Networking Soil Fertility Studies at the Agro-ecosystem Level using Meta-analysis

By Leon E. Parent and Tom Bruulsema

Research supporting 4R plant nutrition must address the complexity of its four factors interacting with many more soil and climatic factors varying among agro-ecosystems. Increasing emphasis must be placed on analysis of networked datasets. Meta-analysis provides statistical rigor for such analysis.

The objective of soil fertility studies is to provide a scientific basis for making fertilizer recommendations. Research considers the environmental context, the goal and the methodology. In classical soil fertility trials, researchers are concerned with Type I error, i.e. rejecting the hypothesis of "no effect" (H_0) when it is true, and Type II error, i.e. accepting H_0 when it is false. Soil fertility research strives to define a set of conditions in which a response is expected, and to distinguish them from conditions in which no response is expected. The conditions may include, but need not be limited to, a soil test value for the nutrient in question. Two errors are common in the interpretation of fertilizer response trials: first, mistaking random variation for a true response (Type I error), and second, failing to detect true responses because of background variability (Type II error).

When conducting fertilizer experiments, one assumes that either (1) all other factors are equal or (2) all factors except the ones being varied are at a sufficient but not excessive level. Methods designed to address a narrow set of questions at any one experimental site may restrict the number of answers specifically related to any underlying assumptions. Averaging site-specific optimum rates across experiments within an assumed group of trials disregards the fact that several factors may vary widely among sites. In most fertilizer experiments, one factor is varied at a time, assuming no significant interaction with factors other than the soil test.

Within most jurisdictions, crop fertilization guidelines are based on grouping procedures defined only by soil test levels, rather than agro-ecosystems. The crop, however, grows in the context of higher-order interactions including the climatic zone, soil classification (soil series and texture), soil degradation state (compaction, aggregation, erosion), and crop and soil management (e.g. crop sequence, conservation practice, etc.). The problem of assumed invariant factors in making fertilizer recommendations may lead to wrong decisions.

Type III Error

Type III error occurs when the null hypothesis (H_0) is rejected for a wrong reason (as related to definitions and methodologies). In other words, any relationship between a risk factor and an output may also depend on the prevalence and patterning of other risk factors in the population (Schwartz and Carpenter, 1999). For example, a crop grown in a high-nutrient soil may respond significantly to added nutrients due to soil degradation problems such as compaction or genetic horizons that restrain rooting. Arguing that crops are responsive to added nutrient in all high-nutrient soils would clearly be wrong, and even for the subset of high-nutrient soils with the specific degradation, the application of nutrients should not be concluded to be the only means of obtaining the yield response; repairing the degradation by relieving compaction should be evaluated as an alternative. Degraded soils may be prevalent in this case although the answer was "right" as controlled by Type I error (α). The question must be reformulated considering crop response to added nutrients on soils of hampered quality. The solution may thus be to improve soil quality rather than applying fertilizers. Relying on fertilization alone may lead to even more soil and water degradation and deny principles of sustainable agriculture. Research supporting practical management should be more concerned about interpreting results for the best possible system performance, rather than relying on a single mathematical model based on a single factor.

Common abbreviations and notes: N = nitrogen.

Soil and climate effects on corn N response can be revealed by meta-analysis.

The 4R concept (the right source, applied at the right rate, time and place) may help to avoid Type III errors. Its 4-factor interaction introduces a problem for the science of soil fertility: high-order interactions are difficult to interpret from limited volumes of observed field data. Single-factor research has the greatest power to precisely measure responses, but multi-factor research has more power to identify interactions and can suggest more management alternatives to attain the same result.

Models recognizing factor variation and high-order interactions while minimizing the size of datasets are needed to solve this concept in practice. The parsimony principle to simplify complex problems to manageable solutions, or Occam's Razor, states "Of two equivalent theories or explanations, all other things being equal, the simpler one is to be preferred." Meta-analysis is a procedure to analyze and synthesize datasets from separate studies pursuing similar objectives (Borenstein et al.,

