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# Data and monitoring needs for a more ecological agriculture

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## Abstract

Information on the life-cycle environmental impacts of agricultural production is often limited. As demands grow for increasing agricultural output while reducing its negative environmental impacts, both existing and novel data sources can be leveraged to provide more information to producers, consumers, scientists and policy makers. We review the components and organization of an agroecological sensor web that integrates remote sensing technologies and *in situ* sensors with models in order to provide decision makers with effective management options at useful spatial and temporal scales for making more informed decisions about agricultural productivity while reducing environmental burdens. Several components of the system are already in place, but by increasing the extent and accessibility of information, decision makers will have the opportunity to enhance food security and environmental quality. Potential roadblocks to implementation include farmer acceptance, data transparency and technology deployment.

**Keywords:** agriculture, environmental monitoring, science policy, agroecology, food security

## 1. Introduction

The global agricultural system has provided food, feed, fiber and fuel to a population that has quadrupled over the past century. While output of agricultural products has increased over time, so too have negative environmental impacts (MEA 2005, Foley *et al* 2005). The market prices of most agricultural goods produced today do not reflect the life-cycle environmental impacts of production, transportation and consumption. Such information must be available if we are to have a more informed market, one that internalizes the environmental costs of agricultural production currently borne by society.

The challenge to provide for a larger, more affluent population in the coming decades while decreasing the environmental impacts of agriculture is increasingly clear to

both scientists and policy makers (World Bank 2008, Federoff *et al* 2010, Godfray *et al* 2010). Improved monitoring, cataloging, interpreting and dissemination of data about the status and trends of agroecosystems is needed if agricultural products are to be delivered with smaller environmental footprints and if their prices are to reflect the life-cycle costs of production.

Farmers and land managers have become the *de facto* managers of the largest anthrome, on earth—agroecosystems (Ellis and Ramankutty 2008). Often they do not have the proper resources for managing agroecosystems to maximize productivity and deliver ecosystem services simultaneously. In most cases, farmers make management decisions based on assessment of local conditions, previous experience and desired outcomes. Their knowledge can be supplemented with management recommendations derived from satellites, on-the-ground sensors and computer models that monitor and help forecast environmental conditions and crop needs.

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These new observations are like an added ‘pair of eyes’ that can help improve management decisions (Porter *et al* 2009). Limited examples of this adaptive management cycle exist where precision agriculture (PA) tools have been adopted, but there is a need for improved monitoring and information dissemination infrastructure to aid in decision-making (Bramley 2009, Lindenmayer and Likens 2010).

While the whole structure of an improved agroecological monitoring system has yet to be designed, researchers in both public and private sectors are currently developing many elements. These elements bridge remote sensing and ground-based monitoring systems with real-time, smart, wireless, internet-connected sensor webs (Rundel *et al* 2009, Adamchuk *et al* 2004). New technologies can assist in analysis and reporting of spatial and temporal variability across the agroecological landscape, while models can be used to transform raw data into useful information assets in the decision-making process (McLaren *et al* 2009, Hale and Hollister 2009). With these new data streams, systems must be designed to aggregate, coordinate, organize and synchronize within and between monitoring networks.

Expanding the current agroecological monitoring and analysis systems will not only require new technologies, but cooperation between governments, academia, private industries and farmers as well. Policy and economic incentives that explicitly value public goods will be vital to the success of any system. To overcome these challenges, an innovative multidisciplinary approach that leverages the available tools to deliver a more ecologically sound agriculture will be required. The momentum needed to implement this type of system can be initiated by policies to reduce the life-cycle impacts of agricultural production. This will require a more robust system to collect, analyze and disseminate data on the functioning of the agricultural system. Putting these data in the hands of decision makers has the potential to decrease environmental impact while increasing efficiency of production. In this context, we include a variety of actors in the term ‘decision maker’ whose choices can have an impact on the agroecological landscape.

There are many challenges related to sustainability to be addressed at the intersection of science, technology, agriculture, and policy. Availability of data on the dynamics of the agroecological system will be a necessary input toward information used in decision-making processes at the forefront of ensuring the sustainability of these systems. Here we review the state of on-going monitoring activities and propose pathways to implement an enhanced agroecological monitoring system that can assist producers, consumers, policy makers and scientists to make more informed decisions at the interface of the food system and environment.

