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RESEARCH ARTICLE

A landscape perspective on sustainability of agricultural systems

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Abstract Agricultural sustainability considers the effects of farm activities on social, economic, and environmental conditions at local and regional scales. Adoption of more sustainable agricultural practices entails defining sustainability, developing easily measured indicators of sustainability, moving toward integrated agricultural systems, and offering incentives or imposing regulations to affect farmer behavior. Landscape ecology is an informative discipline in considering sustainability because it provides theory and methods for dealing with spatial heterogeneity, scaling, integration, and complexity. To move toward more sustainable agriculture, we propose adopting a systems perspective, recognizing spatial heterogeneity, integrating landscape-design principles and addressing the influences of context, such as the particular products and their distribution, policy background, stakeholder values, location, temporal influences, spatial scale, and baseline conditions. Topics that need further attention at local and regional scales include (1) protocols for quantifying material and energy flows; (2) standard specifications for management practices and corresponding effects; (3) incentives and disincentives for enhancing economic, environmental, and social conditions (including financial, regulatory and other behavioral motivations); (4) integrated landscape planning and management; (5) monitoring and assessment; (6) effects of societal demand; and (7) integrative policies for promoting agricultural sustainability.

Keywords Context · Farm · Incentives · Indicators · Scale · Spatial heterogeneity · Systems

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Introduction

Agriculture is the oldest way in which humans interact with natural systems, particularly through alteration of land for crop and livestock production and the redirection of energy, nutrients, water, or biomass flows towards human consumption. As people began to alter the land to produce food, fiber, and fuel, these activities started a process in which settlement patterns, land-management practices, crop selection, animal production, and landscape heterogeneity influenced each other over time in a continuous process of adjustment and development.

Current estimates of cropland and pasture vary between 24 and 38 % of the Earth's land. Crop production

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occurs on about 1500 million ha of the Earth's land surface [FAO (Food and Agriculture Organization) 2012a]. This area includes arable land and land under permanent crops and is about 30 % of the land estimated to be suitable for rain-fed crop production [FAO (Food and Agriculture Organization) 2003]. World crop production is expected to increase primarily through crop intensification complemented by the ongoing reallocation of land uses and expansion of arable land. Some studies suggest that increasing production to feed the world in 2050 could be achieved by closing "yield gaps" (e.g., Lobell et al. 2009; Sánchez 2010; Foley et al. 2011; Mueller et al. 2012). For example, yield of 17 major crops could be increased by 45–75 % if all lands planted to those crops achieved current attainable levels (Mueller et al. 2012). To feed the world in 2050, the Food and Agriculture Organization projected arable land area could increase by about 5 % as the result of expansion in the developing world of 120 million ha and a loss of 50 million ha in developed countries for a net expansion of 70 million ha [FAO (Food and Agriculture Organization) 2010]. About 90 % of the anticipated growth in crop production is expected to result from higher yields and cropping intensities [FAO (Food and Agriculture Organization) 2010]. Changes in climate, disturbance regimes, markets, management and other factors will affect the production and location of agricultural systems and add uncertainty to future projections.

Agricultural systems have expanded and contracted in response to the needs of a growing population and by becoming specialized for specific regions with favorable soils and weather conditions, such as rice in lowlands, sugar cane in Brazil and maize in the United States. Water-management practices include irrigation and drainage. Large areas of the landscapes with rain-fed agriculture, like the upper midwestern United States or low-lying regions of northern Europe, are drained to remove excess water, while Mediterranean and arid landscapes around the world require irrigation for intensive production. Some agricultural practices are similar to those employed hundreds or even thousands of years ago. For example, cultivation of Mayan gardens based on ancient farm practices continues to sustain production in some regions of Central America today (e.g., shifting cultivation and participatory land-use planning) (Dalle et al. 2011).

Increased human population has placed great pressure on agriculture by increasing demand for food, feed, fiber and energy and by displacing some of the best agricultural soils for other uses. Farmland continues to be diverted to urban and suburban development, industrial expansion, transportation networks, water management, biodiversity, leisure, tourism and other demands. A key question for sustaining agriculture is how to meet the growing demand for primary products while retaining or even enhancing ecosystem services (Millennium Ecosystem Assessment 2005; Mueller et al. 2012). Many of these services are related to processes occurring at scales much larger than that of a farm: preservation of water quality, pollination by non-domesticated bee species, nutrient retention in landscapes, soil retention, carbon sequestration, flood control, sustained water yield, and biodiversity conservation (Smith et al. 2012). Enhancement or degradation of environmental conditions can affect agricultural productivity (Dale and Polasky 2007) and, as a consequence, agricultural sustainability.

