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PERSPECTIVE

Effective monitoring of agriculture: a response

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The development of effective agricultural monitoring networks is essential to track, anticipate and manage changes in the social, economic and environmental aspects of agriculture. We welcome the perspective of Lindenmayer and Likens (J. Environ. Monit., 2011, **13**, 1559) as published in the Journal of Environmental Monitoring on our earlier paper, "Monitoring the World's Agriculture" (Sachs *et al.*, *Nature*, 2010, **466**, 558–560). In this response, we address their three main critiques labeled as 'the passive approach', 'the problem with uniform metrics' and 'the problem with composite metrics'. We expand on specific research questions at the core of the network design, on the distinction between key universal and site-specific metrics to detect change over time and across scales, and on the need for composite metrics in decision-making. We believe that simultaneously measuring indicators of the three pillars of sustainability (environmentally sound, social responsible and economically viable) in an effectively integrated monitoring system will ultimately allow scientists and land managers alike to find solutions to the most pressing problems facing global food security.

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Environmental impact statement

The current global agriculture system is not sustainable. It is marked by widespread hunger and malnutrition, rural poverty, vulnerability to climate change and environmental degradation and pollution. Solutions to agriculture challenges are elusive because tradeoffs among goals such as food security, economic development, and environmental sustainability are not being evaluated. A global network for monitoring agricultural landscapes[2] can empower science to better quantify the costs and benefits of agricultural practices within the context of multiple outcomes across spatial and temporal scales. Such analysis can inform restoration, extension, and other intervention efforts. By responding to the perspective by Lindenmayer and Likens[1] on 'Effective monitoring of agriculture', we aim to move forward the science underlying such a global network. The sooner we can accurately quantify opportunities in multifunctional agriculture systems, the sooner it will be possible to transition to a healthful, equitable, and environmentally sustainable global agricultural system.

Farmers around the world, be they poor smallholder or rich industrial scale corporations, are connected in a system through markets, policy and the environment. The current global agriculture system is not sustainable. It is marked by widespread hunger and malnutrition, rural poverty, vulnerability to climate change and environmental degradation and pollution. Solutions to agriculture challenges are elusive because tradeoffs among goals such as food security, economic development, and environmental sustainability are not being addressed. In a previous paper,[2] we argued that a global network for monitoring agricultural landscapes can empower scientists to more effectively quantify the costs and benefits of agricultural practices within the context of multiple outcomes across spatial and temporal scales. A major motivation of our short opinion paper was to instigate new thinking and engage participation for stronger agricultural monitoring.[3–5] By responding to the critique by Lindenmayer and Likens, we aim to advance the science underlying such global a network.

Overall, Lindenmayer and Likens' perspective[1] is predominantly oriented toward ecological monitoring paradigms and objectives. The monitoring program we suggest emphasizes and aims to monitor the social, economic and environmental outcomes of agriculture, including food and nutrition security, human health, economic viability, social well-being and environmental sustainability. Taking into account this transdisciplinary approach involving scientists, policy-makers, farmers and others, we would like to comment and expand on each of the three major concerns they identified with the monitoring network suggested in Sachs *et al.*[2]

A major critique is labeled as the "passive approach", lacking scientifically tractable questions and an explicit and robust experimental design.

First, we agree that in order to build an effective monitoring program, it is critical to start from a set of well-defined research questions. The central questions of our network are outlined in box 1, together with some specific examples from a recent list of the top 100 critical questions about global agriculture.[6] While these questions were implicitly present in Sachs *et al.*,[2] we agree they should be stated explicitly. We further embrace the paradigm of adaptive monitoring as previously described by Lindenmayer and Likens[7] that would allow for the incorporation of new questions generated using research outcomes. In addition, we believe that the development of these questions should be a participatory and iterative process involving multiple stakeholders to facilitate not only adaptive monitoring but also adaptive management.