## 2. Gaps in tools currently used to facilitate decisions in the agricultural sector

Predicting the impact of the global food system on the environment requires data assets on system functioning, responses to change, and the potential impacts of management decisions. Development of extensive datasets and numerous

models has been progressing, although enhancements in data collection methodology, aggregation and dissemination to decision makers at a range of scales are necessary to meet both production and environmental goals. Gaps in the patchwork of currently available data prohibit a broad evaluation of the current state and trends of environmental impacts from agriculture, and more effective responses could be implemented if adequately informed models and indicators were available to decision makers (O’Malley *et al* 2009).

### 2.1. Ground-based and remote data collection

Observations of agroecosystems monitor changes in agricultural or ecosystem processes, but seldom both (Lovett *et al* 2007). Commonly collected production data include the crop type (McNairn *et al* 2009), phenology/crop progress (Sakamoto *et al* 2005), area covered (Ramankutty *et al* 2008), and yield (Monfreda *et al* 2008, Wang *et al* 2010, Ross *et al* 2008). The US Department of Agriculture’s Foreign Agriculture Service provides agrometeorological data through their Crop Explorer tool that integrates stations, models and satellites on a regional scale (USDA 2010). Other satellite systems, such as SPOT (Satellite Pour l’Observation de la Terre), can be contracted to provide imagery that assists in monitoring a range of agricultural parameters. The spatial and temporal scales at which remote sensing and ground-based monitoring are conducted are seldom coordinated, which can hamper efforts to synthesize crop data at regional and global scales.

Environmental field data most often collected include quantification of soil water (Robock *et al* 2000, Zhang *et al* 2010), greenhouse gases (Baldocchi 2008, Bréon and Ciais 2010) and nutrient cycling (Batjes 2009). However, environmental data collection methods in agroecological landscapes vary based on the scale of interest and intended purpose. Irrigated areas can be detected from satellites, but on-farm water use data are best collected at the field scale. Fertilizer use (or run-off) can be calculated through production, sales data and application records, but these data are not often spatially referenced. Mapping of the global distribution of fertilized lands has only recently been accomplished (Potter *et al* 2010). Integrated monitoring of crop input needs and environmental variables is rarely undertaken in unison. A unified infrastructure of data assets has yet to emerge to organize the ongoing collection of ground-based and remotely sensed data.

### 2.2. Models

Models are useful tools for synthesizing data, simulating the relationship between environmental conditions and agroecosystem variables, and exploring such scenarios as potential management decisions, climate change, increased atmospheric CO<sub>2</sub>, and their impacts. Model output can sometimes replace field data when data collection is too costly, impractical or time consuming. Models can also be used to project the end of season field conditions based on initialization with field data and scenarios of seasonal weather. Some models are designed on first principles and validated by field data, while others are designed to reproduce the variability seen in

observations. Agronomic models that use input data (soils, climate, etc) in order to perform simulations rely both on the underlying structure of the model and on the quality of the input data. Therefore, if input data are limited or of poor quality, the model results may be inaccurate. Many models report a static set of results, but internet-based models can produce user-generated simulations on-the-fly (Eckman *et al* 2009).

There are three general modeling frameworks to simulate the components of the agricultural system that range in scale and complexity. Detailed crop models, like DSSAT (the Decision Support System for Agrotechnology Transfer), are used in both research and management activities (Jones *et al* 2003). Agroecosystem models, like Agro-IBIS (Integrated BIOSphere Simulator) and LPJmL (Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model), incorporate crop specific modules into existing models designed to study the interactions of ecosystems with environmental drivers of change (Kucharik 2003, Bondeau *et al* 2007). Integrated models, such as IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) and BLS (Basic Linked System) World Food Model, incorporate socioeconomic parameters into environmental and agronomic relationships to simulate the broader food system (Rosegrant *et al* 2008, Parry *et al* 2004). Given this variety of tools, there are many opportunities to improve the data flow between agroecological sensors, models, and end-users. Tighter integration between models and decision support systems can provide added value to decision-making processes by providing timely, relevant information to the hands of decision makers.