Agricultural sustainability issues

Defining agricultural sustainability

Agriculture has much to gain from the science of sustainability, which focuses explicitly on the interaction between nature and society (Wu 2006). Sustainability can be a philosophy or ideology, a set of strategies, the capacity to fulfill a set of goals, or the ability to continue making improvements over time under changing conditions (Hansen 1996). It commonly refers to practices that are environmentally sound, economically profitable, and socially just. How these practices are defined and balanced reflects society's priorities and therefore, definitions may change with time and circumstances. Reaching agreement on tradeoffs to achieve noneconomic sustainability goals remains a challenge (Kareiva et al. 2007). Devising cost-effective means to measure, monitor, and assess the relative sustainability associated with different components of heterogeneous agricultural systems, and the interactions among these components and broader landscapes over time, makes it difficult to reach definitive or universal conclusions about "best practices" for more sustainable agriculture.

The definition of agricultural sustainability depends critically on the boundary conditions established for the analysis (Hansen 1996). At a field scale, changes in environmental conditions are often the focus. At the farm level, profit margins and the consumption and production of resources are often the focus. At the larger social or policy scale, concern may exist for economic efficiency, equity, or the distribution of costs and benefits. The characterization of agricultural sustainability further depends on contextual considerations, such as the purpose of analysis, the production and distribution system, policy conditions, stakeholder values, location, temporal influences, spatial scale, baselines, and reference scenarios (Efroymson et al. in press). Here we take a landscape ecological perspective in considering sustainability of agricultural systems.

Consideration of agricultural sustainability must derive from the objectives of agriculture to provide an adequate food, fiber, and fuel supply for today's population without jeopardizing the capacity to provide the same services to future generations. Agriculture may involve additional objectives: providing a high-quality diet for all people at a reasonable price, maintaining farmers' income, maintaining the natural-resource base of farm systems (e.g., soil quality), and maintaining the supporting and provisioning functions of ecosystems. Farming objectives must be met within specific constraints derived from local and varying agro-ecological, economic, and social conditions.

Resource management options assessed in terms of specific aspects of sustainability can generate divergent outcomes. For example, modern beef production presents challenges in providing protein sustainably because there are large inefficiencies and energy losses in feeding grain to livestock to produce beef compared with feeding grains to other animals such as poultry or directly to humans (Horrigan et al. 2002; Foley 2011). But animal production can also contribute to overall system sustainability, for example, by using ruminant livestock that prefer perennials (Janzen 2011; Schiere et al. 2002), incorporating animals in organic farming systems (Kaffka and Koepf 1989), feeding post-consumer food wastes to animals, and using low quality resources for animal feed such as residues from the food processing industry, grain that fails to meet market standards for human consumption, and dried distillers grains (DDGs) that are a byproduct of corn ethanol production (Swanepoel et al. 2010). Optimal conditions for achieving different objectives can be defined for each level of analysis but are not likely to be consistent across different scales of analysis.

Measuring sustainability

Developing effective and cost-efficient methods to measure sustainability requires (1) selection of a limited set of indicators; (2) collection of data over appropriate spatial and temporal scales and a range of farming systems; (3) management and analysis of those data; (4) engaging stakeholders; and (5) communicating and acting upon results. Implementation of these steps should contribute to a social learning process reflected by continual feedback and improvement that builds capacity to respond to new social, economic, and environmental conditions. While progress has been made in addressing these steps [for example, by the U.N. Food and Agriculture Organization (FAO)], improvement is still needed across all five steps, including sampling methods, management practice definitions, and analytical tools that can be implemented inexpensively and quickly at the farm and watershed scale. However addressing these needs requires long-term research, which is both costly and time-consuming.

