determines the soil's capacity to store water and support crop growth during rain–free periods (Rattalino Edreira et al., 2018). Figure 2 shows TED units in the continental USA based on 10 categories of GDD, 10 categories of aridity index, three categories of temperature seasonality, and six PAWHC categories in 2–inch increments to a maximum total root–zone water storage capacity of 12 inches. A tutorial about how to use the TED framework can be found at: https://bit.ly/3f8zcLw, and the TED designation for a given field, and the extent of that TED unit, can be found using the "TED Framework Tool" at: https://nutrientstar.org/ted-framework/. If a grower, crop consultant, or researcher knows the GPS coordinates of a field, they can identify the most prominent TED unit
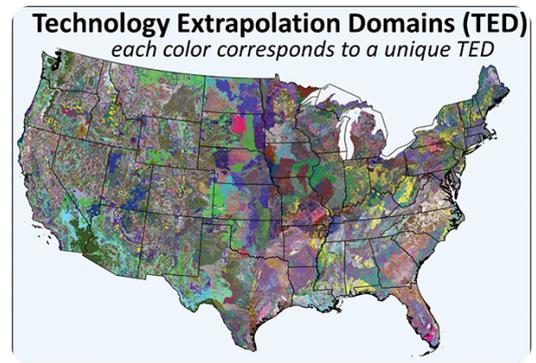

Figure 2, *Technology extrapolation domains (TEDs) in the United States. Each TED corresponds to a unique combination of growing degree-days, aridity index, temperature seasonality, and plant-available water-holding capacity. Source: Rattalino Edreira et al. (2018).*

represented in that field as well as any large inclusions of other TED units due to subfield differences in PAWHC caused by variability in rootable soil depth and/or texture.

Improving Field Research Efficiency

Although there are 1,800 possible TED categories (i.e., 10 GDD × 10 aridity indexes × 3 temperature seasonality bins × 6 PAWHC increments), only a relatively small number of this total account for most of the maize production area in the Corn Belt. For example, less than 20 TED zones account for 50% of total corn and soybean acreage, and 60 TEDs include 75% of the total for both crops (Figure 3). Such high concentration of crop area in a relatively small number of TEDs attests to the fact that growers choose the crops and cropping systems that work best under the specific climate and edaphic conditions on their farms. This concentration is typical in major rainfed breadbaskets of the world like the U.S. Corn Belt, Argentine Pampas, Brazilian Cerrado, European wheat belts, and the north China Plain where topography is relatively flat and gives rise to large TED units.
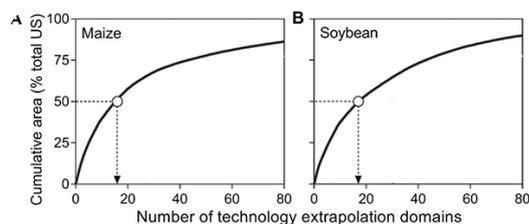

Figure 3, *Crop area coverage as a function of the number of technology extrapolation domains (TEDs). TEDs were sorted from largest to smallest according to their 2015 harvested maize (a) and soybean (b) area. Black dashed lines indicate 50% of U.S. national maize or soybean area coverage,*

Because conducting field research is costly and time consuming, it is important to obtain greatest impact from the time and money invested in the effort. To this end, the TED framework can be used to identify locations to establish field research sites that maximize coverage of the targeted crop production area. For example, if a fertilizer dealer wanted to put out 10 strip trials on corn in farmers' fields within its business region, the TED framework can be used to identify fields representing TEDs with greatest corn area within that region to maximize coverage. Similarly, if the field test involved a technology that tended to work best under a specific combination of climate and soil type, sites within TEDs that best represent this environment can be selected for establishing the trial locations. And while the actual weather during the growing season in which the field trials are run may differ significantly from the long-term average climate, TED climate regimes are relatively stable in the more favorable regions of the central and eastern Corn Belt. In contrast, TED climate regimes in harsher rainfed climates that occur in the western Corn Belt and High Plains have greater uncertainty in rainfall amount and timing. As a result, it typically requires a greater number of years of testing to rigorously evaluate the performance of a new technology or technology package in harsh rainfed environments. In both cases, using the TED framework for identifying research sites increases opportunities for adoption of new technologies because it helps define the inference zone for extending results from field research conducted at a limited number of testing sites.

Using TEDs to Identify Optimal Management Practices

The combined use of farmer data and an appropriate analytical spatial framework can also help identify management practices with the greatest potential to increase yield for a given environment. For example, Rattalino Edreira et al. (2017, 2020) and Mourtzinis et al. (2018) used yield and management records from farmer fields across the U.S. North–Central region to identify candidate management options for increasing soybean yields. Based on GPS coordinates, fields were grouped by the TED in which they were located. Within each TED, it was assumed that climate and soil were relatively similar, and hence, the remaining yield variation was mostly attributable to management practices. This approach led to identification of management practices associated with high soybean yields across 27 TEDs, which together, included 51 million acres of soybean, or about 62% of the total harvested soybean area (https://bit.ly/3yaPxGJ).

For example, Rattalino Edreira et al. (2017) used the TED framework to evaluate farmer–reported data and found that sowing date, tillage method, and in–season foliar fungicide and/or insecticide significantly helped to explain yield variation in several major soybean–producing TEDs. Although the degree to which these three factors influenced producer yield varied across TEDs, analysis of in–season weather helped interpret these management × TED interactions: Yield increase due to earlier sowing date was greater in TEDs with adequate soil moisture during the pod–setting phase between the R3 and R5 stages. About 100 (rainfed) and 50 (irrigated) fields per TED were required to have sufficient statistical power to detect yield differences attributable to management practices. It would not be unusual for cooperatives, input suppliers, and crop consultants to have access to farmer–reported data for this number of fields within the major corn– and soybean–producing TEDs.

Summary and Conclusions

U.S. crop producers are faced with increasing challenges to maintain productivity growth and profit while also addressing environmental concerns about nutrient losses and climate change. Because progressive producers must optimize a large number of strategic and tactical crop and soil management decisions, conventional, replicated field experiment designs with two or three management treatment factors (e.g., fertilizer rates, seeding rates, and tillage method) are not up to the task. The number of treatment factors that can be evaluated are too limited while the number of sites and years of testing required is simply too costly and time consuming. It is therefore important to utilize crop performance evaluation methods that more efficiently identify those management factors with greatest impact on yield and input requirements, and their interactions with other management practices, across the wide range of soil and climates that comprise our major crop-producing regions.

Strategic decisions are generally made before planting and sometimes require investment in new equipment and software; they include decisions about crop rotation, hybrid and cultivar selection, seed treatments, use of a cover crop, and tillage method. Photo by Kaitland Miller.

The TED analytical spatial framework has been used successfully to identify management factors with the greatest impact on soybean yields in the Corn Belt and the reasons why a given practice works in one place and not another. Using the TED framework makes the management regime in each field a separate "experiment" because its performance can be compared with the management regime and performance of many thousands of other fields with similar climate and soil. Moreover, the power of the TED framework to identify influential management factors is

comparable to other analytical spatial frameworks that have considerably more input data requirements (Mourtzinis et al., 2020).

An online version of the TED framework is publicly available for use by researchers, crop producers, crop consultants, and industry agronomists at **https://nutrientstar.org/ted-framework/** and on the Global Yield Gap Atlas website at **www.yieldgap.org/web/guest/technology-extrapolation-domains**. Complete raster files supporting the TED framework can be obtained for commercial uses under license.

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