### 2.3. Indicators

In lieu of real-time data on the functioning of agroecosystems, a variety of indicators have been developed to relay information about the state of a system and how it might be changing. The Heinz Center (2008) defines an indicator as 'a specific, well-defined, and measurable variable that reflects some key characteristic that can be tracked through time to signal what is happening within and across ecosystems.' These indicators include information on the extent, chemical, biological and physical characteristics, amongst other goods and services provided by agroecosystems. Data collected at various spatial and temporal scales are used as inputs for indicators, but the use of an indicator can mask the complexity of a system (Payraudeau and Van Der Werf 2005). Current sets of indicators are useful, as they can assist in targeting regions and variables that are poorly monitored. The Heinz Center developed a thorough set of indicators for United States ecosystems, but adequate data existed to calculate only 30% of indicators, while another 30% had partial data, and 40% of indicators had insufficient data for calculation (Heinz Center 2008). The Organisation for Economic Co-operation and Development (OECD) created a similar set of indicators for the Heinz Center (2008) to provide information about the environmental performance of agriculture for their 30 member states (OECD 2001). Of the 37 indicators they developed, only

20 (54 per cent) were deemed to be scientifically sound; on average, 18 of the 30 countries (60 per cent) had adequate data. The paucity of data available to activate indicators further highlights the need for improved data collection, standardization and distribution.

### 3. Improvements in agroecological monitoring systems

Improved monitoring and integrated decision-making can help overcome many of the challenges that face the agroecological system. Many of these technologies are already available (Gebbers and Adamchuk 2010), but have seldom been incorporated in a systematic manner. Benefits from enhanced observations are likely to emerge when monitoring networks, reporting across different spatial and temporal scales, are integrated so as to reveal novel system behaviors. We propose that relaying these data, trends and management recommendations to decision makers in the field, or those crafting policy can bring about a positive feedback loop which can help achieve desired production and environmental outcomes.

Agroecosystems not only have their own ecological behavior, they are embedded within ecologies at larger scales. We suggest that monitoring should encompass the nested scales at which decisions are made across agroecological systems. These systems respond to drivers across many dimensions of space and time; from daily variation in soil micronutrients within a field to changes in weather over days and seasons, and climatic changes over decades. Monitoring current conditions gives decision makers the ability to manage with greater precision, while documenting trends over a longer length of time can help reveal potential thresholds and discontinuities, and assist in both short-term forecasts (e.g. end of season yields) and long-term adaptations. On-farm monitoring systems and portable imaging systems should be able to capture differences within and between fields, while earth observing systems can obtain a broader perspective of changes. The integration of ground-based monitoring networks with remotely sensed data into Earth system models has the potential to offer added value to scientists and decision makers alike.

At the farm scale, data from enhanced monitoring will likely be used if it is presented in a form that is easily integrated into existing decision-making structures (Kitchen 2008). If data from on-the-ground and remote systems is going to be utilized by several parties (e.g. farmers, scientists, policy makers, consumers), additional infrastructure will be needed to aggregate, process, model, store and disseminate data products. Wireless systems are already in place, at a small scale, to aggregate data from several monitors within a field (Wang *et al* 2006), and for satellite systems (Duveiller and Defourny 2010). However, an integrated information infrastructure foundation will be needed to transform raw data into useful products, and thereby ensuring effectiveness. Standards-based data transfer protocols from Open Geospatial Consortium (Nash *et al* 2009, Kooistra *et al* 2009) have been developed to seamlessly integrate multiple data sources.

To be effective, an agroecological monitoring system must capture changes over a range of processes. While crops in different biomes have individual biotic and abiotic needs, a general framework for monitoring needs can still be assembled. Agricultural inputs including nutrients and water support productivity, which is usually measured as yield. Records of crop varieties, planting extent and timing are also useful to treat food security issues. Ecological indicators such as soil type and fertility and meteorological indicators such as solar radiation and humidity help us understand longer-term production and environmental changes.

These data are the basic building blocks needed to ensure that the timing, magnitude and location of management decisions have the desired agroecological outcomes. The spatial scale and frequency of data collection will vary depending on the needs of the manager, with more frequent temporal data and greater spatial resolution preferred. The regional to continental extent of monitoring activities must include well-managed, highly productive systems as well as those in sub-optimal locations or with limited management in order to capture the full range and responses of agronomic and environmental variables.

Environmental sensor technology has continued to improve because of increased availability and sensor capacity and decreased cost. Given the extensive nature of agriculture, sensors capable of providing data at spatial and temporal scales useful to on-the-ground managers have been increasingly adopted (Lamb *et al* 2008). These improved sensors take advantage of innovations in data collection technology, data transfer capabilities between sensors and to the internet, on-the-fly data processing, and renewable and energy efficiency technologies (e.g. Pierce and Elliott 2008, Sun *et al* 2009, Conover *et al* 2009). This portends reduced monitoring costs, increased data availability, better spatial and temporal measurement scales and the ability to monitor more components.