We endorse the use of quantitative indicators that are appropriate for assessing prevailing conditions, monitoring trends, providing a warning signal of impending changes, and diagnosing causes of change (Cairns et al. 1993). Much research has been conducted on environmental indicators related to agriculture (e.g., Bockstaller et al. 1997; Pretty et al. 2000; Rigby et al. 2001; Boody et al. 2005) as well as socioeconomic measures (e.g., Wei et al. 2009; Sachs et al. 2012). The challenge is to develop and deploy a suite of indicators that are readily measurable, that are related to social and environmental conditions at appropriate scales (Smith et al. 2012), and that can be used in establishing targets and baseline conditions for farm management, public health, and efficient policies (see Langeveld et al. 2007; Theobald et al. 2005).

Sustainability indicators include measures of both environmental and socioeconomic conditions. Environmental aspects of sustainability include climate forcing, biodiversity, productivity, and soil, water, and air quality (McBride et al. 2011) as well as resource use efficiency (Kaffka 2009). Socioeconomic aspects are tightly linked to environmental conditions but focus on social well-being, security, trade, profitability, resource conservation, and social acceptability (Dale et al. in press). However untangling the relationships among so many cross-cutting factors is challenging (Raudsepp-Hearne et al. 2010). Indicators have been proposed on the basis of being practical, sensitive to stresses, unambiguous, anticipatory, predictive, calibrated with known variability, and sufficient when considered collectively (Dale and Beyeler 2001; McBride et al. 2011; Dale et al. in press). Many studies have developed and applied specific agricultural indicators [e.g., on nitrogen management in the Netherlands (Langeveld et al. 2007), France (Pervanchon et al. 2005), and Africa (Smaling et al. 1999); landscape quality (Groot et al. 2010) and biodiversity (Dornburg et al. 2010; Guerrero et al. 2011; Langeveld et al. 2012)].

Some indicators proposed to assess sustainability require additional effort to develop standard, consensus-based definitions and protocols for measurement. Challenges persist and more research is required to develop data and measurement tools at appropriate scales for indicators of greenhouse-gas emissions, food security, energy security, and risk of catastrophe such as severe drought or major disturbance (McBride et al. 2011; Dale et al. in press). Compare, for example, different approaches applied for the calculation of GHG balances of biofuel production chains in Brazil (Do Amaral et al. 2008), the USA (Liska and Cassman 2008) and Europe (Mortimer et al. 2004). Furthermore, the absence of consistent definitions and relevant data needed to assess food security at appropriate scales for sustainability analysis has led to contentious debate [NRC, (National Research Council) 2012]. And while energy security is related to food security (energy is essential to grow, transport and prepare food), it is also entwined with economic security and military and foreign policy (Greene and Leiby 2007). For example, biofuels can enhance agricultural and energy security when they lead to reduced dependence on imports from unreliably or non-competitively supplied fuels and when market diversification reduces price volatility. However, untangling the interactions and feedbacks among agriculture, energy, water and other competing resource sectors at multiple scales remains a major challenge.

Data and indicators are crucial in providing insight into the way existing practices interact with their environment and affect quality of resources and living conditions. Their application in analyses or decision-making requires, however, an evaluation of the validity, reliability and relevance of the methodological and theoretical frameworks underpinning the data, indicators and tools used for their interpretation. Ideally, indicators and related analytical tools should be practical, transparent, user-friendly and corroborated by good data and balanced research. Examples of analysis tools that incorporate sustainability indicators are the Centre for Economic and Environmental Development (CEED) Green Light Sustainability Toolkit (http://ukceed.org/what-we-do/sustainability-tools/) and radar diagrams as a way to present multi-dimensional sustainability analysis (e.g., http://www.planbleu.org/publications/cahiers3_imagine_uk.pdf).

Toward integrated sustainable farming systems

Evaluation of agricultural systems is not limited to land and production resources but also includes storage, transportation, processing of primary and secondary products, packaging, distribution, and waste management along with the infrastructure associated with each of these steps in the supply chain. Integrated agricultural systems include the full supply chain and are designed to have all components work together smoothly. The goal is to minimize inefficient use of inputs like fertilizer or the unsafe use of pesticides, which can cause harm to the environment or affect the health of farmers, consumers, and other species. Well-designed integrated management plans can help optimize the use of important assets for agricultural systems, including natural, social, human, physical, and financial capital. Pretty (2008) identified examples of integrated sustainable agricultural practices and systems that include pest, watershed, irrigation, forest, and credit management. Mueller et al. (2012) highlighted opportunities to increase global cereals production with minimal changes to total worldwide nitrogen and phosphate applications by eliminating overuse of these fertilizers in some regions and targeting fertilizer use on deficient soils.

