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OPINION & POLICY

Structural Equation Modeling Facilitates Transdisciplinary Research on Agriculture and Climate Change

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ABSTRACT

Increasingly, funding agencies are investing in integrated and transdisciplinary research to tackle "grand challenge" priority areas, critical for sustaining agriculture and protecting the environment. Coordinating multidisciplinary research teams capable of addressing these priority areas, however, presents its own unique set of challenges, ranging from bridging across multiple disciplinary perspectives to achieve common questions and methods to facilitating engagement in holistic and integrative thinking that promotes linkages from scholarship to societal needs. We propose that structural equation modeling (SEM) can provide a powerful framework for synergizing multidisciplinary research teams around grand challenge issues. Structural equation modeling can integrate both visual and statistical expression of complex hypotheses at all stages of the research process, from planning to analysis. Three elements of the SEM framework are particularly beneficial to multidisciplinary research teams; these include (i) a common graphical language that transcends disciplinary boundaries, (ii) iterative, critical evaluation of complex hypotheses involving manifest and latent variables and direct and indirect interactions, and (iii) enhanced opportunities to discover unanticipated interactions or causal pathways as empirical data are tested statistically against the model. Using our ongoing multidisciplinary, multisite field investigation of climate change adaptation and mitigation in annual row crop agroecosystems as a case study, we demonstrate the value of the SEM framework for project design, coordination, and implementation and provide recommendations for its broader application as a means to more effectively engage and address issues of critical societal concern.

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Abbreviations: AMF, arbuscular mycorrhizal fungal; SEM, structural equation modeling.

Climate change is representative of many of the "grand challenges" facing agriculture and the environment—it is complex, spans traditional disciplinary boundaries, and is both a consequence and driver of coupled physical, biological, and socioeconomic processes acting at multiple spatial and temporal scales (Godfray et al., 2010; Collins et al., 2011; Foley et al., 2011). Researchers have recognized the need for more integrated and multifaceted approaches to examining such challenges, and funding agencies are increasingly investing in the creation of large, multidisciplinary research centers and longer-term (i.e., >3 yr) integrated research projects (Robertson and Swinton, 2005; Reganold et al., 2011). Examples of such integrated and transdisciplinary programs include USDA NIFA's Agriculture and

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Food Research Initiative (AFRI) Agriculture and Natural Resources Science for Climate Variability and Change program and NSF's Coupled Natural and Human Systems (CNH) program and Science, Engineering, and Education for Sustainability (SEES) investment. This shift in funding strategy and research approach will require unprecedented collaboration among investigators in disparate disciplines (Lauer et al., 2012). Here, we will discuss the use of SEM as a visual thinking tool that can improve the outcome of these projects by providing a common frame across disciplines, facilitating constant refinement of hypotheses and methods, and promoting discovery of new questions and relationships. We argue that this use of SEM, particularly when coupled with its more traditional use as a statistical methodology, provides novel opportunities for improving project development, implementation, and coordination.

A case in point of the need for improved project coordination is provided by USDA NIFA's Coordinated Agricultural Projects. These funding programs have offered grants that are at least an order of magnitude greater than typical competitive federal research grants in agriculture; recent awards have ranged from $10 to 25 million. Applicants for such support must develop 'transdisciplinary' approaches and organize 'integrated' projects, in which at least 1/3 of project budgets must support the non-research components, i.e., public engagement and education (USDA NIFA, 2011). These grants offer unprecedented opportunities for integrated and multifaceted approaches, and equally unprecedented opportunities to integrate research with stakeholders, end-users, policymakers, and other social actors that are addressing the complex challenges and opportunities that motivate these funding programs. In an era when low funding rates are at odds with society's increasing demand for sustainable agricultural systems, such large initiatives offer critically important opportunities for agricultural research to address complex problems.

However, successful execution of these complex, multidisciplinary projects on grand-challenge issues requires bridging across multiple disciplinary perspectives to achieve common questions and methods (Lauer et al., 2012). In this context, the practice of 'framing' is emerging as an essential means for organizing successful research teams. Framing is a process by which the most important challenges and opportunities in a complex situation are identified, along with the essential activities needed to achieve these (Dewulf et al., 2007). Each discipline is likely to have a particular framing of grand-challenge issues, and analysis of cross-disciplinary research projects has revealed the importance of an ongoing process of framing that is qualitatively different from the framing activities of single-discipline projects (Dewulf et al., 2007; Oughton and Bracken, 2009). For example, the notion of "productivity" could be framed, and hence examined, very differently depending on the discipline involved. An agronomist might frame productivity in terms of grain yield per quantity of input. A soil scientist might consider productivity an inherent property of the biophysical and chemical status of soils. Finally, an ecologist or sociologist might frame productivity in terms of the transformation and movement of carbon and energy across trophic levels or in terms of the socioeconomic drivers of farm-gate management decisions, respectively. While all of these conceptualizations capture elements of productivity, a more holistic understanding of productivity likely only emerges when they are fully integrated and their respective indicator variables are assessed in concert.

