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REVIEW

Assessing sustainability in agricultural landscapes: a review of approaches[1,2]

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Abstract: Research and development agencies, as well as policy makers and agri-food enterprises, need reliable data to support informed decisions that can improve the sustainability of agricultural landscapes. We present a review of agricultural sustainability assessment frameworks (ASAF) that identifies the features most relevant to monitoring progress towards sustainability goals for agricultural landscapes. This qualitative review considers a variety of approaches for defining goals and for selecting stakeholders, spatial and temporal boundaries, indicators, and analytical approaches. We focused on assessment frameworks that (*i*) include environmental, social, and economic implications of agriculture; (*ii*) are applicable to multiple, non-specified farm system types; (*iii*) are described in an English language, peer-reviewed publication; (*iv*) have been developed for use at a farm system to regional spatial scale; (*v*) engage stakeholders; (*vi*) provide case studies; and (*vii*) could be used in a variety of contexts across the globe. Based on the review, we provide recommendations for further development and use of assessment frameworks to better address the needs of agricultural research, extension, and development organizations. We recommend an agro-ecosystem approach to help stakeholders identify appropriate indicators for their situation. Assessment methods need to be flexible enough for adaptation to a spectrum of agricultural landscapes and changing environmental conditions, and remain relevant as farmers and other stakeholders acquire new information, resources, and different management techniques. We find that to address information gaps across different scales from farm to region will require creativity and some reliance on local knowledge systems to support adaptive management. Assessment results should communicate relationships among ecosystem services and socio-economic activities affected by agricultural landscapes. Visualization tools can facilitate understanding of trade-offs and synergies among sustainability goals as reflected by individual indicators.

Key words: agricultural landscape, sustainability assessment, stakeholder engagement, indicators.

Résumé : Les agences de recherche et développement aussi bien que les décideurs et les entreprises agroalimentaires ont besoin de données fiables pour permettre la prise de décisions éclairées qui peuvent améliorer la durabilité de paysages agricoles. Nous présentons un examen de cadres d'évaluation de durabilité agricole (« ASAF ») qui établit les caractéristiques les plus pertinentes pour le suivi des progrès vers les buts de durabilité pour les paysages agricoles. Cet examen qualitatif étudie une variété d'approches pour définir des buts et pour choisir des parties prenantes, des limites spatiales et temporelles, des indicateurs et des approches analytiques. Nous nous sommes concentrés sur des cadres d'évaluation qui (*i*) incluent les implications environnementales, sociales et économiques de l'agriculture; (*ii*) sont applicables aux types de systèmes agricoles multiples, non spécifiés; (*iii*) sont décrits dans une publication de langue anglaise, examinée par des pairs; (*iv*) ont été développés afin d'être utilisés à l'échelle de système agricole jusqu'à l'échelle spatiale régionale; (*v*) engagent les parties prenantes; (*vi*) fournissent des études de cas; et (*vii*) pourraient être utilisés dans divers contextes à travers le monde. En nous fondant sur l'examen, nous fournissons des recommandations pour le développement ultérieur et l'utilisation de cadres d'évaluation pour mieux considérer les besoins des organismes de recherche agricole, d'extension et de développement. Nous recommandons une approche d'agroécosystème afin

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d'aider les parties prenantes à établir des indicateurs appropriés pour leur situation. Les méthodes d'évaluation doivent être assez flexibles en vue d'adaptation à une gamme de paysages agricoles et de conditions environnementales changeantes et rester pertinentes à mesure que les fermiers et les autres parties prenantes acquièrent de nouvelles informations, ressources et différentes techniques de gestion. Nous constatons que combler les insuffisances d'informations à travers les différentes échelles de la ferme à la région exigera la créativité et l'appui des systèmes de connaissance locaux afin de soutenir la gestion adaptative. Les résultats d'évaluation devraient faire part des relations entre les services d'écosystème et les activités socio-économiques affectées par les paysages agricoles. Les outils de visualisation peuvent faciliter la compréhension des compromis et des synergies parmi les buts de durabilité tels que reflétés par des indicateurs individuels. [Traduit par la Rédaction]

Mots-clés : paysage agricole, évaluation de durabilité, engagement des parties prenantes, indicateurs.