Often, improvements in agricultural efficiency, i.e., increasing outputs relative to inputs, are used as a basis for assessing sustainability (Monteith 1990). The focus on efficiency in business-based agricultural systems has spurred persistent intensification in industrialized agricultural economies such as the United States, where multiple technical advances are often employed simultaneously. However, there can be negative impacts of “efficiency” and “intensification” on other portions of the system. For example, the push for intensification has been associated with adverse social impacts (e.g., Lobao and Stofferahn 2008) and localized declines in biodiversity (Guerrero et al. 2011) and landscape heterogeneity (e.g., Brown and Schulte 2011). But there can also be positive effects such as increased abundance and diversity of foods, lower food prices, better distribution, and food security. And where intensification prevents extensification (the expansion of agricultural production into previously undisturbed forests and other natural landscapes), then biodiversity can be conserved. Collective changes in such systems can differ from the simple sum of costs and benefits measured individually (de Wit 1992). Agricultural intensification has been shown to help reduce greenhouse-gas (GHG) emissions while increasing production. For example, between 1961 and 2005, intensification allowed significant yield increases [e.g., doubled cereal yields, especially in the Americas, Asia and Europe (FAO (Food and Agriculture Organization) 2012a)] and avoided emissions of up to 161 GtC (590 Gt CO_2 eq) (Burney et al. 2010). Thus, investments in yield improvements and more efficient farming practices have been effective tools for reducing GHG emissions from farming and are likely to continue doing so.

The influences of intensification on animal production are complex, and the effects of scale are not always apparent. For example, in confined animal feeding operations (CAFOs), ideally the stocks and flows of nutrients are closely managed to apply animal wastes toward efficient production of animal feed. In practice, manure can accumulate or be contaminated and become a significant pollutant. Matching feed nutrients to animal requirements is realized by the use of animal and crop genetics, optimized least-cost ration balancing, use of feed additives and supplements, precise characterization of all feed components, and accurate growth and intake monitoring to maximize livestock growth and reduce excretion of excess nutrients in manure (Clark 2007). CAFOs in the United States and Europe sometimes manage manure removal, transfer, and storage for nutrient conservation. Such systems monitor nutrient flows to avoid losses and commonly meter applications based on actual nutrient contents of manure, soil needs, and anticipated crop requirements. Yet there are great opportunities to improve human and animal health and environmental conditions (Pelletier et al. 2010). Manure processing can remove water; concentrate and stabilize nutrients; and extract marketable fertilizers, soil amendments, bedding materials, and energy from manure. Technologies are being developed to improve the precision of manure application and crop nutrient uptake (Clark 2007) and to address broad-scale effects such as nutrient leaching impacts on water quality (Cabot et al. 2006; Pretty 2008).

Resource-management decisions in integrated agriculture systems often involve tradeoffs among potential environmental effects and social and economic factors that must be made without adequate supporting data (Theobald et al. 2005). An additional challenge in characterizing sustainable agricultural practices is that those tradeoffs are not always commensurable (Giampietro 2003). This lack of a comparable measure means that it is difficult to analyze comprehensively the costs and benefits of different alternatives. Thus, Giampietro (2003) proposes that sustainable practices must reflect choices made among legitimate, contrasting views about what should be considered an improvement. However, consideration of all implications of tradeoffs is not possible because unintended consequences cannot be fully anticipated.

This concern becomes especially problematic when several different scales or boundary conditions are considered simultaneously, several types of stakeholders are involved, or groups focus on diverse objectives. For example, different judgments have been made about the sustainability of using transgenic crops in Europe and the United States. Gains in efficiency from the use of transgenic crops have not overcome public opposition to their use in Europe. This uncertainty requires that agricultural system performance and the diverse effects of agricultural systems be compared across scales, locations, socioeconomic and environmental conditions, management practices, and farm products. The comparison should also include evaluation of different objectives that may be partly contradicting or that have different weights for specific stakeholder groups. The phased reduction of burning sugar cane fields before harvest in Brazil, for example, improves air quality and reduces carbon emissions related to sugar and ethanol production but also reduces employment of low-skilled laborers (Sawyer 2008).