Framing in large-scale, multi-investigator projects has two critical aspects. On the one hand, the project must frame its relationship outwardly to other social actors that are addressing the challenges or opportunities that motivate the research project. Arguably, this framing is critical to the realization of social benefit from public investments in research projects on grand-challenge issues. The importance of such framing is additionally heightened by an emerging trend among private, governmental, NGO and research sectors concerned with agriculture and its social, economic, and environmental impacts. These sectors appear to be shifting from a problem-focused framing (e.g., the causes of coastal hypoxia) to a broader 'opportunity-focused' framing (Kristjanson et al., 2009; DeFries et al., 2012), that emphasizes opportunities to improve the social, economic, and environmental performance of agriculture via various 'win-win' approaches (e.g., creating new value by new productive uses of water and nutrients that are discharged from current agroecosystems). Such opportunity-focused framing puts a premium on ongoing communication and narratives with other social actors concerned with such emerging opportunities (Klerkx et al., 2010; Leeuwis and Aarts, 2011).

As well, there is a second framing challenge: creating an effective research agenda and work plan that makes good use of the range of disciplines and expertise present in a large-scale, multi-investigator project. This inward-focused framing is the essential complement to the outward-focused framing discussed above. Such framing must be responsive to the relationship between the project and other social actors, while also exerting a reciprocal influence on outward-focused framing. Inward-focusing is challenged by the range of theoretical frameworks, epistemologies, habits of mind, and methodologies among multiple disciplines (Dewulf et al., 2007), even when these are relatively closely related (e.g., agronomists and soil scientists).

Evidence suggests that both outward- and inward-focused framing can proceed by certain communicative activities within projects (Dewulf et al., 2007; Oughton and Bracken, 2009). Crucial activities include convening project participants, providing 'translation' to avoid misunderstandings, and mediating disputes (Leeuwis and Aarts, 2011). The purpose of these activities is to cultivate critical self-awareness among participants about their frames and the framing process, to promote a willingness to learn the frames of others, and to foster the integration and synthesis needed to create an effective frame from the research project. Even when communicative processes are effective, framing is not a rapid process in projects that span disciplines (Stokols, 2006; Oughton and Bracken, 2009). Moreover, such projects should engage in ongoing evaluation, renegotiation, and adaptation of both kinds of framing (Oughton and Bracken, 2009) as projects proceed, both scientifically and in relations with networks of social actors that are engaging with the issues of concern to the project (Bartunek, 2007).

Structural equation modeling (SEM), which can integrate both visual and statistical expression of complex hypotheses at all stages of the research process—from planning to analysis—provides a powerful means for achieving these framing goals. Additionally, there are other approaches for 'visual thinking' via simple graphic models that can complement and extend the insights from SEM. Shared model-building efforts are central to the communicative processes of effective framing (Hovelynck et al., 2010). We propose that, in addition to statistical hypothesis testing, SEM in combination with other visual thinking models provides a basis for framing and re-reframing as research projects progress. Though we will focus on agro-environmental research questions here, we expect this approach is equally applicable to multifaceted research programs in other fields. The statistical uses of SEM have been well documented elsewhere (e.g., Grace, 2006). Thus, our goal here is to highlight the properties of SEM that make it a useful tool for framing, focusing, and conceptualizing multidisciplinary research questions and refining research activities.

In the sections that follow, we briefly describe the foundations and philosophy of SEM. Next, we provide a case study of our experience with SEM as a guiding framework in an ongoing multidisciplinary, multisite field investigation of climate change adaptation and mitigation in row crop agroecosystems using precision zonal management systems. We then discuss three elements of the SEM framework that we feel are most beneficial to multidisciplinary research teams: *common language*, *iterative critical evaluation*, and *facilitating discovery*. We conclude with recommendations for integrating an SEM framework within future research programs, particularly where 'broader impacts' of the research are paramount.

A BRIEF INTRODUCTION TO THE PHILOSOPHY OF STRUCTURAL EQUATION MODELING

Structural equation modeling offers a means of proposing hypotheses about causal relationships among multiple, potentially correlated variables in complex systems (Grace, 2006). There are two features of SEM that make it a particularly flexible tool. First, when considering causal

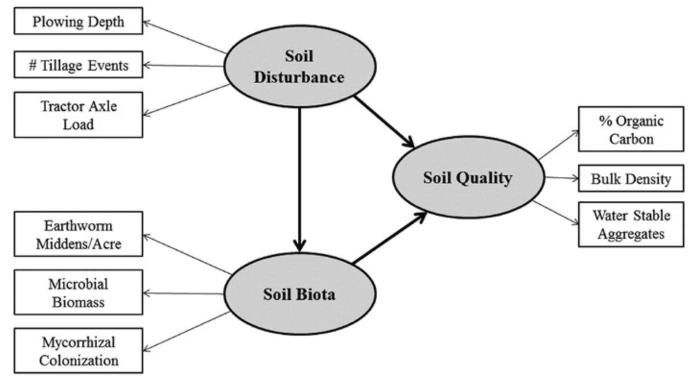

Figure 1. An example structural equation modeling (SEM) illustrating the relationships among soil disturbance, soil biota, and soil quality. Note that the arrows point from the latent variables to the manifest variables. Structural equation modeling uses the convention that the measurements of the manifest variables, such as percent organic carbon, are caused by the latent variables, such as soil quality. In other words, soil quality is the underlying condition that causes variation in the manifest variables, such that higher quality soils will have higher percent organic carbon, not the other way around.