Introduction

Agriculture provides a diversity of services by producing food, feed, fiber, and fuel. Ecosystem services were defined by the Millennium Ecosystem Assessment (2005) to be the ecological benefits people obtain from ecosystems (selected terminology is defined in Table 1). Agricultural practices affect a wide range of ecosystem services, including water quality, pollination, nutrient cycling, soil retention, carbon sequestration, biodiversity conservation, and climate regulation, as well as social and economic conditions of the farm systems and the regions in which they occur. Relationships between agriculture and ecosystem services include beneficial services generated and received by agriculture as well as negative impacts upon services that result from agricultural activities (Dale and Polasky 2007).

Agricultural sustainability is an aspirational goal that challenges stakeholders to consider farming effects on ecosystems and communities while also advancing food and energy security, clean abundant water, healthy productive soils, and other aspects of the United Nations' Sustainable Development Goals (SDGs; United Nations 2015). Although sustainability has been variously defined, it focuses on practices "that aim to make the best use of environmental goods and services while not damaging these assets" (Pretty 2008). Alternative management practices have been generated by farmers, researchers, and development institutions with the aim of producing efficient, profitable agricultural products with fewer negative environmental or human health impacts. Such practices have been mainly developed for application to fields (e.g., improved crop varieties or breeds, cropping systems, soil fertility management, plant protection methods) or to farms (e.g., crop-livestock integration, manure management, crop rotations, integrated pest management; National Research Council 1989). However, agricultural practices affect and are influenced by environmental, social, and economic conditions not only on individual fields and farms but also for the collection of farms and communities that make up an agricultural landscape (National Research Council 2010).

We focus on landscapes by considering the patterns and processes relevant to agro-ecosystem services and functions. Importantly, this perspective highlights how farm systems may interact via shared communities and bio-physical resources at multiple scales, in contrast to assessment studies that focus on a single farm or business enterprise. For example, one could identify multiple geographic domains to which a farm might belong, such as its watershed, aquifer, and airshed; as well as discrete inputs and outputs (labor, feed, fertilizer, fuel, water, crops, soil) and temporally variable energy and material transfers (plant productivity, animal productivity, biogeochemical and nutrient cycles). Figure 1 shows elements of patterns and processes included in a landscape perspective: in the near-term, both biophysical and socio-economic settings of a landscape drive material and energy transfers that are also influenced by the presence, variety, and arrangement of landscape components (Turner 2005; Wu 2013). Transformations may occur between components within a landscape, or externally with other systems or landscapes. Examples for agricultural landscapes are listed in Table 2. We acknowledge that measuring multiple landscape processes is challenging, and therefore methods to select and monitor specific indicators of status are often used to assess change. At regional spatial scales, forests, agricultural fields, reservoirs, rivers, wetlands, and urban areas are among the common classes that can affect and be affected by agricultural practices. Agricultural landscapes vary in diversity from monocultures to complex mosaics of managed and unmanaged ecosystems and may include specific elements such as orchards, lemon gardens, etc. (Cooper et al. 2009 as cited in Gerrard et al. 2012). Landscape processes that determine functionality such as biogeochemical regulation, pollination, and food production are affected by farm-system and landscape management decisions (de Groot et al. 2002).

Quantifying and monitoring socio-economic and biophysical processes for areas larger than individual farms—within a watershed, for example —are necessary to reveal benefits or impacts (National Research Council 2010; Allain et al. 2017). Developing agricultural sustainability assessment frameworks (ASAF) that link farm system and regions is important because at this scale, communities and local governments can be more easily mobilized around common goals (Graymore et al. 2008). Human well-being relies on nature's benefits to people, and sustainability assessments can be used to express shared values as well as conflicts among stakeholders' goals (Dale et al. 2013*a*; Díaz et al. 2015; Griggs et al. 2017; Allain et al. 2017). Furthermore, in the absence of sweeping policy or technology changes, broad support from multiple decision makers including farm operators and local officials is required to achieve sustainability goals in agricultural landscapes.

Assessment frameworks with capabilities to consider broad-scale patterns and processes can support progress toward more sustainable agricultural landscapes. For example, understanding how farm and landscape processes interact can help identify what, how, and where specific practices are most needed (Bonner et al. 2014; Muth et al. 2013; National Research Council 2010). To achieve desired improvements to environmental and socio-economic conditions, practices may be adopted on multiple farms across the landscape. For example, for water quality goals to be met, practices such as reforestation or soil and water conservation structures such as canals or hedgerows need to be applied over areas larger than a single farm. Similar situations arise with invasive species control, communal grazing, and access to equipment or markets (e.g., Foley et al. 2011; Hellin and Schrader 2003). Coordination of such broad-scale and coordinated efforts generally requires formal or informal multi-stakeholder partnerships that consider common resource management plans, which can generate synergies related to socio-economic sustainability—an important topic examined by Nobel prize winner Elenor Ostrom among others (Dietz et al. 2003; Ostrom 2009; Griggs et al. 2017).