Other tradeoffs that may be encountered when evaluating sustainability of integrated farming systems include (1) benefits of intensive animal rearing systems on land requirements and nutrient emissions in contrast to their impact on animal welfare (see Garnett 2011) and (2) the potential boost that small-scale biofuel production from local feedstocks may give to employment and household income while the production of these feedstocks may compete for scarce labor, land, nutrients or water resources [e.g., FAO (Food and Agriculture Organization) 2012b]. Not all tradeoffs need be negative however. Positive interactions between sub-objectives include (1) the enhanced availability of nutrients by limiting soil erosion and (2) reduction of (fossil) energy demand, improved soil organic matter conservation, and enhanced soil water holding capacity by minimizing tillage. Another example (3) was reported by Aarts et al. (2000), who found that increasing the share of silage maize on a mixed arable/dairy farm in The Netherlands reduced nitrogen losses while simultaneously reducing the demand for groundwater irrigation.

Establishing incentives

Most agricultural lands are managed to maximize production or profit within a given set of constraints. More sustainable management systems may defer profit or production in the near term in favor of future gains. The benefits of enhanced environmental conditions or costs of their decline are typically considered only if they affect farm management in an immediate and apparent way. Market-based incentives and government regulations often focus on ways to increase production, sometimes to the detriment of environmental conditions, while other regulations may constrain production in the interests of larger public goods (e.g., pesticide regulations, water use permits, and land set-aside incentives).

Incentives that focus on sustainability at a large scale could help diversify cropping systems and maintain healthy environmental conditions. For example, payment schemes for ecosystem services are already being implemented and tested in Europe (e.g., Ulber et al. 2011). In addition to regulations and prices, cooperative approaches may provide useful ways to address agricultural sustainability (Stallman 2011). Issues particularly suited for collective management include flood control, water quality, habitat conservation, pollination, biodiversity, and recreation (Groot et al. 2010; Stallman 2011; Langeveld et al. 2012).

Determination of acceptable agricultural sustainability standards commonly involves a large number of stakeholders and should include all those affected. Farmers have a direct interest, but their perspective can be influenced by technological, social and economic factors, not the least of which is land tenure. Land management for long-term soil improvement, for example, is not likely to be a priority for farmers with insecure rights to future use of the land they farm. Problematically, some stakeholders interested in only one aspect of sustainability (e.g., biodiversity or child labor) may not be willing to consider tradeoffs among other aspects (e.g. household welfare or cultural acceptability). Inability to make tradeoffs introduces a rigidity that may lead to unsustainable outcomes, while those stakeholders benefiting from the status quo may be incentivized to delay action to keep the system unchanged.

Linking changes in environmental conditions to individual policies, indicators, or incentives is often difficult. Furthermore, policies for large-scale agricultural sustainability sometimes have much broader applicability than do farm practices alone [e.g., incentives applied at watershed or larger scales may be more effective at preserving or enhancing environmental conditions than those at the individual farm or land-owner scale (Seymour and Ridley 2005)]. As a result, agreement on more sustainable pathways is often viewed as being unattainable because the issues are so large, complex, value-laden, and context specific (Efroymson et al. in press).

Multimetric optimization may be used to determine ways to achieve multiple incentives or objectives. A challenge in using optimization approaches is determining the set of objectives to be optimized because this choice involves selecting perspectives and values (Giampietro 2003). If the objectives and constraints used in optimization are appropriately formulated, then the approach can help select incentives for multiple objectives (e.g., see Parish et al. 2012). However addressing social objectives as well as economic and environmental goals introduces additional complexities, for any analysis of multifunctionality must consider tradeoffs.

On a more fundamental level, technologies and markets that increase the economic viability of different land-use options can also increase competition for available land resources (Fischer et al. 2011). Increased competition can promote more efficient land use, create incentives to restore soils, improve management on underutilized lands, or lead to conflict.

One recent assessment examined the influence of global markets on the increasing demands for land for cropping, grazing, protected areas, and urbanization (Lambin and Meyfroidt, 2011). Other assessments have identified social and political issues (transparency, marginalized populations, corruption, and governance) as key factors affecting large-scale land acquisition and land disputes (Anseeuw et al. 2012). Similar factors (governance, marginalized rural poor populations, lack of secure land and forest rights) have been associated with deforestation in less developed nations (Scherr et al. 2003; Chomitz 2007). We need assessment methods that can help identify and assess the key variables and trade-offs affecting sustainability and that can be used to integrate multiple land-use functions and values in order to determine combinations of land use that would be beneficial to society.