### 3.1. Soil physical and chemical properties

Soil sensors to monitor nutrients, physical properties and sub-surface dynamics are already available. A range of sensors exist depending on the variable in question and includes electrical, optical, mechanical, acoustic, pneumatic and electrochemical types (Adamchuk *et al* 2004). Optical methods have shown the most promise for nutrient sensing (Sinfield *et al* 2010). Observation of the correlations between primary properties of optical sensing and quantities such as pH, cation exchange capacity and microbial activity have been documented (Nduwamungu *et al* 2009, Allen *et al* 2007). While the majority of soil sensors are ground-based, airborne hyperspectral imaging has been used to measure soil organic carbon (Stevens *et al* 2010). In comparison to traditional in-lab soil testing, these new approaches have been shown to reduce costs as much as 80% (Nduwamungu *et al* 2009, Wang *et al* 2006, Kim *et al* 2009), and do not require disturbing the soil structure (Serrano *et al* 2010). The accuracy of some measurements is not as great as their laboratory counterparts. For example, Christy (2008) used an on-the-go

near infrared reflectance spectroscopy sensor to map within-field soil organic matter with the laboratory measurements and sensor values that were in agreement with a RMSE of 0.52% and an  $R^2$  of 0.67. While not as accurate, the increase in sampling resolution, decrease in cost and synergy with other management activities has led to their increased acceptance.

### 3.2. Water

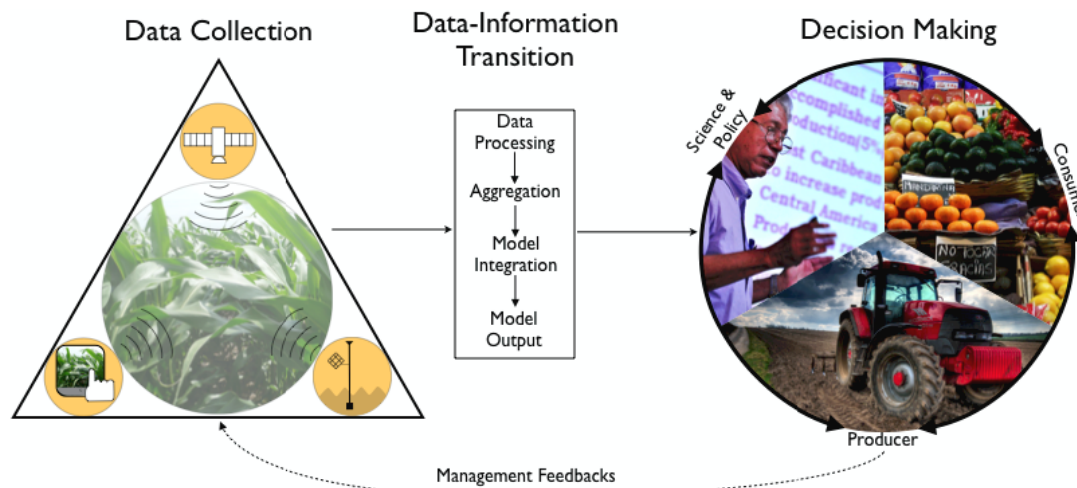
Monitoring soil moisture status, coupled with vegetation vigor, is necessary in order to understand how cropping systems respond to highly variable soil moisture conditions (Ozdogan *et al* 2010). In irrigated systems, crop water needs require higher resolution data than those commonly used so that water is provided in a more efficient manner given heterogeneous soil conditions (Greenwood *et al* 2010, Sadler *et al* 2005). Soil moisture sensors have been developed for below-ground, above-ground and remote monitoring. Champagne *et al* (2010) used a ground-based network to test the ability of a satellite-based passive microwave sensor with promising results. Data from in-ground soil moisture and temperature sensors in a cotton field were transmitted via radio frequency identification (RFID) chips to a central processor to assist in site-specific irrigation scheduling (Vellidis *et al* 2008). A ground-based optical remote sensing system was fixed to a center-pivot irrigation site to provide *in situ* measurements. These were used to compute a water deficit index, thus improving irrigation decisions (Colaizzi *et al* 2003).

