Mechanistic Models: An Underutilized Tool in Soil Science Research

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The Annual Meeting of the Soil Science Society of America, Crop Science Society of America, and American Society of Agronomy always provides a multi-dimensional experience. One of the things I particularly enjoy is the opportunity to visit with vendors and learn of recent advances in the analytical equipment we need to support and advance our research efforts. Current instrumentation provides a level of sophistication unheard of only a few years back. Improved methods of chemical analysis in combination with micro-sampling devices now allow us to explore the action sites in the soil in ways that bulk samples never allowed.

At the same time, new statistical software packages and more powerful personal computers provide us with the statistical tools needed to evaluate our results with greater confidence. Thus our ability to obtain and statistically analyze data in a number of arenas has been vastly improved. However, one very important tool that we need to integrate our discrete findings into an understandable whole has not kept pace with our analytical and statistical progress. And that tool is the quantitative mechanistic model.

Mechanistic models provide a means to bring things together in ways that allow us to test our understanding in a holistic manner. Often unnoticed is the degree to which models have invaded our everyday lives. One very prominent example is the suite of models used to forecast the weather on a day-to-day basis, especially severe weather outbreaks. While not always totally accurate, it is almost impossible to deny that these metrological models are very powerful and useful tools that have been improved by daily use. Once developed and proven to be reliable, mechanistic models applied to soil science research provide a way to test hypotheses, explore areas we cannot currently assess experimentally, as well as make management recommendations.

Overcoming Skepticism and Distrust of Models

Unfortunately, there is still considerable skepticism and distrust in the soil research community when it comes to the utilization of models. In fact, we continue to be largely divided into two camps: experimentalists and modelers. In order to move forward, we need to redouble our efforts to bring the two together. For most of us, this basic divide and distrust probably arose from an initial exposure to an empirical model with a lot of “black boxes” or perhaps it was an inadequately conceptualized or tested mechanistic model. Since most of us prefer to deal in hard data and things we can see and measure, modeling smacks too much of a hand-waving exercise or pseudoscience.

Fortunately, the steadily increasing power of personal computers combined with the development of more user-friendly programing languages can facilitate the application of existing models, as well as the development of new or improved mechanistic models. And we need to take advantage of this opportunity.

Proven mechanistic models that blend basic chemical, physical, and biological understanding have the potential to be powerful tools as we seek to illuminate and integrate our understanding of underlying processes. While some progress has been made, soil science has been somewhat slower than some of the basic sciences to utilize the predictive powers of quantitative models. Part of this reluctance may come from the fact that soil scientists are a somewhat conservative lot by nature since much of our research finds its way either directly or indirectly into management or regulatory decisions. Consequently, we are reluctant to use model data, the veracity of which we question, because of uncertainties associated with the way it was generated.
Working with Proven Models

So how do we move forward? The key is to work with proven models. In order to have access to these potentially useful tools, we need to have a process of model development and verification leading to end products with which we feel comfortable. First, we must recognize, as have our colleagues in chemistry and physics, that models are serious tools and are critical to the development of predictive capabilities based on a holistic quantitative understanding. As previously alluded, thanks to the digital explosion in instrumentation, we now have the capability to make measurements at both the micro- and macro-scale, some in real time, with a level of accuracy and precision that could only be dreamed of a short decade ago. In order to derive greater benefits from these advances in technology, we must come up with ways to harness this capability and generate the data needed to better define and quantify key processes in both the field and lab. In some cases, this means designing our experimental efforts in ways that will ultimately support modeling.

Working Together

Second, we need to create the stimulating environment that arises when we form self-selected teams both locally and regionally. The old adage that no one of us is as smart as all of us certainly applies here. Working together, we can formulate the best approaches to the description of the mechanisms of a key process as well as the research needed to support quantification of those processes. This approach allows modeling to be an identified research goal, not an afterthought. Once defined and described, key processes can be explored individually, or they can be linked together in meaningful assemblages that have the power to provide greater insight and predictive capability. This unified approach also provides a mechanism through which we can develop the independent data sets needed for a true model testing and verification process. The key to success in this activity is to resist the temptation to bite off too much at a time. From my experience, one reason we have not been as successful in developing holistic models as we might like is that in our haste to “eat the elephant,” we have not taken the time to fully chew and digest each bite before moving on to the next. Mechanistic model development is an area where application of the KISS principle is very appropriate, lest we become bogged down in excessive detail or the model becomes too data intensive to be useful.

Transparency in the Process

Third, the model development, testing, and application process needs to be fully transparent. Data sources and methods for their development must be fully and clearly described. And model release needs to be followed by a period of rigorous beta testing. Under ideal conditions, this testing would be done by individuals not directly involved with the development of the model being used. Making newly developed or refined models easily and widely available to other researchers is an integral and important step in building confidence in the power and veracity of a model. An excellent example of this can be found in the evolution of the concepts found in the Barber–Cushman nutrient uptake model developed by Stan Barber and John Cushman at Purdue. The availability and ease of use of this mechanistic model resulted in it being evaluated under a variety of soil conditions as well as with a broad array of plant species. These beta tests did much to point out both the strengths and weaknesses of the Barber–Cushman approach and contributed directly to the evolution of mechanistic nutrient uptake models as researchers sought to improve on their seminal work.

Recently, I had occasion to review the literature on newly available models that describe nutrient uptake. These new models offer exciting new additions to our ability to describe and understand things like three-dimensional root growth, root branching, root exploration of nutrient “hot spots,” and the impacts of root exudates on nutrient uptake to name just a few. I would further note that these advances have in part been made possible by the advent of new measurement technologies and improved software that allow us to measure and describe processes in much greater detail in both space and time. If these new models can be made widely and easily available and their use evaluated by teams of soil scientists under a variety of conditions, we will be well on our way to a new era in research.

While I have only scratched the surface on this topic, I hope that my observations will stimulate others to consider the very important contributions that appropriately conceived and tested mechanistic models, even simple ones, can make to improved understanding and practice. Significant advances can be made by the thoughtful inclusion of a modeling component in our research programs combined with the free and open sharing of information pertaining to the development and application of these models. Mechanistic models are underutilized tools in soil science research, and now is the time to follow the lead of our colleagues in chemistry and physics and make greater use of these potentially powerful tools.