Second, Lindenmayer and Likens[1] emphasize the need for a strong experimental design and they use the Rothamsted monitoring program as an example. We certainly recognize the need and critical value of long-term experiments. A difference in approach is that the proposed network aims to provide a bridge between these plot- and farm-level experiments and monitoring real-time changes and programs at a larger scale, *i.e.* at the landscape, national, regional and global scale

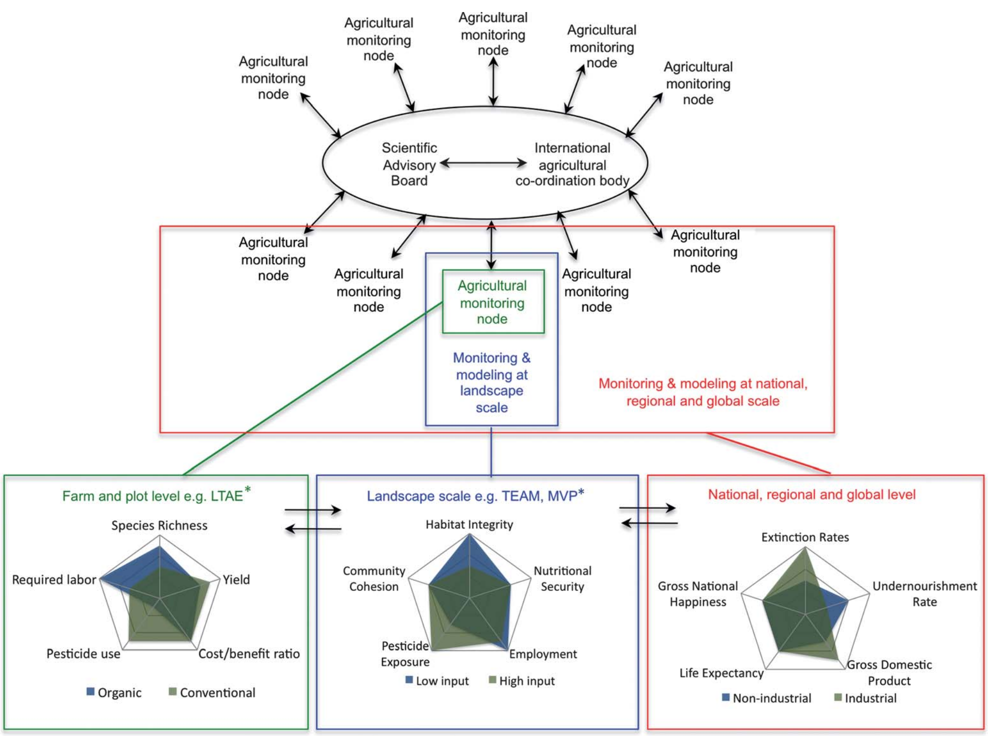

Fig. 1 Structure of the proposed network. The proposed monitoring network would be designed to collect environmental as well as production, social and economic data at varying scales and intensity in a nested hierarchical sampling framework and is illustrated here as an addition to Figure 1 in Lindenmayer and Likens.[1] Each of these three scales would be designed to build on and inform the other. Sentinel sites would be repeated within and across major agro-ecological and anthropogenic gradients, forming a network by design. At each scale, a different set of hypotheses could be tested, tradeoffs and synergies observed and thresholds identified. *LTAE - Long-term agroecosystem experiments; TEAM - Tropical Ecology Assessment and Monitoring; MVP - the Millennium Villages Project.

(Fig. 1). Science includes observational, experimental and theoretical research. Each contributes to scientific progress but is also limited in approach, and scientific knowledge lies at the confluence of all three. Data from long-term experiments like Rothamsted are critical for developing models on agronomic and environmental outcomes, but don't allow validation of how these models perform when practices are adopted on farm, on a wider scale, or under environmental conditions quite different from those used to develop and parameterize models (*e.g.* tropical agroecosystems). Such experiments also do not address the social and broader economic implications. We argue that agricultural monitoring should include experimental monitoring programs but also extend coverage to monitor performance and changes at the landscape and regional scale. We therefore propose a hierarchical sampling design (Fig. 1).

Third, Lindenmayer and Likens[1] highlight the importance of having replicated sites in order to have "adequate spatial replication of monitored sites to quantify relationships between various elements of the biota and different agricultural treatments". We agree with this. Part of the motivation of our paper[2] was to reach out to existing networks and scientists to build a network by design,[8,9] with sentinel landscapes repeated within and across major agro-ecological, climatic and anthropogenic gradients. We contend that such a global network is the most cost-effective way to provide the statistical power required for multivariate and multiscale analyses to quantify change, uncertainty and potential thresholds, and to quantify interactions (synergies and tradeoffs) between competing options and multiple outcomes.

A second major critique addresses the problem of uniform metrics.

