Models informed largely by sensor-supplied data can provide insights into the role of agriculture in carbon, energy, nutrient, and water cycles.

Multiscale Sensing and Modeling Frameworks

Integrating Field to Continental Scales

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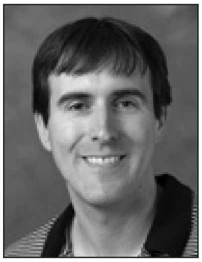
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Agriculture, which has traditionally been considered a source of food, feed, and fiber, is increasingly being identified as a source of energy and ecosystem services, such as biodiversity and climate, water, and pest regulation (MEA, 2005). The growing world population has significantly increased pressure on agriculture in both areas. Historically, agriculture has met societal demands by expanded irrigated and non-irrigated crop-production areas, increased automation, genetic selection and modification of plants, and better management and pest control, among other approaches. Some of these approaches provide few opportunities today for

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increasing agricultural production, but others are in the early stages of development and provide tremendous opportunities for further expansion.

Food production in greenhouses provides a glimpse of the possibilities for meeting increasing demands on agriculture. Modern greenhouse production involves large numbers of sensors and controls, as well as information technologies (IT), to optimize the production of specialty crops, such as fruits and vegetables. Although these specific technologies may not be directly applicable to crop production on a broad scale of watersheds, regions, and even continents, they do provide evidence of the value of sensing and IT in food production. For broader applications, these approaches would have to be greatly expanded and include multiscale sensing.

Computational models and computer-based decision-support systems are increasingly being used to assist with a range of agriculturally related environmental and resource conservation issues. These models rely on data from various sources, including sensors. As ecosystem services provided by agriculture become more important, models and sensor-supplied data in these models that can provide insights into understanding the role of agriculture in carbon, energy, nutrient, and water cycles will also become more important.

Thus, expanding sensing and IT will be critical to meeting the food, feed, and fiber requirements of a growing global population, as well as meeting energy and ecosystem needs.

In this article, we propose a multiscale framework that can meet the need for *in situ* point-scale sensing in continuous time to develop an understanding of fundamental physical and biological processes, spatially continuous sampling over extended areas by remote sensing technologies to represent phenomena at field, watershed, and regional scales, and models of processes that link across these scales and represent associated dynamic processes (Figure 1).