Enhancing agricultural sustainability

We identify three major ways to enhance agricultural sustainability from a landscape perspective. This broad-scale viewpoint relates farm systems to societal practices, cultural heritage, and environmental conditions. The field of landscape ecology provides methods and perspectives for adopting such an approach because it considers scales appropriate for agricultural systems; provides a hierarchical and integrative basis for dealing with complex issues; has developed theory and methods for dealing with spatial heterogeneity, scaling, and uncertainty; and uses a variety of holistic and humanistic approaches (Wu and Hobbs 2002). To support agricultural sustainability from a landscape perspective, we endorse adopting a systems perspective, taking account of spatial heterogeneity and the influences of a particular situation and its boundary conditions, and developing integrated landscape-design principles (Dosskey et al. 2012). To effectively implement these practices, results must be monitored over time, and trends in important environmental and socioeconomic indicators must be analyzed.

Adopting a systems perspective

A *system* is a collection of interacting entities that constitute a unified functional whole and for which the properties cannot be predicted from a separate understanding of each individual component. Systems analysis addresses complexity and evaluates how parts of the system operate in an integrated fashion. A systems approach offers a framework to identify and address gaps in knowledge and information and provides a formal means of quantifying risks.

Systems analysis seeks to evaluate efficiency and assess performance with regard to time, money, resource use, or any other clearly defined criterion. A systems approach involves identifying the components, material and energy flows, positive and negative interactions of system components, and constraints on these interactions. Because of interconnections, systems are characterized by higher order interactions (the whole often being more than the sum of its parts). Feedbacks, in particular, may reveal surprising properties. The application of systems concepts has produced a rich body of analysis and useful ways to view and explore agricultural sustainability (e.g., Ewert et al. 2009).

Systems analysis has successfully been applied in examining the properties and behavior of complex networks of ecological structures and interactions (Pahl-Wostl 2000). Application to agricultural systems requires specification of the structural components (e.g., crop types; management practices, environmental conditions; farm organization; and processing and transportation infrastructure). Insights into dynamics of agricultural systems may result from identifying connections between main components and major influences (e.g., fertilizer applications, harvest practices, market conditions, and policy incentives). Interconnections might occur via flows of energy, material, or information or by management or controls. Agricultural sustainability assessment may benefit from modeling complex animal and crop production networks, provided models used in such analyses capture sufficient detail and reasonably reflect actual connections among subsystems. Interactions within mixed systems can be complex and require specific analytical instruments (e.g., Aarts et al. 2000; Rufino et al. 2008).

Applying a systems approach at a large scale is difficult. Such an approach needs to be based on individual farms but aggregated to a broad scale in a meaningful way that deals with complexity. Farm management and landscape heterogeneity implications for ecological conditions are often region specific (e.g., Tryjanowski et al. 2011). Both local management and regional landscape complexity should be considered in designing sustainable agricultural systems, for local–regional interactions affect ecological conditions (Winqvist et al. 2011). While stakeholder involvement is very important, at a farm scale, individual land rights always become an issue. And how land rights are defined and recognized can vary widely. For example, private ownership is not an option for poor farmers in much of the developing world (e.g., Meshesha et al. 2012). In addition, traditional farming landscapes have developed under the influence of tightly coupled social and ecological systems that differ from place to place (Fischer et al. 2012). Hence the landscape perspective must do a better job of distinguishing differing perceptions of sustainability barriers ranging from the diverse points of view of farmers that use modern intensive agriculture to those that are engaged in subsistence systems.

The benefits of applying a systems approach to agricultural sustainability are many. It requires explicitly defining causal relationships, interactions, and feedbacks. It also requires that components of the system be interpreted in the context of the whole and affords a way to evaluate risks and a method for addressing uncertainties. Finally, a systems approach provides a framework that can be used by decision makers to consider effectiveness, costs, and benefits of alternative strategies. Many tools have been used to implement a systems perspective [for example, integrated assessment (Moreau et al. 2012), multivariate analysis of long-terms trends in environmental and social indicators (Rueff et al. 2012) or integrated spatially explicit biophysical and economic modeling (Schonhart et al. 2011)].