relationships among variables, one may specify direct or indirect pathways. Direct pathways consist of simple regression relationships (A is linearly related to B), whereas indirect causal pathways have two components, a covariance relationship and a regression relationship (A has no direct relation to B, but covaries with C, which is linearly related to B). Whereas unstructured multiple regression models may highlight interactions among variables, they provide little useful information, with respect to scientific understanding or management, on the nature of such interactions. In contrast, structured regression models, such as SEM and classification and regression trees (CART), can decompose important interactions identified by multiple regression into contributing pathways, which may then be further investigated or provide a rational basis for management interventions (Williams et al., 2009, Davis and Raghu, 2010).

Second, SEM features different types of variables: concrete 'manifest' variables and abstract 'latent' variables. Variables that can be observed or measured directly (e.g., plant height or grain mass) are called 'manifest' variables. Variables that are more conceptual in nature, but can be rendered as a composite portrait through the measurement of multiple manifest variables, are called 'latent' variables. Manifest variables are taken as "indicators" of latent variables. For example, the unmeasurable, abstract notion of 'soil quality' could be defined as a latent variable that is estimated as a composite of measurable, manifest variables such as percent organic carbon, water stable aggregates, and bulk density. Causal pathways connect latent variables. To continue with our example, soil disturbance and soil biota may be latent variables that influence soil quality (Fig. 1). Unexplained sources of variation in the system can be dealt with by treating them as latent errors (Grace, 2006). The ability for a user to specify these latent, conceptual variables in SEM is one of its great strengths and forms the foundation for the types of project facilitation we discuss below.

Moreover, SEM encourages research groups to form multiple, alternate conceptual models of complex phenomena. Structural equation modeling itself proceeds by the development of competing causal models, which are then compared in terms of their explanatory power. By enabling specification and testing of a wide range of causal pathways that connect manifest and latent variables, SEM helps multi-investigator groups practice a form of science that is simultaneously conceptual and hypothesis-driven. Rather than focusing on a single hypothesis, SEM helps groups to conceive, specify, and compare alternative mechanistic models of complex phenomena, in the mode of 'strong inference' (Platt, 1964), and iteratively refine or even generate new hypotheses as data are collected.

A CASE STUDY

Structural equation modeling provides a united vision for conceptualizing project goals, critically evaluating methods and measurements, and is a foundation for revisiting (iterating on) previous framings and conceptual maps. An SEM framework has emerged as a central tool in the execution and management of our large, multidisciplinary project focused on climate change adaptation and mitigation in annual row crops. Structural equation modeling was initially introduced to the project during our first annual face-to-face project meeting which occurred soon after we were awarded funding in 2011. Members of our research team come from six universities and two USDA-ARS locations spread across five states, and many of us had not previously worked together. In addition, members of our group represent a number of disciplines including agronomy, plant and soil ecology, biogeochemistry, weed science, and soil science, and therefore each member of our team came to the project with their own disciplinary jargon and biases regarding "what is important" to study and measure. We all had slightly different ideas about what the project was about. Moreover, representatives within a given discipline could not always agree on what was the most appropriate measure of a particular phenomenon. Thus, while our project was not initially conceived within an SEM framework, we quickly discovered during our first face-to-face meeting that we needed to supplement our monthly phone conference calls, shared project website, and annual PI meetings with the development of a *common language* to better define and unify the project goals and activities among all the investigators.

To facilitate the process of developing this common language, each team member was tasked with constructing their own SEM diagram reflecting the factors and processes (i.e., causal linkages) they believed were most important to grain yield variability. Over the course of the ensuing month, each member uploaded their SEM diagram to our online project management site. The next conference call was spent discussing the resulting SEM diagrams (Fig. 2). The SEM diagrams varied in certain respects and were similar in others. For example, some SEM diagrams contained explicit latent variables representing the major conceptual factors and their manifest (indicator) variables, while others were more or less abstract. Certain diagrams elicited more discussion than others; however, each provided unique perspectives that helped each member of the group clarify their thinking, as well as understand their fellow investigators' conceptual models.

The real power of the SEM framework emerged during our next annual project meeting, in 2012, where the structural diagrams were used as scaffolding for ensuing discussions aimed at refining the set of common core measurements that would be collected across the study sites. By enabling us to *critically evaluate* the visual representations of our conceptual hypotheses, the SEM framework allowed us to determine the key variables that we would need to measure at each site. In addition, each project member left the meeting with a clearer understanding of the rationale for each variable measured and its supposed relationship to all other variables and the overall objective of the study.

Our appreciation for the SEM framework grew further during our most recent annual meeting, when we revisited the structural diagrams as a means of framing the meeting agenda. This time we had data with which we could assess our models and explore the adequacy of our initial conceptual hypotheses. We used the analytical results from the SEM to refine our latent variables and their associated manifest variables. Specifically, we reduced some of our core variables and sampling points and added new variables and better temporal resolution for other variables. This *iterative process* of conceiving a structural model and then confronting it with our initial data deepened our own understanding of the system and spurred sampling changes that will allow us to better capture the complexity and dynamics of our system.