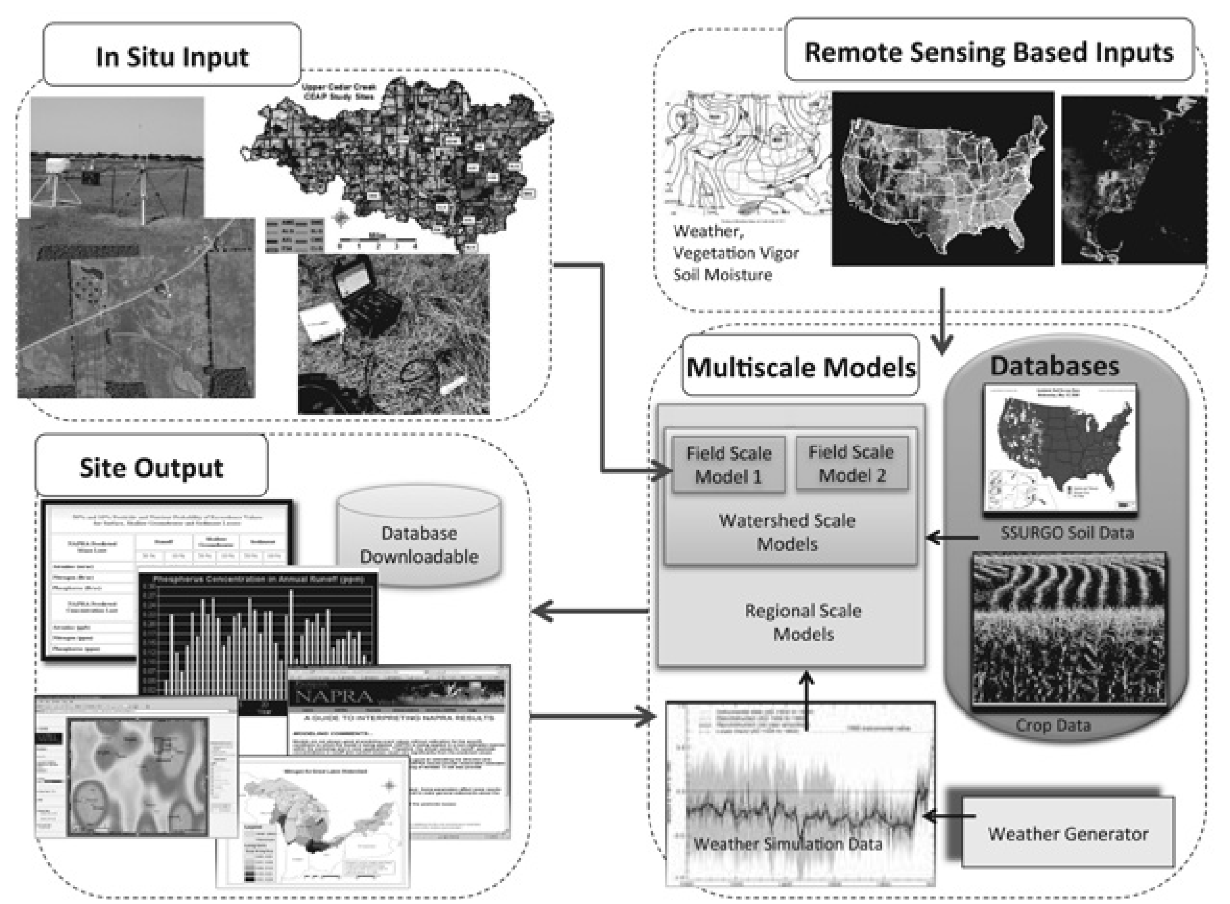

FIGURE 1 Multi-scale framework integrating *in situ* and remote sensing data collection, multi-scale modeling, and process representation to develop agricultural watershed management strategies.

Field-Scale Opportunities: Real-Time Sensing

Soil and climate conditions are key components in growing healthy and productive crops. With advances in precision agriculture, farmers now know more about their soils and crop yields than they have at any time since the mechanization and commercialization of agriculture began in the early 20th century (Lowenberg-DeBoer and Erickson, 2000). For example, yield maps now provide high-resolution information on inter-annual field-scale production variability, enabling farmers to adjust application rates of seed, fertilizer, and pesticides to maximize crop yields.

However, these are static sources of information generated after a crop has been harvested. They cannot provide immediate input about conditions that might lead to reduced productivity, nor can they be used to determine preventive solutions that could increase yield in a given season.

In Situ Technologies

Opportunities and Challenges

Inexpensive sensor technologies and wireless communication are increasingly being used in modern agriculture to provide real-time information on soil and meteorological conditions. Soil temperature and moisture are standard measurements that are important to crop yield. Low temperatures can slow seed germination and cause stress on young plants, thus increasing the likelihood of disease and smaller yields. Late-season planting can avoid cold soil temperatures but also decrease crop yields by delaying growth and development until drier weather later in the summer. Traditionally, soil temperature has been measured at a handful of sites in a state; in recent years daily values have been provided online.

Water stress, induced by limited water availability, is perhaps the biggest factor in reducing crop yield. Soil moisture measurements can provide information on plant water availability, but these data are not regularly collected. However, a growing number of inexpensive soil moisture and temperature sensors are available for use in farm fields to provide information on current conditions, and even to coordinate with irrigation scheduling systems (Oshaughnessy and Evett, 2008; *www.agmoisture.com*).

Measurement of local weather conditions, especially precipitation and air temperature, as well as wind speed, humidity, air pressure, and solar radiation, has been the responsibility of the National Weather Service through the Cooperative Observer Program (COOP), which was launched in 1890. Participants in COOP collect daily precipitation and air temperature measurements, which are distributed through the National Climatic Data Center and many state climatologist offices (*http://dss.ucar.edu/datasets/ds510.0/*).

Much of this information is now available to farmers in near-real time on the Internet, and many weather-related sites provide real-time storm tracking and forecasts ranging from hourly to 10-day blocks. Many commercial organizations have also begun to market meteorological-observation systems, which can be purchased by individuals and installed locally, with direct transmission of data into the corporate system.