### 3.3. Crop identification

Crop identification and yield monitoring data can be used to advise markets on crop production and progress, and for food security related questions, input to models, and on-farm management (Blaes *et al* 2005, Ozdogan 2010). Current approaches for crop identification across large areas use optical sensors, radar sensors, or a combination of the two (McNairn *et al* 2009). Jang *et al* (2009) used a series of Landsat images supplemented with the MODIS normalized difference vegetation index (NDVI) to discriminate between crop types with success. McNairn *et al* (2009) used a combination of optical sensors and radar for individual crop classifications across Canada with accuracies of 80–90%. Yield can be estimated from monitoring sensors located on the tractor (Ross *et al* 2008), or combined with satellite images (which have been calibrated with *in situ* data) for a broader spatial coverage (Dobermann and Ping 2004). Satellite remote sensing images can be used in conjunction with yield-forecasting models, but often need on-the-ground validation (Wang *et al* 2010).

### 3.4. Processing and visualization

Data collected by *in situ* or remote sensors are rarely useful by themselves in decision-making either on or off the farm. Integrating this information with other observations and numerical models, and then effectively communicating it to the decision maker can help to fully leverage these new data sources. Emerging systems include features such as on-the-fly error correction and modeling and the distribution of results



**Figure 1.** Major components of the agroecological sensor web and information infrastructure. Individual sensors including remote (e.g. satellite, aircraft, unmanned drone), automated *in situ* and direct human observations collect data at multiple spatial scales. These data are processed for quality control and data from multiple networks across spatial scales are aggregated. These data are used as inputs to agronomic, agroecological and integrated models. The output of the models can be used by producers for real-time management and long-term planning, consumers to discriminate products based on their environmental footprints, scientists to study the dynamics of agroecosystems and policy makers to guide policies to further reduce environmental impacts of agricultural production. Image credits (L to R): DPMZ and Flickr users stawarz, ostrosky and ciat.

to the internet or cellular phones. The Intelligent Sensorweb for Integrated Earth Sensing combines *in situ* measurements, crop growth models and online maps of predicted crop and range yields and transmits the product to managers (Teillet *et al* 2007). In South Africa, where the internet is less accessible, Singels and Smith (2006) report on a system to provide advice on irrigation scheduling to small-scale sugarcane farmers via cell phone, a technology that is much more readily available. Similarly, Antonopoulou *et al* (2009) created a personalized spatial model that incorporates policy, market, environmental, and agronomic information to the user via cell phone in Greece. In areas where agroecological monitoring may not be available, web crawlers ‘mine’ data from websites to provide information on the changing state of the system (Galaz *et al* 2009). While these examples do not necessarily provide the backbone to a novel monitoring infrastructure, they highlight what is possible with existing data assets and push the boundaries for future innovations.

### 3.5. Agroecological sensor webs

The monitoring systems described here have been deployed for decision-making at the farm and regional scales. The advent of internet-connected real-time wireless sensors presents a new opportunity to integrate data from a wide variety of sources and process them in a manner that the output is useful to decision makers. These sensor webs can reveal emergent biogeochemical properties of the agricultural system that may not have been otherwise observable with current monitoring infrastructure (Van Zyl *et al* 2009). New tools are required to build an agricultural information infrastructure for data organization, synthesis and integration as data become available from individual networks across the agroecological landscape (Hale and Hollister 2009) (figure 1).

As the amount of data produced by environmental and ecological sensor systems has grown, techniques in database management, informatics, statistics, spatial processing and visualization have emerged to meet the challenge of data handling, processing and storage (e.g. McLaren *et al* 2009, Uslaender *et al* 2010, Ball *et al* 2008, Jurdak *et al* 2008). For the most part, these new techniques have emerged at the fringes of traditional disciplines, for example, by bringing together biologists and computer scientists to contribute new tools (Benson *et al* 2010). Many of these tools can be applied to building an agroecological sensor web if these data are used as model input, and the model output is rapidly disseminated directly to the decision maker in a form that is deemed useful for the specific context (e.g. policy or land management).