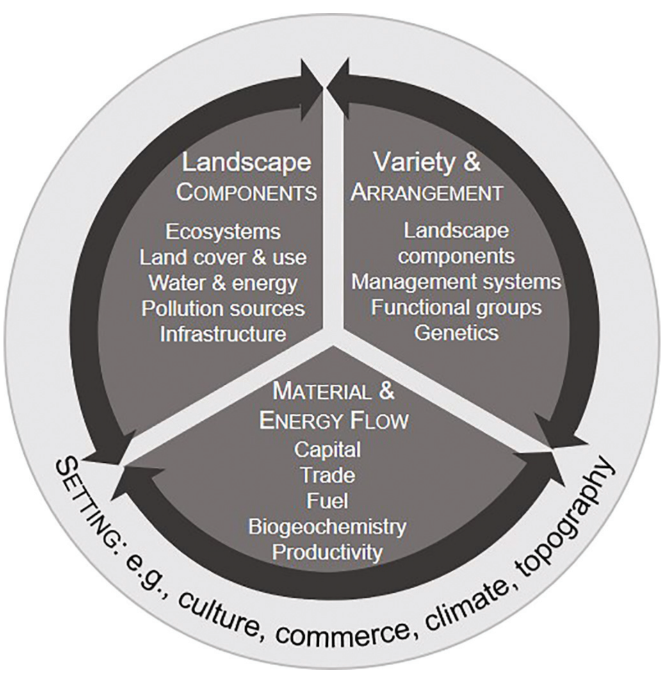
Review objectives

The purpose of this paper is to review agricultural sustainability assessment frameworks to identify what features and approaches are helpful to monitoring progress towards goals in agricultural landscapes. We present a qualitative analysis of assessment pur-

Table 1. Terminology.

Term	Definition
Agricultural sustainability	Production of food, feed, fiber, and fuel that aims to conserve ecosystem services in order to support present and future healthy environments, societies, and economies through a process of adaptive management (Brundtland 1987; Tilman et al. 2002; Pretty 2008).
Ecosystem services	Ecological functions and processes that contribute to human well-being; often categorized as provisioning, regulating, cultural, and supporting functions (de Groot et al. 2002; Millennium Ecosystem Assessment 2005).
Farm system	The mix of crops and (or) animals on a farm, their spatial and temporal arrangement, and their relationships with socio-economic and ecological environments within which the farm operates including community links, markets, labor, and other influencing factors (National Research Council 2010) as well as the households, their resources, and resource flows (Dixon et al. 2001).
Agricultural landscape	The patterns and processes relevant to functioning of agro-ecosystems and encompassing the pertinent spatial and temporal scales of the arrangement and distribution of farm systems, their interactions, and environmental and socio-economic factors that influence them.
Framework	The set of ideas, principles, guidelines, or approaches that provides the basis for an assessment.
Participatory frameworks	Frameworks that seek stakeholder participation and incorporate stakeholder opinions throughout the assessment process, often in an iterative fashion that creates a learning environment for all participants and allows for more comprehensive integration of values (Lopes and Videira 2013; Van Meensel et al. 2012).
Stakeholder	Any person or group with a direct or indirect interest, involvement, or investment in the process under consideration, which for agriculture includes assessors, farmers, farm laborers, extension agencies, production units, legislators, agricultural decision makers, nongovernmental organizations (NGOs), and consumers.
Indicators	Measures that provide information about potential or realized effects of human activities on phenomena of concern (Heink and Kowarik 2010).
Protocols	Procedures for accomplishing a task—in the context of sustainability refers to practices for analyzing data, and the steps required to operationalize a sustainability assessment framework including, for example, defining a purpose (e.g., to evaluate soil quality improvements), realm of application (such as agricultural production regions in western Mexico), and guidelines for selecting indicators.

Fig. 1. Elements of patterns and processes of a landscape perspective: in the near-term, both biophysical and socio-economic settings of a landscape drive (or constrain) material and energy transfers that are also influenced by the presence, variety, and arrangement of landscape components. Each component may be linked to internal or external processes that change over time.



poses, stakeholders, spatial and temporal boundaries, indicators, and methodological approaches. Based on this review, we provide recommendations for further development and use of ASAF to better address the needs of agricultural research, extension, and development organizations in consideration of the UN SDGs (United Nations 2015).