One of the primary goals of our project is to relate soil and plant processes, moving beyond routine measurements of soil nutrient availability to include the biogeochemical drivers of nutrient cycling and yield stability. However, linking plant and soil processes is inherently difficult, in part because our plant and soil measurement techniques do not align in time and space. For example, many soil process measurements capture ephemeral, highly variable processes such as enzyme activity at a single time point or provide insights into microbial communities and their structure but not their functions. On the other hand, soil property measurements such as C stocks or specific C pools reflect interactions among many different processes over decadal time periods. Further, many soil measurements are operationally

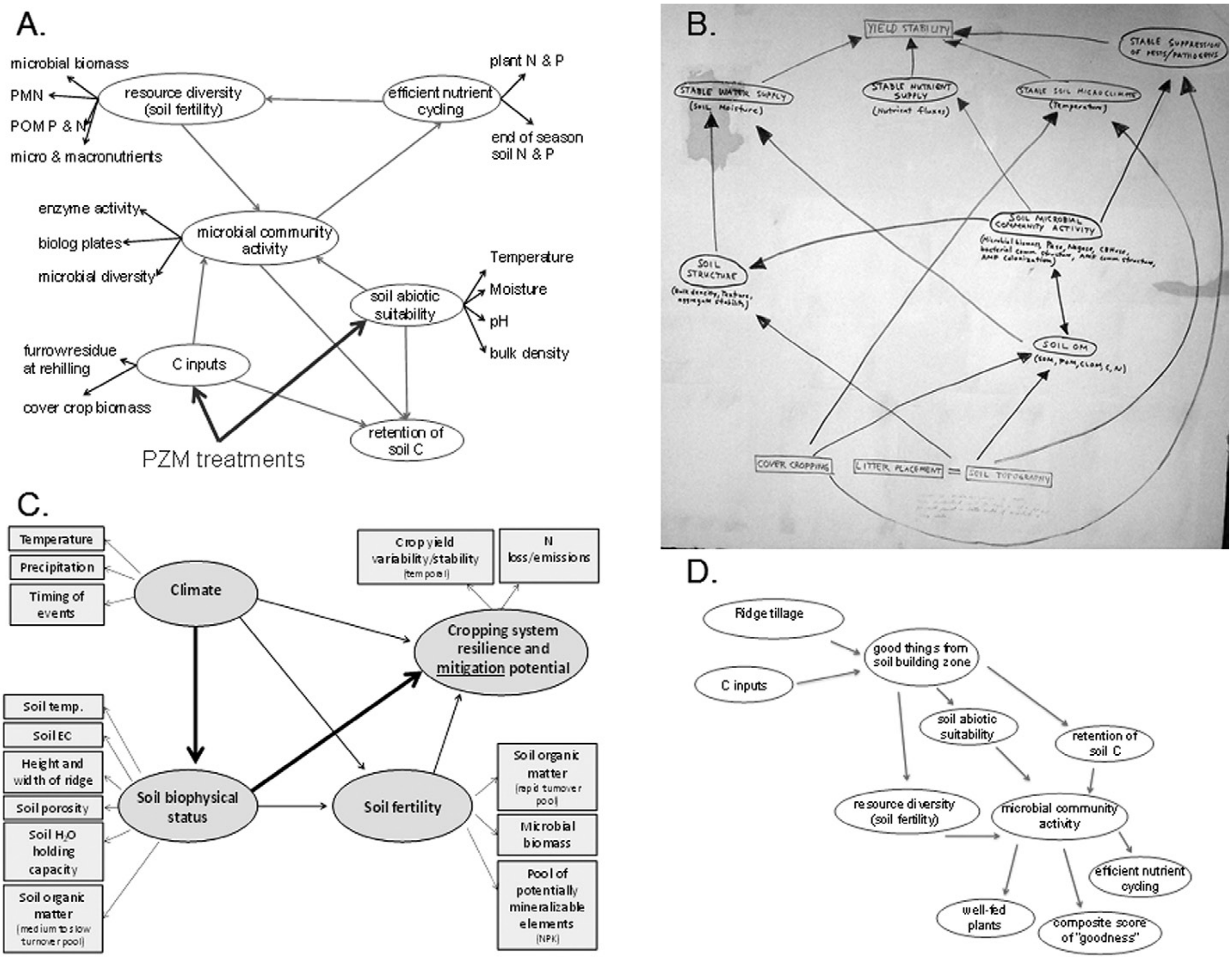

Figure 2. Structural diagrams generated by individual project members during the initial phases of the project. The importance of the soil system and its relationship to nutrient cycling is a common component of each, while conceptual emphases differ in philosophically interesting ways (e.g., note in B the focus on "stability" of outcomes while in A and D a broader range of outcomes are given consideration).

defined, making their interpretation highly subjective and challenging compared to plant yield measurements.