In our paper,[2] we proposed the development of two classes of metrics: "universal metrics" and "site specific metrics". Universal metrics will be measured at all sites, such as what is taking place across 18.1 million sq. km of sub-Saharan Africa in the Africa Soil Information Service project, or in the Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA) project, the China National Soil Fertility Fertilizer Efficiency Long-term Monitoring Network, the Tropical Ecology Assessment & Monitoring (TEAM) Network and others. Site-specific metrics will be added according to local needs and conditions but following an overall common research framework. The goal is that the combination of these universal and site-specific metrics within a common framework will produce datasets that are consistent enough across sites to allow statistical analyses and application of models and site-specific enough to detect relevant change for a given land management type. An example of such an approach is found in the Alternatives to Slash and Burn (ASB) matrix of the Partnership for the Tropical Forest Margins, recognized for its success in producing scientific outputs and real world impacts and as a pioneer in integrated natural resource management.[10]

We are not arguing for a 'one size fits all', but we do argue for monitoring some metrics uniformly across sites for three major reasons.

First, such uniformity will increase comparability across sites and studies. Current lack of comparability often leads to conflicting messages and oversimplification of the debate on how to feed the world's population in the context of changing climate, rising energy costs and widespread ecosystem degradation.

Box 1. Research questions

There are a number of critical questions concerning the future of agriculture that scientists cannot answer given current data and tools. We argue that only through an effective global monitoring network developed through hypothesis driven science can we answer many of these timely questions. Furthermore, such a network could enable us to generate and address future questions that we cannot yet anticipate.

The proposed network would address the following key questions about agricultural sustainability:

- How do different agricultural landscape management strategies impact human well-being and the availability of ecosystem services? How do these impacts differ in different parts of the world and how does this change over time?
- What are the tradeoffs and synergies between the multiple outcomes of agricultural landscape management? How and to what degree are environmental and human outcomes coupled with each other?
- What are the biophysical thresholds and social tipping points for ensuring the availability of ecosystem services in agricultural landscapes? How close are different landscapes to these tipping points?
- What are the major drivers of change in ecosystem services in different agricultural landscapes and to what extent can change be predicted?
- Based on alternative land-use and management options for agricultural landscapes in different regions—with their associated environmental, social, and economic outcomes—what are the most appropriate strategies for allocating and managing land and water at regional to global scales to meet multiple societal objectives?

A global monitoring network would thereby help to answer many of the more specific questions outlined in *The top 100 questions of importance to the future of global agriculture*,[6] such as:

- 20. Where would natural habitat restoration provide the greatest food and environmental benefits to society?
- 21. What type and specific combinations of improved technologies, farming practices, institutions and policies will result in the maintenance of ecosystem services, including soil fertility, in agricultural systems undergoing intensification in developing countries, in particular in sub-Saharan Africa?
- 29. What is the appropriate mix of intensification and extensification required to deliver increased production, greenhouse gas reduction and increased ecosystem services?
- 68. How can the transition from today's smallholder based agriculture to sustainable agricultural intensification occur in ways that maintain livelihoods for smallholder farmers?

Examples are debates concerning the merits of chemically intensive agriculture using fertilizers and pesticides *versus* knowledge-intensive agro-ecological approaches,[11,12] land-sparing *versus* wildlife-friendly approaches[13] and policies that encourage biofuel production.[14,15] Discussions and decisions on these issues should be based on scientific evidence, be context specific and be responsive to the multiple goals of agricultural sustainability.

Second, consistency will enable the identification and quantification of social and ecological patterns and the availability of ecosystem services across sites and across agro-ecological and anthropogenic gradients. For example, as landscapes move towards agricultural intensification, the range and quantity of available ecosystem services change (Box 2).[16,17] It is, however, not known to what extent the availability of these ecosystem services changes with intensification, and to what extent these ecosystem services could be maintained or restored through alternative production systems. Using sites across the gradient of agricultural intensification will give critical insights to these relationships and enable a better understanding of the dynamics of human natural systems and how these change with different production and management systems.

Third, uniform metrics will be critical to generate and validate novel analytical local, regional and global models that allow evaluation and prediction of tradeoffs, synergies and thresholds in agricultural landscapes and that can be used as supportive tools for decision-making on the ground. Although there are numerous tools for data analysis, there is a critical need to improve the flow of information between agro-ecological data collection and modelers. By connecting sentinel sites through a global network, ground-level monitoring will provide consistent data critical for parameterizing and ground-truthing landscape models that can be linked to regional and global models. Further, by engaging stakeholders in the selection of metrics and monitoring process from the beginning, a global network will facilitate adaptive management and enhance understanding of mechanisms of decision-making.