Monitoring progress towards more resilient and sustainable agricultural landscapes requires a systematic assessment that integrates environmental and socio-economic indicators to document effectiveness of changing agricultural management practices at multiple spatial and temporal scales. A variety of assessments are available for food, agriculture, and bioenergy enterprises where the goal is certification of compliance with a specific standard, for example, Fairtrade Certified (fairtradecertified.org) or USDA Certified Organic (https://www.ams.usda.gov/rules-regulations/organic). However, these approaches are not appropriate for assessing effects and interactions across different landscape elements. Determining appropriate indicators for documenting the effects of practices that support more sustainable systems depends on one's definition of sustainability as well as the goals of the assessment (Gasparatos and Scolobig 2012; Marchand et al. 2014).

Prior reviews of assessment frameworks use various typologies including the use of reference indicator values (Acosta-Alba and Van der Werf 2011), types based on the method of aggregation to a single index (Singh et al. 2012), and the emphasis on valuation (monetary, biophysical, or indicator; Gasparatos and Scolobig 2012). Marchand et al. (2014) reviewed assessments based on the categorization being a rapid versus full farm-level sustainability assessment, which was related to the number and specificity of indicators. Schader et al. (2014) focused on the purpose and scope of assessment in their review. An inventory of assessment frameworks including a detailed classification and analysis of 53 ASAF for temperate systems pertinent to a variety of spatial and temporal levels is provided by Wustenberghs et al. (2015). Ease of prac-

Table 2. Examples of agricultural landscape patterns and processes that should be considered in order to develop, implement, and monitor adaptive management decisions to achieve progress toward context-specific, agricultural landscape goals.

Elements of landscapes	Examples for agricultural landscapes
Settings (context of place and time)	Slope, erosion, elevation, exposure, salinity; Soil quality, retention, management (drainage, tillage); Growing conditions: solar maximum, moisture, season; Traditions, values, adaptations; Subsistence, micro, local, and global markets; Risk of extreme events.
Landscape components (identifiable features or unique processes contributing to heterogeneity of the area of interest)	Ecosystems: crops, pastures, waterways, uncultivated areas; Land cover: Critical host habitat: pollinators, pests, pest control; Land management: Annual rotation, fallow rotation, tillage system, harvest system, perennial management (grazed, harvested, abandoned), forestry activities, livestock and manure management, irrigation, drainage, etc; Water resources: rain, surface and ground reserves; Energy resources: Solar, wind, hydropower, biomass, fossil; Pollution sources: Fertilizer, pesticide, manure, residues, waste; Infrastructure: Housing, storage, irrigation, roads, power, communication, industry.
Variety and arrangement (the relationships and relative diversity of the features and processes contributing to landscape functionality at the scale of interest)	Landscape components; Farm types and intensity; Cultural systems and decision-makers: gender, age, ethnic equity; Functional groups: perennials, annuals, forages, grains, legumes, feeds, foods, macro- and micro-nutrients, livestock, wild harvests; Species: cultivated, native; symbionts, pathogens, pests, fungi, bacteria, plants, animals; Genetic resources: wild types, breeds, varieties, landraces.
Material and energy flows (transfers or transformations within the area of interest or across hierarchical levels)	Monetary capital: cash, credit; Human capital: knowledge to derive mechanical work, management; Trade or exchange of products, labor, information; Produced: yield of feed, food, fiber, fuel; Consumed: feed, fertilizer, traction, refrigeration, processing, household; Intensity: yield/area, yield/input; Nutrients: soil, plant, animal, water, particulates, gases.

tical application for specific farm-level agricultural assessments was discussed in De Olde et al. (2016). Some consensus on employing landscape approaches to development exists (Sayer et al. 2013), and efforts have been made to include landscape indicators in sustainability assessment frameworks (e.g., Renetzeder et al. 2010; Musumba et al. 2017). However, we did not find a review focusing on how sustainability assessment frameworks address the composition and functionality of agricultural landscapes. Such landscape patterns and processes help frame the dynamics, opportunities, and constraints that farmers and other stakeholders should consider in working towards contextualized agricultural sustainability goals. Landscapes host a diversity of ecosystem services, which provide significant assets to agriculture (Pretty 2008), and many of these services are threatened or in decline (Millennium Ecosystem Assessment 2005). This paper complements prior work by discussing how ASAF may accommodate a landscape perspective by assessing patterns and processes occurring within agricultural landscapes.