Such challenges in linking plant and soil dynamics proved a major obstacle early in our study, often setting the soil scientists and agronomists at odds over what soil measurements to make, not to mention how many samples to take. This resulted in a laundry list of measurements that included everyone's favorites. Among these were enough soil organic matter fraction techniques to fill up a textbook on the topic, including those based on chemistry (e.g., arguments were made for using pyrolysis gas chromatography–mass spectroscopy, nuclear magnetic resonance [NMR], and traditional chemical digestion methods) and biology (e.g., laboratory respiration rate measurements, which are so strongly influenced by the experimental approach that several different ones were considered essential), and combining these to understand C dynamics in multiple different density or particle size fractions. Similarly, we wanted to couple advanced genomic approaches to examining microbial community processes with whole food web characterization. While overly ambitious, our reasons at the time were grounded in our experimental approach: we wanted to capture how our precision residue management practices influenced the spatial and temporal synchrony between soil processes and crop growth. There is also a powerful psychological element at play that prevents restraint during the early stages of project development. In our newly formed project, we were quick to defer to someone with more expertise, and no one wanted to argue that someone's proposed measurements might be impractical.

We relied heavily on the SEM blueprint to sort through all potential measurements and select soil measurements that could provide insights into yield dynamics at multiple sites. Structural equation modeling forced us to ask whether our proposed measurements were sensitive to different soil management practices, sufficiently broad to reflect potential changes in a range of soil functions, and directly relevant to crop growth and yield. In other words, what soil measurements would help strengthen our SEM's predictive capacity by linking directly to yields or strengthening the relationship between a latent variable and its expected indicators? In the case of soil biological variables, we decided that earthworm populations, enzymes, short-term respiration rates, and coarse estimates of microbial community structure met these criteria. All these biological variables can be measured rapidly and should broadly reflect, and directly influence, differences in soil processes important to yield. Differences in microbial enzyme activities, for example, may indicate fine-scale variation in C, N, and P availability, while earthworms directly influence water flow dynamics and nutrient cycling. Regarding soil physical properties, we decided to focus on bulk density and aggregation. Aggregation—strongly influenced by soil organic matter dynamics, texture, and tillage management—also strongly regulates water dynamics, root growth, and long-term soil carbon storage. Thus, through an iterative process, our SEM blueprint helped us to narrow down our soil measurements and do it without offending our colleagues' interests in particular measurements.

So what became of our interest in more intensive, hypothesis-driven measurements? To more deeply probe the soils in our study, specifically the microbial communities and their relationship to soil C dynamics, we turned to our SEM to identify gaps in basic science that should be further explored. These projects are being performed by graduate students using cutting-edge genomic and molecular chemical methods. For example, using a subset of our treatments and sites, we currently have two Ph.D. students examining arbuscular mycorrhizal fungal (AMF) communities and their influence on microbial populations and nutrient cycling. Other students are examining similarly relevant questions, including the relationship between soil food web complexity and stability, the dynamics of nitrogen cycling at fine spatial and temporal resolutions, and the involvement of soil microbes in processing fresh cover crop residues and weed communities. Focusing on more intensive probing of fewer sites, we anticipate these studies will advance our fundamental understanding of crop–soil relationships under changing environments.

In this hierarchical research approach, our large-scale foundation study uses an SEM blueprint to find links between soil processes and yield dynamics, while the graduate students' process-level studies are intended to better understand these links. The SEM ensures these research tiers are constantly interacting, thus enhancing our opportunities for *discovery*. As our SEM is populated by data, new and probably unexpected relationships are likely to emerge. These relationships can be tested in follow-up studies performed by graduate students. For example, observing relationships between yield stability and microbial communities, AMF abundance, or interactions between water availability and earthworms would lead to new hypotheses to test in follow up experiments. Indeed, SEM generates clearer hypotheses than other multivariate methods, many of which can't provide more than a loose association among variables. The graduate student projects will also help inform the SEM, and point to possible gaps in our foundational experiment measurements.

BENEFITS OF THE SEM FRAMEWORK

The case study described above illustrates how a SEM framework has been instrumental in focusing our research questions, refining our data collection, and identifying gaps that could be addressed through process-level experiments. These benefits are explored more fully below.

A Common Language

An SEM framework facilitates a common, visual "language" among project participants with differing backgrounds and expertise by presenting a concrete representation of variables and their hypothesized inter-relationships (i.e., a causal diagram). This visual structure helps to organize disparate points of view and expertise and allows participants to overcome the technical jargon often inherent in each discipline. By representing the structural relationships among both conceptual (latent) and measurable (manifest) variables with a causal diagram, SEM enables participants to understand why particular variables are deemed important and how they relate to the "bigger picture." In contrast, many of us have experienced a less productive approach to multidisciplinary projects in which each project member advocates for measuring their own discipline-specific variables and the larger group cannot evaluate how these variables relate to other variables or the larger goals of the project. This often leads to coordinated projects that are interlaced, but that lack true multidisciplinary functionality.