## 4. Discussion

The limitation to implementing an enhanced agroecological monitoring infrastructure is not the sensor technology; rather it is leveraging the output data for decision-making on several levels that would reduce the negative impacts of agriculture on the environment. Unlike the current approach of precision agriculture, agroecological data must be paired with innovative policies to incentivize simultaneous production and environmental goals. There are many potential users of enhanced agroecological data, and there is no one-size-fits-all approach that incorporates data collection, processing and dissemination. The challenge ahead is not purely technical, as there are potential social barriers, such as privacy concerns, to data collection and dissemination. Designing useful products from such a system will require input from end-users to ensure their applicability and relevance to the challenges at hand. Information and decision support tools from agroecological monitoring can be used throughout the supply chain of

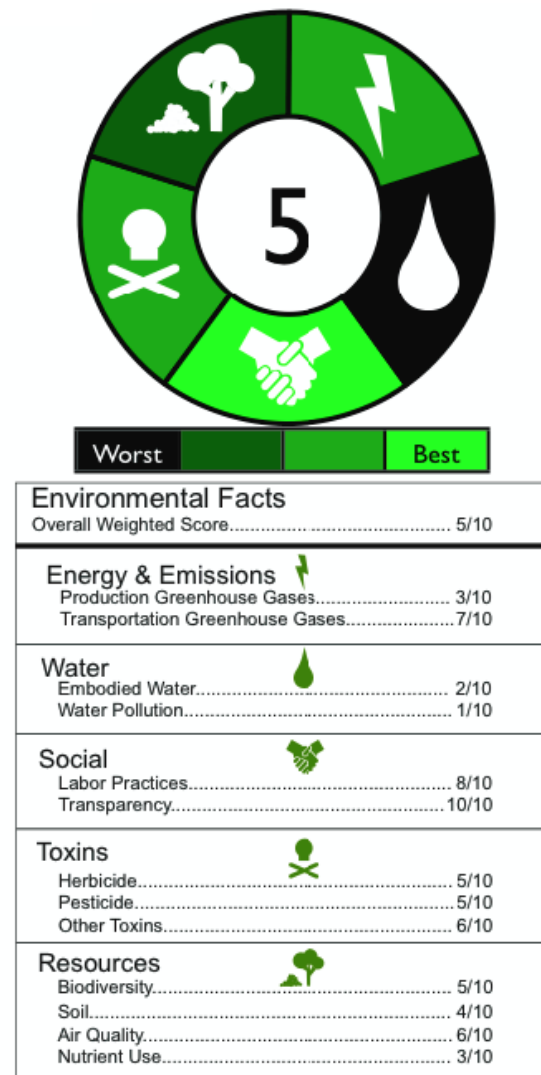
products, from producers and consumers to policy makers and scientists.

#### 4.1. Producers

Technology vendors, scientists and policy makers can extol the virtues of sensor web technology ad nauseam, but results will be limited to scientific results until a significant proportion of the agricultural community adopts it. For producers in developing countries, here is an opportunity to leapfrog the traditional development pathways and adopt the latest methods and technologies. But the acceptance of precision agriculture technology has been relatively slow thus far (Daberkow and McBride 2003, Sumberg 2005). One strategy to avoid falling from the ‘peak of inflated expectations’ to the ‘trough of disillusionment’ of technology adoption, as described by Lamb *et al* (2008) is to ensure the delivery of decision-relevant information to the producer, compared to raw data which has limited usefulness. Before too much hype is made about the many potential benefits of agroecological sensor webs, the systems sensor data need to be incorporated into decision support systems that allow the producer to explicitly understand potential trade-offs between management decisions and ecological and production outcomes (Fountas *et al* 2006). Some elements of this can be seen in precision agriculture systems currently deployed, although many systems lack the ability to provide real-time information on trade-offs related to economic and environmental outcomes of management decisions. Access to this type of management information can decrease costs for producers as agricultural inputs could be targeted. While some systems are in development, additional work is needed to ensure the transparency, reliability and ease-of-use of the software and its integration into current agricultural management tools. Once these objectives are met, there is a higher likelihood that a rapid adoption of agroecological sensor webs will ensue.

#### 4.2. Consumers

Informed consumers have the ability to shift markets through changes in their purchasing habits. Eco-labels and certifications are emerging as an approach to inform consumers about the products they purchase. Labels for products such as organic foods, sustainable wood products and energy-saving appliances have been growing in recent years (Ibanez and Grolleau 2008, Kotchen 2006). Additional food labels provide information on how the items were produced, such as fair-trade, shade-grown or dry-farmed (Howard and Allen 2010). While comparisons can currently be made between products with eco-labels and those without, little specific information is communicated to the consumer about the life-cycle impacts. As supply chains shift to increase the transparency of their products, data from agroecological sensor webs can be used to communicate the back-story of the product to the consumer (Opara and Mazaud 2001). Building on the success of other eco-labels, Faludi (2007) proposed ‘eco-nutrition’ labels that mimic the current labels on food products (figure 2). These labels would communicate energy, resource, water, toxins and social scores of the product’s life-cycle to the user and would



**Figure 2.** A representation of an eco-label that integrates data from several monitoring sources and clearly communicates the life-cycle environmental impacts of the product to the consumer. Figure adapted with permission from Faludi J 2007 *The Eco-Nutrition Label* (available at <http://www.worldchanging.com/archives/007256.html>).

allow for more in-depth comparisons among products. Similar graded eco-labels can provide consumers with information on multiple environmental performance indicators (Bleda and Valente 2009). Labels like these could be improved with enhanced agroecological sensor web technology.