Assessment frameworks

Assessment frameworks can be deployed in several ways. They may be used to compare indicators of environmental, social, and economic conditions within specific production systems (e.g., coffee; COSA 2013) or within a single theme of sustainability—such as soil quality (Jokela et al. 2011). Indicator values used in an assessment may be compared to reference points, such as baseline values, relative to a similar system's values, science or policy derived values, targets, or thresholds (Acosta-Alba and Van der Werf 2011). These comparisons may take the form of ex post analyses of survey data (e.g., of farm practices; Rigby et al. 2001). In contrast, some frameworks are designed for ex ante comparison of possible future alternative scenarios and are often used as a tool in agriculture planning or policy development (e.g., Smith et al. 2000; Helming et al. 2008; Sadok et al. 2009). Generally, the results of an assessment are intended to guide decisions about management options and may be used to monitor progress toward goals after management changes occur. Assessment results are communicated in different ways, for example, by mathematically derived aggregation of multiple indicators to an index or visual summaries (Reed et al. 2006; Ness et al. 2007). Some frameworks provide guidance on compiling and simplifying the indicator data to reduce complexity and summarize themes (Pollesch 2016).

Assessment purpose and stakeholders

Assessments serve a wide variety of purposes including research, monitoring, certification, policy development, farm advising, self-assessment, consumer information, and landscape planning (Schader et al. 2014; Wustenberghs et al. 2015) and ultimately should inform decisions. Stakeholders have unique roles within assessments for agricultural landscapes because of their diverse concerns as well as varying degrees of input (or lack of input) regarding farm management decision. Reed et al. (2006) categorize assessment frameworks for sustainable development as top-down or bottom-up based, in large part, on the engagement and role of local stakeholders in selecting indicators. In farm or business focused assessments, stakeholders may be limited to the landowner, farm household, operators and workers, and perhaps a government unit. In contrast, stakeholders for agricultural landscapes represent a larger population whose well-being is affected by landscape conditions and include community members, suppliers and retailers, consumers, educators, natural resource managers, and governments and non-government organizations, in addition to farm households and employees. Farm extension or outreach organizations often play a critical stakeholder role by interfacing research programs with potential beneficiaries in practical, non-formal educational settings. Extension agents may be involved in collection of data and act as interpreters of assessment outputs, and, as such, they must establish and maintain credibility for providing useful information with a robust grounding in science. The differing values of each stakeholder group influence how a sustainability assessment framework is applied, as choices are made regarding which indicators to include or exclude, which procedures to use to obtain indicator values, and the relative importance of each indicator in the assessment result or output.

Stakeholders include development organizations that work to reduce poverty, improve food security and nutrition, or restore natural resources and ecosystem services (CGIAR 2015). These organizations need an effective sustainability assessment framework that encompasses farm system to regional indicators, provides sufficient flexibility for application to differing farm systems and contexts, and takes a societal/landscape perspective rather than a business/product/supply-chain approach. Research and extension agencies working toward sustainability goals prioritize farmer engagement and often emphasize social justice considerations in their outreach (Smyth and Dumanski 1993). For example, targets are set for gender and youth equity (CGIAR 2016; FAO and SAFA 2013*b*), and farmer preferences towards alternative methods or markets are examined (Hellin et al. 2017). Subsequently, a sustainability assessment framework should facilitate evaluating, monitoring, and obtaining feedback regarding development program activities. It should allow efficient, cost-effective documentation of baseline conditions as well as changes associated with interventions for improved livelihoods on farms and across communities and landscapes.

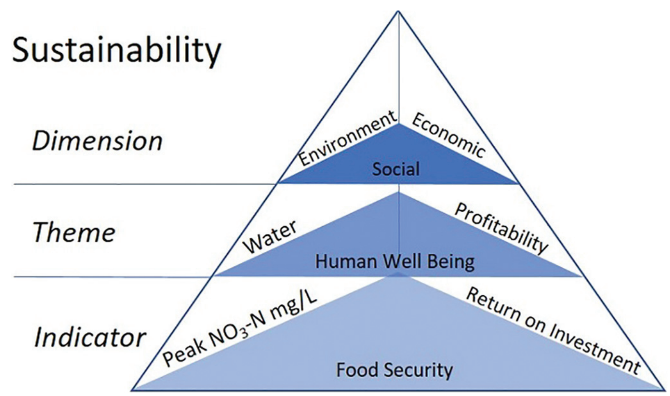
Boundaries of space, time, and system components