Use of an SEM framework is ideal for focusing the discussion at the beginning of annual project meetings. In addition, an SEM framework can be nonhierarchical in that it doesn't depend on a "taskmaster" making assignments to the group. Rather, the process of causal model development encourages group input and expertise, improving group dynamics (Fig. 3). Because the analytical component of SEM requires that models be tested against alternative model structures, an SEM approach encourages—and indeed requires—alternative perspectives and variability in "world views" (i.e., hypotheses). Finally, revisiting the SEM at annual meetings ensures that the research project continues to be viewed as a whole, rather than broken into its discrete subdisciplinary parts.

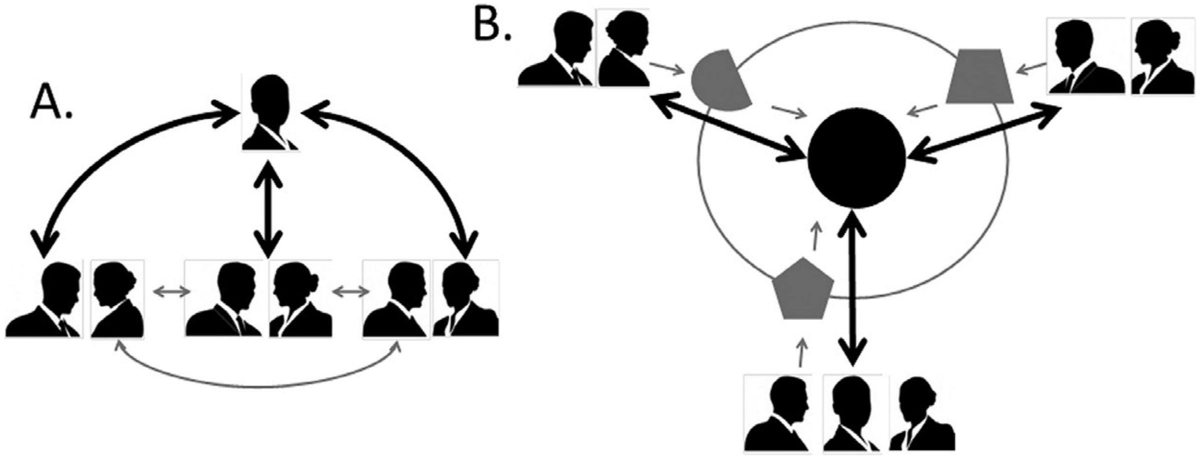

Figure 3. Two approaches to project development and organization. (a) In a hierarchical project organizational model, information flows mostly between groups from different disciplines and a single leader/coordinator, with less exchange between independent groups. (b) In the structural equation modeling (SEM) project organizational model, each group contributes a hypothesized model which is integrated with the others into a "consensus" or "working" model, providing a basis of shared language and understanding. Ideas flow from each group through the model to each other group. The big circle represents the consensus/working model, and the other grey shapes are the contributed models.

Iterative Critical Evaluation

One of the most important benefits of the SEM framework is that it encourages critical evaluation (and re-evaluation) of both the goals of the project and the causal assumptions and logical implications of the causal diagram (Grace et al., 2012). This critical evaluation results in more careful consideration of the data collection protocol (what, why, when, how, how many, and how often). Because the SEM framework facilitates translating latent variables into their component manifest variables, using the SEM framework to illustrate relationships among latent and manifest variables allows for the determination of which measurement variables to use to capture the nonmeasurable phenomena of interest. This process also illuminates the links between measurements and processes, thereby helping to refine the experimental design, prune out unnecessary or redundant measurements, and identify missing variables. In short, the SEM framework forces groups to be explicit in defining their question, experimental design, and data collection strategy.

The SEM framework also facilitates iterative refinement of the model and hypotheses over time as new information comes to light. While it may seem that this would introduce confusion into later statistical analyses, in fact, the development of multiple models representing competing hypotheses about mechanisms underlying agroecosystem performance offers an important opportunity for learning more about the system. This is particularly powerful for projects concerned with medium and longer-time scale phenomena such as ecological stability or climate resilience, since mechanistic models of stability are complex and can involve multiple indirect relationships. When model parameters are estimated using maximum likelihood methods, the group may evaluate the relative ability of different versions of the model to explain the experimental data (Grace, 2006). Such analyses can highlight the consequences of including certain processes or variables, or connections among them, for our understanding of agroecosystem function. This process can also be useful for identifying gaps and unexplained mechanisms that might be outside the scope of the project that investigators can use as a springboard for future corollary experiments. Because of this iterative element, an SEM framework will likely be of greater utility in longer-term (longitudinal) experiments than in shorter-term (e.g., <3 yr) studies, though the initial structuring process is useful for any experimental design (McCune and Grace, 2002).

An additional benefit of this critical evaluation via SEM, particularly when latent variables are considered, is to identify logical focal areas around which working subgroups can be formed. These working groups may include members with disciplinary expertise to help refine measurements and protocols associated with indicators of latent variables.

Facilitating Discovery

A number of the authors of this paper have been involved in large multiyear projects in which the feeling of progress is elusive. One of the main benefits of the SEM framework is that it demonstrates that progress is being made, as empirical data are tested statistically against the model. Evidence of progress is also apparent through the integration of measurements from disparate fields in a way that is not merely additive, because we discover that distinct components are actually interacting—something that would not be discovered if the different fields were not brought together through the causal modeling component of SEM. This systems-level approach fosters a holistic view of the problem and therefore is more likely to result in meaningful solutions (Fiksel et al., 2009).