These technologies not only provide farmers with site-specific meteorological information, they also contribute to new markets for companies that use these observations to create user-friendly agricultural decision-support products. Examples of such services include forecasts of good weather windows for planting, spraying, or harvesting and site-specific climate information for evaluating crop rotation or pest management strategies.

> *First-generation biosensors, such as the root oxygen bioavailability sensor, are leaving the laboratory and being used in the real world.*

Future Possibilities

Biosensor technology is still in its infancy, but first-generation biosensors are now leaving the laboratory and being used in the real world. One such technology, the root oxygen bioavailability sensor (Liao et al., 2004; Porterfield, 2002), mimics the consumption of oxygen by a root, and therefore the transport of water and nutrients into the plant. Oxygen consumption is as important to crop yield as soil moisture because the rate of consumption is sensitive to both dry and overly wet (oxygen-limited) conditions (Drew and Stoltzy, 1996).

Biosensors have also been developed that are sensitive to nutrients and contaminants of interest in agriculture, including nitrate and phosphate (McLamore et al., 2009). These sensors are currently limited in operational applicability by their short lifespan (days to months) and because they are designed for use in liquid media. However, as scientists merge their knowledge of biosensors with modern manufacturing technologies, such sensors will surely make their way into agricultural applications, including monitoring the distribution of nitrogen and phosphorous across fields and informing next-generation farm equipment about where more fertilizer should be applied to maximize production.

Measurement of carbon storage and fluxes will be important for agricultural systems to offset emissions in other parts of the economy. Current fluxes of carbon from soils are poorly understood, primarily because making accurate measurements is difficult and costly; it requires proper installation of chambers at the soil surface to capture fluxes or micrometeorological stations taking rapid measurements to estimate fluxes just above the soil surface. To be useful for climate-change adaptation and mitigation plans, however, newer, more cost-effective systems that require less operational oversight will be necessary for quantifying carbon fluxes and eventually for monitoring carbon sequestration.

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Communications Technologies

Exploiting Multipurpose Communications Systems

The integration of new and existing sensor technologies with wireless communication systems has already begun, and many companies now offer wireless meteorological and soil moisture sensor systems. With these tools, farmers can check the status of their fields before leaving the house.

Connections to cellular phone networks, satellite uplinks, long-distance radio frequency communications, and direct Internet or WiFi connections have all become relatively common and are often options for commercially available sensor systems (e.g., *http://www.campbellsci.com/communications*). However, there are still significant difficulties in initial installation of many of these technologies.

Advancing the State of the Art for Production Agriculture

Self-organizing wireless hardware and software for sensor networks have recently become commercially available (Martinez et al., 2004), making the development and deployment of sensor networks possible. Although these networks have great potential for agricultural applications, integrating communications, data acquisition, and sensor technologies into operational nodes in a stable, functional sensor network requires significant effort and knowledge and will require overcoming major challenges to their deployment.

Agricultural sensor networks must be robust enough to survive environmental extremes including rain, sun, and flooded fields. They must also be minimally intrusive, so they do not hinder access to the field by heavy machinery, and they should be designed to survive inadvertent run-ins with such machinery. In addition, sensor nodes must be designed for easy installation and removal, so nonfunctioning nodes can be easily replaced and all nodes can be removed prior to tillage.

Once these technological problems are resolved, probably in the coming decade, self-organizing networks could be integrated with inexpensive sensor technologies, making it possible for farmers to deploy networks rapidly across their fields and giving them immediate access to spatial and temporal information about field conditions. In addition, it should be possible for sensors to communicate directly with farm equipment and personal electronic devices, such as smart phones.

This would give farmers in the field access to both real-time and archival information about field conditions as they survey or work in their fields. Smart software or links to service providers could provide additional input about potential problem sites, potential ways to resolve those problems, and even suggestions for where to find materials or equipment or bids from other service providers.

Remote Sensing: Technologies for Scaling Information

Current Capabilities for Production Agriculture

"Remote sensing" refers to technologies that can make measurements without being in direct contact with the target of interest. Often characterized not only by the acquisition of a measurement, but also by the spatial and temporal resolution of data, information based on remote sensing provides capabilities for scaling *in situ* measurements and understanding physical and biological processes in systems that operate on watershed, regional, continental, and global scales. These technologies extend spatial coverage, provide information about inaccessible areas, and acquire unique measurements via a variety of sensing modalities.