#### 4.3. Science

Many of the models that simulate crops, ecosystems and economies are hampered by a scarcity of data about the system of interest. Limitations in computing power to run the simulations are being lifted as computers have become cheaper and more powerful. Integration of new data at higher spatial and temporal resolution, supplemented by historical data, can improve the precision and accuracy of model output. In addition, new streams of multivariate and multidisciplinary data will require the expertise of many disciplines to unravel

**Table 1.** Summary of the current and potential future components of an agroecological sensor web.

	Current	Future
Markets for food, carbon and other EGS	Carbon markets limited by lack of available data: nutrient markets in their infancy	Markets informed by data from agroecological sensor web
<i>In situ</i> and remote monitoring	Yield monitoring becoming common in high-input system, remote sensing algorithm output not explicitly designed for agricultural users	Access to data available to on-farm decision makers via internet and cellular phones in real-time
Data transparency	Limited public availability of data	Agricultural sousveillance joins other emerging monitoring systems
Product labeling	Product certification labeling lacks differentiation between impact categories	Products assigned grades based on water, carbon, nutrient, biodiversity impacts
Scientific models	Models driven and validated by limited observations	Social economic and environmental data streams used to constantly update model validation and modify projections
Impacts of production	60% of ecosystem services negatively impacted by agriculture	Reduced environmental impacts, increased food security
Social and environmental costs of production	External to product cost	Internalized in product cost

the agroecological complexities veiled under the many new layers of information.

While new data streams, such as those from an agroecological sensor web, may assist in further refining these models, they can also help to elucidate previously unknown or poorly understood relationships within the modeled system. Some newly collected data may not even fit into the structure of current models, and in this case new models will need to be built that can harness an input dataset with increased dimensionality over time and space. These new models can also help to create links between disciplines, especially in the physical and social sciences that are needed to solve problems and produce solutions for policy makers. These systems can also help to strengthen partnerships between developed and developing countries and foster the co-development of new models and knowledge sharing.

#### 4.4. Policy

At the most basic level, the interactions between policy makers and the agricultural system occur both at the marketplace and through the regulatory structure. Broad policies such as the US Department of Agriculture Conservation Reserve Program and markets for ecosystem goods and services have similar goals of striking a balance between production of agricultural goods and protection of vital ecosystem services. However, they must often rely on generalized information that lacks a connection between a parcel of land and its delivery of ecosystem goods and services. By incorporating data from agroecological sensor webs into a policy framework, a structure can be developed to provide incentives for lands that produce a suite of ecosystem goods and services, as well as the ability to value these services separately. These incentives can be modified according to updated data, an improvement on a program that values all areas equally. Performance-based incentives can reward producers for meeting environmental targets while decreasing the environmental burdens of production. Monitoring compliance for this type of incentive would be streamlined through the use of sensor web data.

In the near term, the fundamental data gap in need of attention is the monitoring of greenhouse gases (GHG) from

agricultural lands. As policies are negotiated to reduce GHGs across the US economy, emissions from agriculture may be excluded from a cap-and-trade system because they are hard to measure, monitor and verify (Smith *et al* 2007, Dale and Polasky 2007). The added transaction costs, and uncertainty in emissions reductions, have marginalized the 7 per cent of US GHGs emitted by agricultural activities (EPA 2010). Improved monitoring of carbon dioxide, nitrous oxide and methane from agriculture could provide the information and incentives necessary for carbon markets, policy makers and farmers to reduce emissions from the production life-cycle.

#### 4.5. Getting from here to there: innovation, investment and transparency

Many of the technologies highlighted here have yet to be deployed at the scale necessary to display the emergent properties of an agroecological sensor web (table 1). As the focus on agricultural innovation shifts to incorporate both production and environmental objectives, information and communications technologies (ICT) are likely to play a larger role. As investments and technological breakthroughs in ICT have generally been focused on sectors other than agriculture, there is tremendous potential to apply the technology already available to agroecological uses (Sassenrath *et al* 2008). Important advances are likely in approaches to transmit, store, process and aggregate data from multiple sources to aid in site-specific decision-making.