LIMITATIONS OF THE SEM FRAMEWORK

Like all research methods, the SEM framework has its limitations. Developing, discussing, and evaluating competing SEMs is time consuming and may not be appropriate for simpler, disciplinary research projects. In addition, appropriate use of SEM requires that the group contain at least one member proficient in the method; otherwise, additional training will be necessary. Finally, the unifying power of the SEM framework must be balanced against the value of including component experiments that contribute to science, even if they do not contribute directly to the central model of interest. The SEM must not become so overriding that such component experiments are discounted.

RECOMMENDATIONS

It is recommended that a clear statistical approach be developed before the design of any experiment (Gotelli and Ellison, 2004). Building a SEM framework for project development at the proposal stage would be a means for achieving this goal. Revisiting the model at the start of meetings is an effective approach for ensuring that the experimental design remains robust. It is also important to note that employing a SEM framework does not mean trying to find the "right" model, but rather testing different models to see which is the most "useful." Additionally, the SEM framework does not obviate traditional statistical methods; SEM provides a framework and allows exploration of the relationships among multiple variables.

Several authors of this paper have been on other large, longer-term, multidisciplinary projects, and believe strongly that had an SEM framework been used, these projects would have proceeded quite differently. We recommend that more researchers become versed in SEM. A number of very accessible introductions to the application of SEM in the environmental sciences are available and include Grace (2006) and Pugesek et al. (2002). Our recommendation is that new proposals should be required to have structural models in much the same way that logic models are becoming standard proposal components. Revisiting the initial SEM in project annual reports/progress reports could be used as milestones in demonstrating progress.

More broadly, scientists working at the nexus of agriculture and other 'life-support systems' such as water, energy, and land, are increasingly aware of the need to link their scholarship to societal efforts to address challenges and opportunities in that nexus. As well, funding agencies are increasingly paying close explicit attention to how such linkage will be accomplished, for example, via the National Science Foundation's (NSF) emphasis on 'broader impacts' and USDA's logic models, which link scientific outputs to societal outcomes.

To better address this crucial question of 'linkage' or engagement, it is widely recognized that investigators must 'up-scale' their thinking about how their scholarship can provide resources for action on complex challenges and opportunities. This requires the outward-focused framing that specifies how a research program can provide knowledge that can lead to change on broad spatial-temporal scales, biophysically and socially (Jordan et al., 2007; Robertson et al., 2008). For example, research programs might consider how their results might interface with emerging strategies for transformative change in agriculture (Reganold et al., 2011), such as the development of more extensive and effective social networks that can recognize and address complex environmental challenges and opportunities. Further, we recommend that this type of outward framing, which appears crucial to attaining 'broader impacts' on complex agro-environmental challenges, be conducted within the context of and in concert with the inward-focused project framing that is facilitated by use of an explicit SEM framework.

CONCLUSIONS

Our purpose with this paper is to contribute to the development of effective methodologies for interdisciplinary research on climate change and other grand-challenge issues, because such methodologies remain major challenges despite urgent calls for interdisciplinarity (Phillipson and Symes, 2013). We believe that a SEM framework—which facilitates collaboration and transdisciplinary synergy via a common visual language, encourages iterative, critical evaluation of complex hypotheses, and promotes systems-level discovery—is one such methodology. A SEM approach to interdisciplinary research also offers opportunities for both outward- and inward-focused project framing necessary for strengthening linkages between research and engagement objectives. Wider adoption of SEM, and allied methodologies, within the agricultural and environmental science communities could be promoted by requiring interdisciplinary research teams to incorporate such approaches in proposals and resulting project activities. The grand challenges facing society are complex and will require a concerted effort among researchers, funding agencies, and stakeholders to capitalize on the creative synergy that arises from interdisciplinary and transdisciplinary research teams; a SEM framework could be a fruitful step in this process.

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References

Bartunek, J.M. 2007. Academic-practitioner collaboration need not require joint or relevant research: Toward a relational scholarship of integration. Acad. Manage. J. 50:1323–1333. doi:10.5465/AMJ.2007.28165912

Collins, S.L., S.R. Carpenter, S.M. Swinton, D.E. Orenstein, D.L. Childers, T.L. Gragson, et al. 2011. An integrated conceptual framework for long-term social-ecological research. Front. Ecol. Environ 9:351–357. doi:10.1890/100068

Davis, A.S., and S. Raghu. 2010. Weighing abiotic and biotic factors in weed seed predation. Weed Res. 50:402–412. doi:10.1111/j.1365-3180.2010.00790.x

DeFries, R.S., E.C. Ellis, F.S.C. Iii, P.A. Matson, B.L.T. Ii, A. Agrawal, et al. 2012. Planetary opportunities: A social contract for global change science to contribute to a sustainable future. Bioscience 62:603–606. doi:10.1525/bio.2012.62.6.11

Dewulf, A., G. Francois, C. Pahl-Wostl, and T. Taillieu. 2007. A framing approach to cross-disciplinary research collaboration: Experiences from a large-scale research project on adaptive water management. Ecol. Soc. 12:14. www.ecologyandsociety.org/vol12/iss2/art14/.