Remote sensing technologies on tractors and combines and on airborne and space-based platforms are now integral to modern agriculture, with applications ranging from subsistence farms to large-scale mechanized production farms and high-value specialty crops. Remotely sensed precipitation, temperature, and wind speed are incorporated into weather predictions; Global Positioning System (GPS) data are assimilated into guidance systems for field operations; and advanced sensors are incorporated into specialty equipment for use in precision agriculture.

Imaging technologies most commonly used in production agricultural applications flown on satellites, airplanes, and unmanned vehicles record reflected light or energy from land/water surfaces. Multispectral sensors, such as the advanced very-high-resolution radiometer (AVHRR) sensors on NOAA satellites, have provided daily global coverage at kilometer scale for decades, resulting in widespread use of vegetation indices as indictors of crop vigor (Lillesand et al., 2007). In fact, these simple indices, which provide free data globally, are the most widely used inputs for models of agricultural yield and for empirical indicators of crop health.

More advanced products derived from the next generation of these sensors, such as NASA MODIS (*modis-land.gsfc.nasa.gov/*), are slowly being incorporated into models used in agricultural research and applications. Data products derived from the Landsat series of missions (*landsat.usgs.gov*) have also significantly improved a wide range of agricultural applications, although the 16-day repeat cycle is a limiting factor, particularly in cloud-covered regions. The availability of products based on multispectral data acquired by both space-based and airborne platforms has increased dramatically in the past decade, as satellites launched by both governments and the private sector provide capability for timely products to support agricultural applications.

Future Contributions to Agriculture

Imaging technologies can now simultaneously acquire hundreds of measurements in narrow windows (bands) of the electromagnetic spectrum. New active sensing technologies that emit energy in specific wavelengths and measure associated responses are also becoming commonplace. Three technologies that are evolving to operational level on airborne and space-based platforms are particularly promising for advancing the science of agriculture: (1) hyperspectral imaging; (2) active and passive microwave systems; and (3) laser-based systems.

> ***Soil moisture, a critical factor in crop condition, irrigation strategy, and predicting crop yield, cannot be measured directly and is difficult to derive from remote-sensing data.***

Coupled with corresponding advances in agricultural modeling and data-delivery systems, these technologies can revolutionize the characterization and prediction of agricultural processes on multiple scales. Like *in situ* sensors, these new remote sensing technologies provide opportunities for entrepreneurs to develop and deliver products to farmers.

Hyperspectral imaging sensors, which mimic laboratory spectrometers that provide chemistry-based information related to reflectance and absorption, provide two-dimensional images in hundreds of narrow bands. These data can advance the science of agriculture in physically based and empirical models to estimate chlorophyll content (Haboudane et al., 2008) and nitrogen content (Chen et al., 2010), monitor water stress, detect invasive species, evaluate water quality, and so on (Thenkabail et al., 2000). Commercially flown airborne hyperspectral sensors monitor high-value agricultural crops, and hyperspectral satellite missions are being developed by the international community for launch in the next decade.

Remote sensing-based soil moisture products are primarily based on **measurements in the microwave region of the spectrum**, where dielectric properties of soils under different conditions can be related to soil moisture. Although soil moisture cannot be measured directly and is difficult to derive from remote sensing data, it is one of the highest priority measurements for agricultural remote sensing. In addition to being a critical factor in crop condition, soil moisture is an important parameter for characterizing atmospheric and land-surface interactions and plays a role in regional and global weather patterns. Soil moisture is also of paramount importance in developing agricultural management strategies (e.g., irrigation) and predicting crop yield, as well as detecting and monitoring drought.

Current operational space-based soil-moisture products have low resolution (tens of km), which is useful for regional and global applications but of limited use for watershed-scale applications (Jackson et al., 2010). However, the upcoming launch of the NASA Soil Moisture Active/Passive (SMAP) mission (*smap.jpl.nasa.gov/Imperative*) is widely anticipated by the agricultural community because it is expected to provide advanced soil moisture products at resolutions that will be useful for watershed management.