Spatial heterogeneity and human–nature interactions across scales

Interlinked levels of spatial hierarchies govern the performance of systems (pests, host plants, plant genotypic make-ups, plant and crop physiology, trophic chains, and the physical environment) (Savary et al. 2012). These linkages suggest that landscape management and policy development should address all levels in the hierarchy of both biological systems (from organisms to populations to communities to ecosystems) and social systems (farmers to communities to nations).

Understanding how to build more productive agricultural systems requires interpreting current conditions in the context of changes that have occurred over decades or centuries and balancing short-term and small-scale objectives against long-term and broad-scale goals. Such goals must be identified. It cannot be assumed that any one variable (e.g., type of crop grown) determines outcomes; instead, context-specific approaches and stakeholder support are needed to assess the critical drivers for each circumstance.

While it is generally recognized that patterns of land cover and land use have a variety of effects, most agricultural practices (growing, harvesting, handling, storage, processing, and transportation) do not consider landscape interactions [exceptions are noted by Meyer et al. (2008) and Rundölf et al. (2008)]. Unlike ecology and geography, most disciplines in agricultural sciences do not focus on patterns and processes at different scales. Thus, more research and management should consider ways to integrate quantitative analyses that take into account the juxtaposition of issues, past and future land-use scenarios, and scale dependencies necessary to understand multiple environmental factors and subsequent tradeoffs. Pioneering work in this respect has been done in development-related research [e.g., in Africa (Bingen and Gibbon 2012), and, later, in redesign of sustainable farming systems in Europe (e.g. Aarts et al. 2000) and Australia (García et al. 2006)].

Decisions and management plans could vary with the scale of the perspective. For example, decisions about what crops are grown, where they are grown, and how they are managed influence carbon sequestration, biodiversity, food production, greenhouse-gas emissions, water and air quality, and other environmental attributes as well as economic viability and benefits to rural communities.

Yet it is not always recognized that where certain crops are grown and how they are grown are in constant flux. For example, while total U.S. cropland area fell from 193 million ha in 1949 to 180 million ha in 1964 and rebounded to exceed 190 million hectares at least three times between 1969 and 1978 (Nickerson et al. 2011), it was not the same land, for significant areas of cropland rotate in and out of grassland and forest land classes (Lubowski et al. 2006). Since 1982, total U.S. cropland area declined persistently from 190 million hectares to 165 million hectares in 2007; however, the net loss of 25 million hectares masks larger shifts to and from cropland that exceed 40 million hectares during the same period (Nickerson et al. 2011). Cultivated area dedicated to maize and soybean (generally grown in rotation with each other) increased while acreage for wheat, barley and sorghum declined over this period. Commodity markets and production costs (perceived risks and opportunities) are primarily responsible for these fluxes. Variability is also common at smaller scales among the areas planted to arable crops, in grassland, and under specific management practices (such as irrigation, no-till, multi-cropping, and fallow season cover crops).

Decision makers need to understand that scientific analysis at appropriate spatial and temporal scales is necessary to support fair comparisons among available management options (Groot et al. 2010; Dale et al. 2011a) or crop production systems (Langeveld et al. 2012). Large-extent and long-term experiments combined with careful monitoring provide a means to assess effects across different system scales (Lindenmayer and Likens 2009). These experimental systems are characterized by tractable questions, careful statistical design, appropriate conceptual models, and an adaptive monitoring framework that allows questions to be addressed, learning to occur, and monitoring programs to evolve as new information emerges, management improves, and new questions arise (Lindenmayer and Likens 2009). Nevertheless experiments conducted over relevant scales and timeframes are few yet are inseparable from designing agricultural systems that are truly efficient and sustainable. Due to the lack of adequate data, nearly all policy and large-scale management decisions are based on idealized, modeled conditions that lack proper parameterization or validation.

Furthermore, transfer of information among scientists, practitioners, and policymakers needs to be improved in order to manage agricultural systems more sustainably (Pretty et al. 2010). Many nongovernment, governmental, and international organizations play an important role in defining criteria for sustainability by moving the discussion outside the science arena to application. The use of indicators to evaluate performance of complex and dynamic production systems may be helpful to enhance stakeholder involvement (Langeveld et al. 2007).