A third critique focuses on the problem of composite metrics, *i.e. metrics whose values are determined by a mathematical formula involving other metrics.*

While we are aware of potential problems of composite metrics, *e.g.* limited relevance of some metrics across sites, we also recognize the need for some composite metrics to translate certain measurements into decision-making tools. Examples of such metrics that are relevant across different settings, include yield per unit of greenhouse gas emissions, nitrogen and water-use efficiencies, nutrient availability for human consumption and dietary quality index. Composite metrics can give useful insights across sites, particularly when

Box 2. Value of a global network for answering key questions about agriculture: an example

Question #68 from Pretty *et al.*[6]'s "*Top 100*": "How can the transition from today's smallholder based agriculture to sustainable agricultural intensification occur in ways that maintain livelihoods for smallholder farmers?"

Nowhere currently is this question more important than in sub-Saharan Africa where countries are investing in a new "African Green Revolution." To address this question, the hypotheses to test need to reflect the multiple potential outcomes (social, environmental, and economic) of intensification. By outlining the specific hypotheses in the African context below, we illustrate that such analyses would require a hierarchical sampling framework that incorporates 1) controlled experiments – at the plot scale, 2) monitoring – at the plot, household, community and landscape scale, and 3) modeling at the plot, landscape, region and global scales.

In the context of the current African Green Revolution our hypotheses and their monitoring framework thus might be:

H1. Relative to current low-input agriculture or to conventional high-external input intensification, agro-ecological intensification of maize production in the bimodal humid tropics of East Africa will:

H1.a. Increase food security of farmers

• Conduct controlled experiments at the field scale comparing yields and crops growth under different types and rates of inputs and management in different agro-ecological zones

• Monitor farm and plot inputs, outputs, food and nutrient availability, access and utilization

• Correlate production and consumption at the household, community and foodshed level

H1.b. Improve health for the farmer and their family

• Monitor nutritional status at the individual, household and community level

• Monitor the incidence of vector-borne diseases at the individual, household and community level

• Model the relationship between production and health outcomes across agro-ecological and anthropogenic gradients

H1.c. Increase income generation for the farmer

• Monitor household economics

• Model financial benefits for the farmer (taking into account subsidies, human and natural capital)

H1.d. Reduce environmental impacts

• Conduct controlled experiments to compare greenhouse gas emissions, nutrient leaching and runoff under different types and rates of inputs and management in different agro-ecological zones

• Landscape-scale monitoring of water quality, habitat and ecosystem service availability

• Model landscape level processes, hydrology, habitat, connectivity

H1.e. Increase social cohesion in the farmer's community

• Assess community interactions and stability

H2. There will be significant differences in the tradeoffs and synergies between the multiple outcomes of sustainable agricultural intensification, compared to current low-input agriculture, or conventional intensification they are generated relative to targets, to identify trends over time and spatial scales, and possibly indicate tipping points.[18] Furthermore, for these analyses to inform stakeholder decisions, it is imperative for scientists to convey our results in units that are readily understandable and meaningful to decision makers. Composite metrics are thus not being proposed as a substitute for underlying observed conditions, but as a complement.

In summary, we agree with Lindenmayer and Likens on most of their criteria for an effective monitoring program as follows:

• well-formulated questions that are posed at the outset of the work in dialogue with a diversity of stakeholders;

• ongoing development of new questions as initial ones are answered or as insights from research reveal important new issues;

• robust statistical design;

• high-quality data collection and careful attention to field data and field sample storage;

• well-developed collaborative partnerships among scientists, resource managers and members of other key groups;

• access to ongoing sources of funding; and

• strong and enduring leadership.

We argue that these attributes are necessary but not sufficient. To provide guidance for agricultural stakeholders, monitoring must be done beyond the extent of the plot or farm in order to capture dynamic ecological processes that happen at the landscape scale. We must also link agricultural production practices more strongly to social and economic outcomes, not just to ecological changes.[12] This will require co-location of data collection across these disparate disciplines. The design of this multiscale and multidisciplinary data collection is a challenge we need to address as a scientific community. The data must be collected in such a way that enables global comparisons across time and space, and thus requires some degree of uniformity. We thank Lindenmayer and Likens for their thoughtful comments and challenge them to help us design a system that will provide meaningful decision support taking into account the ecological, social and economic outcomes of agriculture.

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