Sensor webs have already emerged at several spatial scales. Examples include the Global Earth Observing System of Systems (Justice and Becker-Reshef 2007), National Ecological Observatory Network (Keller *et al* 2008) and Chesapeake Bay Environmental Observatory (Ball *et al* 2008). These systems are driven by their own science questions and can serve as useful building blocks to address new agroecological questions. Like these examples, an agroecological sensor web will require the buy-in and support from many entities, expanding beyond the public sector. While the metrics for success will be variable, explicit goal setting amongst sensor web partners will be necessary to avoid unrealistic or unattainable goals.

The cost of installing an agroecological monitoring system is likely to vary as a function of the area covered, the variables tracked and the degree of integration with other systems. The diversity of potential stakeholders and end-users of the data introduces a variety of actors to help burden the cost of such a system and help bring it to fruition. Even with high initial capital costs, the benefits are likely to be high. Private benefits can include increased yields and decreased costs from inputs; public benefits include increased availability of ecosystem services from biodiversity, carbon sequestration, and water infiltration. Public and private investments will be essential to realize these benefits (Alston *et al* 2009).

The availability of data on how management decisions affect the provision of ecosystem goods and services can help to inform markets and offset the costs of monitoring (Swinton *et al* 2007, Dale and Polasky 2007). Tracking changes in production and ecosystem service delivery facilitates the internalization of costs from agriculture that were previously external. While developing these markets will require outside capital, as markets grow they should provide returns that help to build additional monitoring capacity.

The increased availability in wireless monitoring devices is not limited to the agricultural sector, but examples can be found in cell phone photography and closed caption television systems (Dennis 2008). The public availability of these new data streams has had a positive social benefit since they act as a deterrent for 'anti-social behaviors' (Ganasia 2010). The rise of sousveillance, where societal monitoring activities are becoming widespread and data are publicly available, has yet to be explored for agricultural applications. If the maximum benefit of sensor web technology is to be realized, then the data collected will need to have both on- and off-farm uses.

To date, most data collected on-farm for management purposes is not used in other ways and scientific and census data are usually collected independently. For example, The US National Agricultural Statistics Survey (NASS) promotes 'confidentiality and data security' in regard to data about agricultural production. With additional production and environmental data being potentially readily available, making all collected data publicly available and transparent has its merits. Consumers will be able to trace the origins of their products and monitor the conditions under which they were produced. This will compel producers to improve the environmental performance of their products. Increased transparency in the agricultural system can close the gap between producers and consumers through the monitoring and open distribution of agroecological data.

## 5. Conclusions

The grand challenge for agriculture over the next generation is to reduce its environmental impact while producing enough food, feed and fiber for a larger and wealthier population (Robertson and Swinton 2005). While the first green revolution brought increases in productivity, these carried environmental costs and the next generation of farmers will be in the vanguard to reduce those impacts. This cohort will be an increasingly digitally connected group and will have access to

unprecedented numbers of novel tools. As new farmers will be recruited into an occupation that has steadily decreased in size over the past generation, the image of the farmer needs to be recast as a 21st century steward of the land, equipped with digital tools, knowledge and skills to meet increasingly stringent multi-functional demands.

Moving enhanced agroecological monitoring infrastructure from research lab to farm field will take commitments and investments from a diverse array of stakeholders (Sachs *et al* 2010). Not only are there many technical elements in need of further development in the proposed system, but also the agricultural sector has been slow to adopt other potentially important innovations. Therefore the social, economic and environmental stakeholders in the system will need to be on board before a successful introduction is possible.

The opportunity to establish a global agroecological monitoring infrastructure along with information dissemination tools comes at a time when increasing agricultural demands and reducing environmental impacts from production have gained attention at the highest political levels. While this is a formidable challenge, we have recently entered an era where monitoring, data processing, numerical modeling and communications technologies have the ability to give agroecological decision-making new dimensions. Policies that provide incentives to create these new data streams and leverage their data to put an objective value on the ecosystem goods and services connected to agriculture are paramount. While the investment needed for such a system is large, the return on investment, as measured by agricultural productivity and reduced environmental impacts, can be great as well.

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