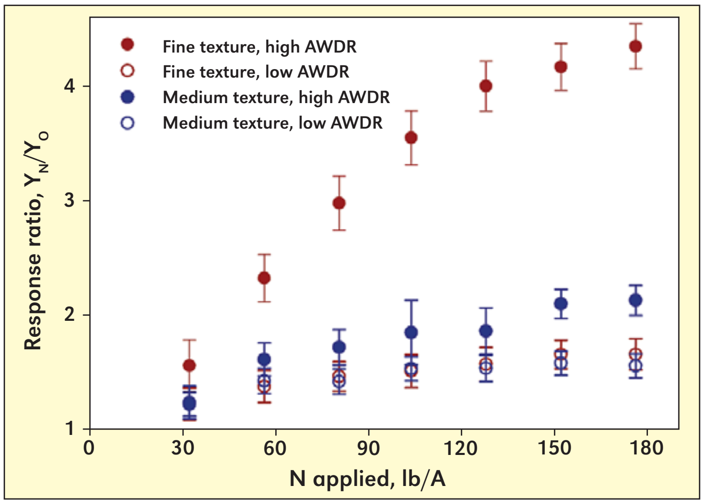

Figure 1. Ratio of corn yield with N versus without N, as a weighted mean across sites in four categories of soil texture and AWDR. AWDR refers to a measure of abundant and well-distributed rainfall during the period from 15 days before to 30 days after side-dress application of N. Error bars represent standard errors derived from meta-analysis. Adapted from Tremblay et al., 2012.

2009). It provides a quantitative synthesis of results that is objective and statistically defensible, compared to the traditional narrative review (Ainsworth et al., 2007). Meta-analysis has been introduced recently in soil fertility studies (Tonitto et al., 2006; Valkama et al., 2009). By combining studies, meta-analysis tests whether an effect is robust over a wider range of conditions, and estimates the magnitude of the effect more precisely, as compared to a single study.

Grouping is a means to reduce the heterogeneity commonly observed in crop response data. Subsets of studies may be selected based on agro-ecosystem hierarchy: climate, soil classification and quality, conservation practice, crop sequence. The significance of within-subset crop response is measured by the Q statistic that is distributed like a χ^2 variable. The heterogeneity of within-subset means is measured by the I^2 statistic. Heterogeneity is minimized by assigning studies to other subsets or by forming new ones. Meta-analysis is conducted using metafiles that contain metadata and experimental results.

Metafiles

Metafiles provide the necessary data for conducting meta-analyses. Factors and variables influencing crop yield and quality are assembled into metafiles. Metafiles comprise metadata on climate, soils (series, texture, chemical analyses, physical properties, etc.), fertilization treatments and plant response (leaf chemical analysis, crop yield and quality, crop chemical analyses). The more subsets formed, the more fertilizer trials are needed to reduce the heterogeneity of the controlling factors in the agro-ecosystem.

Meta-analysis

Meta-analysis requires reliable classification criteria that are accurate and relevant in order to avoid ideological biases and personal preferences (Littell et al., 2008). Sites must be classified by institution and year, as annual or long-term, and by size (small vs. large plots). The control treatment must be identified univocally; for a fertilizer experiment it should be zero nutrient addition whenever possible. This is different than the traditional relative yield response model, where the control is yield with the nutrient in question at non-limiting levels (Nelson and Anderson, 1984). The response ratio used in meta-analysis is the log ratio between treatment and control (Borenstein et al., 2009). The related variance term weighs the effect size that is statistically evaluated using Q and I^2. Where crop response patterning is too heterogeneous within the subset, sites may be re-allocated to other subsets, or to another grouping of subsets. As the number of subsets increases, the need for more data increases dramatically. This is why research networking is essential to support meta-analysis of fertilizer experiments accounting for heterogeneous agro-ecosystems.

In meta-analysis, the inverse of each site's variance (determined by ANOVA) is used to assign weights in the global analysis of a subset. The within-subset analysis across several sites provides more statistical power for the computation of the optimum economic rate compared to examining individual sites one at a time (Kyveryga et al., 2007). The combination of soil and climatic conditions acting on crop response to added nutrients should provide fine-tuned information in decision-support systems for precision agriculture and the 4R concept applied at the farm level. In Quebec, metafiles are being updated to facilitate knowledge transfer to farmers. We are in the process of acquiring the climatic and soil datasets to improve the interpretation of crop response by agro-climatic region, and other derived or observed properties such as soil textural class, susceptibility to erosion and compaction, etc.