Agricultural landscape assessments should consider broad spatial scales beyond a field or farm and take into account dynamic patterns and processes. There is a large diversity of agricultural landscapes that vary by the products, production system, financial, information, market access, and settings of topography, climate, and soils. Goals for agriculture and means of achieving goals are therefore specific to each context. Relationships between sustainability goals and management practices are important. Some relationships are reinforcing (synergistic) to multiple goals; while others are neutral, or negative (trade-offs). Interactions among synergies and trade-offs result from changing management practices to address landscape sustainability goals and should be reflected in selected indicators (Kanter et al. 2018; López-Ridaura 2005). Agricultural practices that focus solely on increasing production, for example, do not necessarily improve social equity and economic profitability. Synergies and trade-offs related to achieving the SDGs are beginning to be examined (Griggs et al. 2017) and influence which agricultural practices are promoted for improving sustainability in a local context. However, many of the existing ASAF are designed for a narrow agricultural context (Schader et al. 2014; Wustenberghs et al. 2015), emphasize one dimension of sustainability (e.g., economics), or have limited relevance to agricultural managers (De Olde et al. 2016) and thus are not capable of addressing trade-offs and synergies among management practices.

Indicators

The indicators recommended for integrated ASAF typically fall under different themes and dimensions of environmental, economic, and social effects (Fig. 2; Table 3). The indicators generally relate to the following services: food and materials for human consumption, water quality and quantity, soil quality, greenhouse gas emissions, pollination, seed dispersal, pest mitigation, biodiversity, habitat, and protection from disturbance (Dale and Polasky 2007). Spatially explicit socio-economic patterns and processes such as access to markets, pricing, employment, migration,

Fig. 2. Typical organization of sustainability assessment levels, using SAFA terminology (FAO and SAFA 2013*a*; De Olde et al. 2016) and showing example agricultural landscape themes and indicators under each of the three dimensions.



education, access to credit, and land tenure are also important in agro-ecosystems. These phenomena can affect agricultural practices such as crop or product choices, fertilizer and irrigation use, labor decisions, and market participation among others, which, in turn, drive changes in ecosystem services (Anjichi et al. 2007; and see Chapter 3 in National Research Council 2010). Categories of indicators for assessing social equity and economic profitability could include social well-being and acceptability, energy security, and external trade (Dale et al. 2013*b*). Additionally, research on sustainable intensification in agriculture has acknowledged the importance of including measures of distributional and procedural justice and equity (e.g., equitable access, food sovereignty) in ASAF (Loos et al. 2014). As modes of agricultural production differ along a shifting rural to urban gradient (Lawson 2016; Thebo et al. 2014), other indicator themes may become relevant (Haase et al. 2014). De Olde et al. (2017*a*) used a quantitative comparison of four ASAF applied to farms to show that assessments yield different results (i.e., better or worse scores of sustainability) despite similarities of dimensions, and themes, as well as scope and purpose.

Assessment frameworks sometimes provide guidelines for selecting unique indicators. A method for selecting indicators for multi-scale evaluation of small holdings based on stakeholder objectives is described in López-Ridaura et al. (2005*a*). The indicator selection process occurs within the systems analysis phase of an ASAF, in which the study area is contextualized, impact scales are identified in consultation with stakeholders, and specific indicators are derived relative to objectives for each impact scale (López-Ridaura et al. 2005*a*). Dale et al. (2015) describe a systematic approach to selecting indicators for bioenergy sustainability assessment by first identifying sustainability goals, defining system context, and consulting stakeholders. These steps occur prior to identifying objectives for analyses, selecting indicators, defining baseline and target indicator values, highlighting potential trade-offs, and conducting the assessment (Dale et al. 2015). Some ASAF do not provide flexibility in selecting indicators, (e.g., Public Goods assessment discussed below; Gerrard et al. 2012) and instead focus on comparing the same indicator suite across sites. Multi-criteria decision-aiding methods (MCDA) have been reviewed for application to ASAF (e.g., Sadok et al. 2008) and often require explicitly constrained indicator data to facilitate mathematical or if/then decision rules. MCDA are not explicitly reviewed here for applicability to landscapes (but see Allain et al. 2017).