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Laser-based systems, such as LIDAR (light-detection and ranging) systems, emit laser pulses of given wavelengths and detect energy that is intercepted and scattered back to the sensor. GPS-derived trajectories and the platform motion are combined with the time to interception of the backscattered energy to derive high-resolution three-dimensional presentations of the landscape (*lidar.cr.usgs.gov/*).

Airborne LIDAR products, which are widely used for floodplain, bathymetric, and urban mapping, are being investigated specifically for agricultural applications. LIDAR provides the most accurate remote sensing-based estimates of topography (and therefore slope and sun exposure), which are relevant to agricultural management decisions related to runoff (e.g., fertilizer application), crop production in high-relief areas, and soil mapping and management. Information related to the vertical structure of vegetation (e.g., height, density) can also be derived from LIDAR, providing a non-intrusive alternative to traditional destructive sampling (Dubayah et al., 2010; Selbeck et al., 2010).

These three advances in sensor technologies provide clear evidence of the potential of new data sources to support research and applications in agriculture in both the developed and developing worlds. Coupled with decision-support models and rapidly evolving communication technologies, these new sources of data have much to contribute to next-generation agriculture.

Closing the Gaps with Models

Enabled by the widespread availability of computational resources, significant advances have been made in agricultural models that can link and integrate across scales and processes. However, major challenges will have to be overcome before we can take advantage of the power of simulation modeling to evaluate agricultural production, its impact on environment and ecosystem services, and the development of sustainable management strategies. A few of these challenges are described briefly below.

Integration of Models at Different Spatial and Temporal Scales

In situ observations have long been used for the development, calibration, and evaluation of models—from field-scale models such as DRAINMOD (Skaggs et al., 1995), which simulates water and nutrient movement through subsurface drainage, to the WEPP model (Laflen et al., 1991), which simulates soil erosion from hillsides, to the soil and water assessment tool (SWAT) (Arnold et al., 1998), one of the most widely used catchment-scale models that can evaluate impacts of agricultural management decisions on crop production, hydrology, and water quality (*swatmodel.tamu.edu*).

Agricultural management decisions are made at field scales, but policy decisions apply on regional, national, or international scales. Currently, simulation models for analyzing the impacts of agriculture on the field to river-basin scale work in isolation from models that work on global scales. To enable agricultural production evaluations in a single modeling environment, these models will have to be integrated.

Remote sensing and sensor networks are two technologies that are helping to bridge the gap by providing spatial observations that can be used to scale processes from the field and watershed to larger scales. For example, large-scale variability in soil moisture is controlled largely by general conditions (e.g., when it last rained and vegetation type), whereas small-scale variability depends much more on local conditions (e.g., Crow and Wood, 1999).

Process Representation to Evaluate Competing Demands

Evaluating competing demands for services from agricultural lands (e.g., biomass production for food and fuel, water-quality improvement, minimum-flow requirements to meet the needs of ecosystems, etc.) will require an integrated modeling framework that includes ecosystem services, production of food and fuel, and the use of water to support agricultural production and ecosystem demands. The development of such models and frameworks will be essential for sustainable agricultural production in the future.

Sensors and Networks for Monitoring Water Quality

Monitoring water quality is very expensive and time consuming. This is the primary reason for the limited availability of global water-quality data products. In addition, *in situ* and remote sensing technologies for monitoring water quality can only evaluate a limited number of indicators. For the next generation of water-quality models, we will need sensors that can easily and inexpensively monitor parameters such as nitrogen and phosphorus concentrations, pathogens, and sediment in real or near-real time.

New Applications for Modern Communication Devices

Applications to support daily decisions (e.g., the location of the nearest gas station) on mobile communication devices have increased dramatically in the last few years, and the agricultural community also has access to some real-time data (e.g., crop yield). However, we need applications that can be used to evaluate the impacts of agricultural production on hydrology, water quality, and ecosystem services. The development of such applications will facilitate education and decision making for sustainable agricultural production and environmental quality.

Looking to the Future

Although the hurdles described above will be difficult to surmount, attention is now focused on advanced sensing, data storage and retrieval, communication capabilities, modeling, and advanced applications in the agricultural community. Coupled with the increasingly interdisciplinary nature of agricultural education, research, and commercial activities, the future looks promising for the development of new capabilities for meeting both growing demands for food, feed, and fiber, and for diverse ecosystem services in a rapidly evolving world.

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