As agro-ecosystem studies face problems of complexity, agricultural scientists must analyze their data in a more organized way to avoid Type III errors, rather than limiting themselves to primary statistical analyses. In Quebec, networking among agricultural scientists led to several metafiles that formed the basis for new fertilizer guidelines (Parent and Gagné, 2010). Soil grouping was conducted using soil testing since the climatic and soil datasets were not available for site grouping at that time. However, data on year and exact location of the sites were collected, allowing data importation from climatic and soil datasets. Groups with insufficient information were identified to update the metafile with new research. Much larger datasets than before will be required to understand the complex patterning of crop response to added nutrients.

An example of the application of meta-analysis to find common factors controlling the response of corn to N is shown in **Figure 1**. In this study, conducted over 51 sites across North America, the response ratio was shown to relate to groupings based on soil texture and rainfall. Sites with fine texture and abundant and well-distributed rainfall showed much greater response to N than those in the other three categories. The results demonstrate the need for adaptation of N recommendations to variations in both soil and weather, simultaneously.

Future Prospects

Although widely accepted in other disciplines like medical, physical and behavioural sciences, meta-analysis of agronomic data is in its infancy. As was the case in ecology, it must be used correctly and at full potential and be open to the large arsenal of other statistical tools (Ainsworth et al., 2007). Agricultural scientists will also face new challenges on data classification, such as grouping sites where different fertilizer rates were applied, how to define a subset, how to improve current models, and how to apply other methods of linear statistics to meta-analysis. Last but not least, in order to achieve the agro-ecosystem level of data synthesis and bring the 4R concept into practice, the networking of research efforts across political jurisdictions is urgently needed. BC

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Potassium Fellowship Program Request for Proposals

Over 50% of the world's food supply exists today because of the use of commercial fertilizers. By 2050, global demand for food is expected to increase by 70 to 100% and it is highly likely that its production will be even more dependent on fertilizers than it is today. The three nutrients most frequently limiting to crop production globally are N, P and K. It is critical that the science of how these nutrients can efficiently and effectively contribute to productivity in rapidly evolving cropping systems be advanced to meet the increased demand for agricultural products. Due to environmental aspects, significant research funding is often available on N; however, funding for production-oriented P and K research is more difficult to acquire. Nutrient stewardship based on the 4Rs—application of the right nutrient source at the right rate, time and place—requires a balanced approach addressing the full complement of needed nutrients in systems focused on meeting economic, environmental and social goals. Therefore, P and K must be efficiently and effectively managed if N performance is to be optimized. Leading fertilizer manufactures have established the *Phosphorus and Potassium Graduate Fellowship* programs to help fill the need for additional P and K research. This request for proposals is part of the *Potassium Fellowship* program.

Goals of the Potassium Fellowship Program

The program is a long-term commitment by the fertilizer industry to:

1. Establish research programs that will attract top students and additional funding for production-oriented aspects of K research.
2. Build human resources needed by the industry that are strong scientifically, knowledgeable about K as a plant nutrient, and understand how farms and the fertilizer industry function.
3. Advance the science of K use in agriculture.

Funding and Donors

Individual fellowships are for a maximum of $70,000 per year for a maximum of four years. Fellowships cover the tuition, fees and stipend for the institution plus expenses associated with the research project proposed in response to the Fellowship Program RFP. The fellowship program is supported by voluntary contributions from K fertilizer manufacturers servicing the needs of the North American Corn Belt and Great Plains. Program donors are: **Agrium Inc., Intrepid Potash Inc., Mosaic Company, PotashCorp, and Simplot.**

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium.

Eligibility

Fellowships are awarded to individuals in the early stages of their graduate study or about to enter a graduate program in sciences relevant to plant nutrition and management of crop nutrients. Typical applicants would be seniors in a B.Sc. program who want to start a Ph.D. program, M.Sc. candidates in their final year who want to pursue a Ph.D., or First year Ph.D. students. Eligible institutions must be degree granting and generally located within the Corn Belt or Great Plains of the U.S. or Canada. Exceptional applications from outside these regions will be considered.

Submissions

Research proposals in response to this request should be received by IPNI (e-mail: ppates@ipni.net; phone: 605-692-6280) by April 1, 2013. Awards will be announced by June 1, 2013.

These and more details on this opportunity are available at http://info.ipni.net/KFellow BC