Synthesizing diverse information from indicators representing all three dimensions of sustainability is a challenging yet crucial

Table 3. Agricultural sustainability dimensions and themes typically found in assessment frameworks that could be used to monitor changes in agricultural landscapes.

Sustainability dimensions and some underlying themes		
Environmental	**Economic**	**Social**
Productivity*	Access to markets	Social well-being
Energy	Employment	Social acceptability
Water quality and quantity	Pricing	Energy security
Soil quality	Income	Equity (youth, gender)
Air quality	Profit	Fair access to production*
Pollination	Access to credit	Food sovereignty
Seed dispersal	Land tenure	Education
Biodiversity	External trade	Migration
Pest mitigation		
Protection from disturbances		
Greenhouse gas emissions		
Habitat conservation		

Note: Indicator themes may relate to multiple ecosystem services, and those services affect aspects of all sustainability dimensions.

*Food, feed, fiber, fuel.

step in assessments (Graymore et al. 2008). The process of summarizing information should be transparent to stakeholders, regardless of stakeholder priorities or systematic analytical biases that may occur, for example, during aggregation. Creating a balanced synthesis of information from all dimensions of the agricultural landscape is a difficult and subjective task that is influenced by the biases within the themes and selected indicators, as well as the mathematical procedures used to summarize information (Pollesch 2016). Aggregation functions applied to indicator values, as well as how the indicators are grouped and weighted, influence the way the information is communicated (Pollesch and Dale 2015; Wustenberghs et al. 2015). Aggregation choice affects how trade-offs or compensation among indicators may be addressed (Mori and Christodoulou 2012). If non-aggregated indicator values are lost during the assessment, it is difficult to gauge how the full suite of indicators is affected, and thus, what management practices should be adapted to make progress toward sustainability goals (López-Ridaura et al. 2005*a*). Ultimately both what types of information an assessment integrates, as well as how that information is analyzed, synthesized, and presented, influence assessment results and usefulness to stakeholders.

Gathering appropriate and high-quality indicator data can be a challenge to sustainability assessments, irrespective of the scale to which the data apply. Reliable data for the specific region being studied may not be available (Graymore et al. 2008). Whether information is based on international, governmental, farmer-generated, or empirical measures, models, or expert opinion, the source influences the quality, quantity, and resolution of data available for indicators and, subsequently, the level of trust with which stakeholders regard the assessment process. Regardless of which indicators and methods for obtaining indicator data are chosen, they should be practical, sensitive, unambiguous, anticipatory, predictive of manageable changes, and sufficient (Dale and Beyeler 2001; Dale et al. 2013*b*). In some instances, these requirements may mean limiting options and creating a standardized group of indicators and methodologies that facilitates comparisons across sites and is grounded in strong science (Rosenstock et al. 2017). Under time or resource limitations, proxies for preferred indicators may be adopted: for example, pesticide use may be a key indicator, but pesticide sales by municipality or region may be the only realistically obtainable data that becomes useful to decision-makers because of documented linkages between use, sales, and ultimately human-health, or environmental risks (OECD 2001). Below we review example indicator-based integrated ASAF.

Approach

Of the dozens of ASAF available (Wustenberghs et al. 2015), few are stakeholder-friendly and broadly applicable for agricultural landscapes. Therefore, we examined features of assessments that contribute to evaluating conditions, patterns, and processes towards developing sustainability assessment frameworks for agricultural landscapes. Our selection of assessment approaches for review was initiated from the classification scheme and extensive list of 48 ASAF provided by De Olde et al. (2016). Additional ASAF were discovered by investigation of frameworks citing that literature, as well as Web of Science and Google Scholar searches. We did not attempt an exhaustive inventory or comprehensive review here (see Wustenberghs et al. 2015). Rather, we looked for a diverse sampling of published ASAF that relate to integrated assessment (i.e., that include environmental, social, and economic implications) of agricultural systems independent of the specific production system. We selected for further review only frameworks that meet the following seven criteria: (*i*) include environmental, social, and economic dimensions; (*ii*) take a systems view applicable to multiple, non-specified farm system types (e.g., maize, wheat, or other crop and livestock; mechanized or non-mechanized) rather than a single product or component; (*iii*) are described in an English language, peer-reviewed publication; (*iv*) have been developed for use at a farm system to regional spatial scale; (*v*) engage stakeholders in a participatory process to obtain indicator data as described by the published framework; (*vi*) provide an example of its application to case studies; and (*vii*) could be used to monitor outcomes from alternative agricultural practices in a variety of contexts. The resulting nine ASAF are listed in Table 4 and further described in Table 5.