Fiksel, J., T. Graedel, A.D. Hecht, D. Rejeski, G.S. Sayler, P.M. Senge, et al. 2009. EPA at 40: Bringing environmental protection into the 21st century. Environ. Sci. Technol. 43:8716–8720. doi:10.1021/es901653f

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, et al. 2011. Solutions for a cultivated planet. Nature 478:337–342. doi:10.1038/nature10452

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, et al. 2010. Food security: The challenge of feeding 9 billion people. Science 327:812–818. doi:10.1126/science.1185383

Gotelli, N.J., and A.M. Ellison. 2004. A primer of ecological statistics. Sinauer Associates, Inc., Sunderland, MA.

Grace, J.B. 2006. Structural equation modeling and natural systems. Cambridge Univ. Press, Cambridge, UK.

Grace, J.B., D.R. Schoolmaster, Jr., G.R. Guntenspergen, A.M. Little, B.R. Mitchell, K.M. Miller, et al. 2012. Guidelines for a graph-theoretic implementation of structural equation modeling. Ecosphere 3:73. doi:10.1890/ES12-00048.1

Hovelynck, J., A. Dewulf, G. Francois, and T. Taillieu. 2010. Interdisciplinary knowledge integration through group model building: Recognizing dualities and triadizing the conversation. Environ. Sci. Policy 13:582–591. doi:10.1016/j.envsci.2010.04.002

Jordan, N., G. Boody, W. Broussard, J.D. Glover, D. Keeney, B.H. McCown, et al. 2007. Sustainable development of the agricultural bio-economy. Science 316:1570–1571. doi:10.1126/science.1141700

Klerkx, L., N. Aarts, and C. Leeuwis. 2010. Adaptive management in agricultural innovation systems: The interactions between innovation networks and their environment. Agric. Syst. 103:390–400. doi:10.1016/j.agsy.2010.03.012

Kristjanson, P., R.S. Reid, N. Dickson, W.C. Clark, D. Romney, R. Puskur, et al. 2009. Linking international agricultural research knowledge with action for sustainable development. Proc. Natl. Acad. Sci. U. S. A. 106:5047–5052. doi:10.1073/pnas.0807414106

Lauer, J.G., C.G. Bijl, M.A. Grusak, P.S. Baenziger, K. Boote, S. Lingle, et al. 2012. The scientific grand challenges of the 21st century for the Crop Science Society of America. Crop Sci. 52:1003–1010. doi:10.2135/cropsci2011.12.0668

Leeuwis, C., and N. Aarts. 2011. Rethinking communication in innovation processes: Creating space for change in complex systems. J. Agric. Educ. Ext. 17:21–36. doi:10.1080/1389224X.2011.536344

McCune, B., and J.B. Grace. 2002. Analysis of ecological communities. MjM Software Design, Gleneden Beach, OR.

Oughton, E., and L. Bracken. 2009. Interdisciplinary research: Framing and reframing. Area 41:385–394. doi:10.1111/j.1475-4762.2009.00903.x

Phillipson, J., and D. Symes. 2013. Science for sustainable fisheries management: An interdisciplinary approach. Fish. Res. 139:61–64. doi:10.1016/j.fishres.2012.09.012

Platt, J.R. 1964. Strong inference. Science 146:347–353. doi:10.1126/science.146.3642.347

Pugesek, B., A. Tomer, and A. von Eye, editors. 2002. Structural equations modeling: Applications in ecological and evolutionary biology research. Cambridge Univ. Press, Cambridge, UK.

Reganold, J.P., D. Jackson-Smith, S.S. Batie, R.R. Harwood, J.L. Kornegay, D. Bucks, et al. 2011. Transforming U.S. agriculture. Science 332:670–671. doi:10.1126/science.1202462

Robertson, G.P., V.G. Allen, G. Boody, E.R. Boose, N.G. Creamer, L.E. Drinkwater, et al. 2008. Long-term agricultural research: A research, education, and extension imperative. BioScience 58:640–645.

Robertson, G.P., and S.M. Swinton. 2005. Reconciling agricultural productivity and environmental integrity: A grand challenge for agriculture. Front. Ecol. Environ 3:38–46. doi:10.1890/1540-9295(2005)003[0038:RAPAEI]2.0.CO;2

Stokols, D. 2006. Toward a science of transdisciplinary action research. Am. J. Community Psychol. 38:63–77. doi:10.1007/s10464-006-9060-5

USDA NIFA (2011) USDA National Institute of Food and Agriculture AFRI Agriculture and Food Research Initiative 2011 annual synopsis. USDA NIFA, Washington, DC.

Williams, M.M., A.S. Davis, T.L. Rabaey, and C.M. Boerboom. 2009. Linkages among agronomic, environmental and weed management characteristics in North American sweet corn. Field Crops Res. 113:161–169. doi:10.1016/j.fcr.2009.05.005