Developing integrated landscape-design principles

Landscape sustainability for agricultural systems should address how the full farm production and supply chain interacts with social, economic, and environmental conditions at a local and regional scale (e.g., see Skår et al. 2008). The need to meet increasing global demands for food, feed, fiber, and fuel may benefit from the implementation of alternative analytical approaches, such as those associated with a landscape vision. A landscape perspective is insightful for agricultural systems focused on providing food and energy by blending multiple feedstock streams [CAST (Council for Agricultural Science and Technology) 2012]. A coordinated approach involving multiple producers may lead to enhanced carbon sequestration, improved water quality and biodiversity, increased productivity and profitability, reduced producer and environmental risks, and enhanced rural development [CAST (Council for Agricultural Science and Technology) 2012]. A landscape approach also benefits from field-scale precision farming based on spatially explicit knowledge of soil conditions, drainage patterns, and land tenure to design specific crop-management practices (Kitchen et al. 2005; Lerch et al. 2005; Karlen et al. 2010). For example, linking geographic positioning systems (GPS) with spatially explicit soil assessment allows fertilization rates to be adjusted at the sub-field scale (Robert 2002). Such practices can reduce nutrient inputs and conserve or boost yield (McConnell and Burger 2011) thereby increasing production on the same or a reduced land area. Any systematic landscape design to support more sustainable agricultural development should consider (1) dynamic patterns and behavior of sub-systems and (2) how expected future developments will interact with stakeholder needs and initiatives [for an overview of design of systems under dynamic conditions see Schiere et al. (2012)].

In our view, a landscape-management approach should link past, current, and future (desired) environmental and socioeconomic conditions; agricultural management practices (e.g., cultivation, fertilizer, and pesticide applications); interactions with neighbors and neighboring land uses (e.g., pesticide drift, odor, fish kills); and ecological and biogeochemical feedbacks of land-use practices (Dale et al. 2011a). Other elements that should be considered include the projected consequences of climate change, population dynamics and migrations, disturbance and land-conversion trends (Dale et al. 2011b; CAST (Council for Agricultural Science and Technology) 2012). Maybe the largest effect on agricultural sustainability can result from changes in societal demand for farm products. For example, reducing animal protein consumption in favor of more plant-based diets can significantly reduce some impacts (Horrigan et al. 2002), but the global trend is in the other direction (Foley et al. 2011).

We expand landscape design beyond that proposed by Nassauer and Opdam (2008) as "intentional change in landscape pattern for the purpose of sustainability" to also focus on processes. Thus landscape design should include (1) an assessment of effects of current and proposed systems on water and air quality, hydrology (including flooding and reduced flows), carbon sequestration, and native plants and animals and their habitats; (2) identification of the appropriate spatial and temporal scales at which to examine social, economic and environmental effects; and (3) evaluation of potential tradeoffs including social, economic and environmental costs and benefits. Options for agricultural production thus can be evaluated by determining optimal socioeconomic and environmental benefits given prevailing conditions and those anticipated for the future.

Conclusions

Building upon recommendations by CAST (Council for Agricultural Science and Technology 2012) for major research needs, we propose that the following issues be addressed to move toward more sustainable agricultural systems at a landscape perspective:

- Development of tools and protocols for quantifying material and energy flows through agricultural systems at field, farm, and regional scales.
- Broader efforts to define management parameters (e.g., tillage intensity over time) and to quantify the effects of combinations of specified management practices on carbon sequestration, and local and large-scale nutrient, water, and energy fluxes.
- Development and implementation of incentives for (and/or decrease barriers for) adoption of practices that reduce pollution and conserve energy, reduce wasteful fertilizer and water use, conserve wildlife habitat, and sustain ecosystem services at field, farm, and regional scales.
- Further development and implementation of integrated landscape planning and management to maintain profitability while making efficient use of land, water, nutrients, and energy.
- Implementation of approaches to monitor and assess changes in both environmental and socioeconomic attributes of sustainability at watershed and regional scales.
- Analysis of how societal demand affects sustainable agriculture and implementation of practices to take advantage of this linkage.
- Adoption of integrative policies for agricultural systems that promote sustainability at watershed and regional scales.

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