Relative to the De Olde et al. (2016) appendix list, we selected tools that met our criteria based on the following steps. First, we eliminated (*i*) tools that did not cover environmental, social, and economic dimensions based on both the De Olde et al. (2016) description and a review of the reference abstracts (which eliminated 20 tools); then (*ii*) those that were sector-specific (9 more); then (*iii*) those that were neither peer-reviewed nor otherwise available with detailed English descriptions (8 more) leaving 11 tools. We searched for English descriptions of the tools eliminated in this last step to confirm lack of fit for our analysis. References for these 11 tools were examined, and we made further eliminations: (*iv*) FARMSMART (Tzilivakis and Lewis 2004) is a useful software tool to disaggregate national statistical data within England for presentation and discussion with farmers; however, it is not

Table 4. A comparison of sustainability assessments for agriculture according to the criteria that the framework (*i*) include environmental, social, and economic dimensions; (*ii*) take a systems view applicable to multiple, non-specified farm system types rather than a single product or component; (*iii*) are described in an English language, peer-reviewed publication; (*iv*) have been developed for use at a farm system to regional spatial scale; (*v*) engage stakeholders in a participatory process to obtain indicator data; (*vi*) provide an example of its application to case studies; and (*vii*) could be used to monitor outcomes from alternative agricultural practices in a variety of contexts.

Name/reference	Description	Goals/objective	Intended audience
APOIA-NovoRural (Rodrigues et al. 2010)	A protocol for environmental impact assessment of ag and non-ag activities with 62 indicators within five dimensions: landscape ecology, environmental quality, sociocultural values, economic values, and management/administration pertaining to sustainable development; provides sustainability index relative to target values.	To promote the environmental management of rural activities toward local sustainable development.	Farmers, entrepreneurs, and decision makers.
Bioenergy Sustainability Target Assessment Resource (BioSTAR) (Pollesch 2016; Parish et al. 2016)	Framework for assessment using environmental, social, and economic dimensions with 12 themes and customizable subthemes and indicators; comparison of indicator values for business-as-usual relative to alternative scenarios.	To assess progress toward bioenergy sustainability for production systems to regional level.	Farmers, foresters, landowners, extension agents, students, industry, scientists, and policy makers.
Indicateurs de Durabilité des Exploitations Agricoles (IDEA) (Zahm et al. 2008)	Protocol related to European Union Common Agriculture Policy, based on sustainable development literature, and accommodates trade-offs in agro-ecological, socio-territorial, and economic dimensions using 10 subthemes and 41 indicators.	To support sustainable agriculture on farms using self-assessment by farmers.	Policy makers and farmers.
Framework for Assessing the Sustainability of Natural Resource Management Systems (MESMIS) (López-Ridaura, et al. 2002; Astier et al. 2011)	Framework for assessing smallholder agriculture; research teams work with farm households to select indicators and strategize alternative practices with expert input to achieve sustainability goals using a local (field or resource) management focus.	To derive, measure, and monitor sustainability indicators via a framework that is flexible and adaptable to local data and current conditions.	Evaluation teams along with smallholder farmers, research institutions, NGOs, and producer associations.
Multi-scale Methodological Framework (MMF) (López-Ridaura et al. 2005*a*, 2005*b*; López-Ridaura 2005)	Framework to evaluate sustainability of peasant systems at multiple impact scales within attributes of productivity, stability, resilience, reliability, adaptability; includes derivation of site and scale-specific indicators.	To build a multi-stakeholder and objective-driven evaluation process with useful indicators that reflect aspirations and constraints of stakeholders at farm, community, municipality, and regional scales.	Research and development organizations along with peasant land managers.
Public Goods (PG) (Gerrard et al. 2012)	Protocol for assessing provisioning of public goods (agro-ecosystem services) across social, economic, and environmental dimensions and 11 themes, developed with stakeholder input.	To assess provisioning of public goods from England's "Organic Entry Level Stewardship" program farms.	Policy makers and farmers.
Response-Inducing Sustainability Evaluation (RISE) (Häni et al. 2003; Grenz et al. 2011; Bern University of Applied Sciences 2017)	Protocol for assessing economic, societal, and ecological dimensions with 10–12 themes using 42–46 indicators; version 3.0 has flexibility to indicators.	To provide practical indications of the changes necessary to improve sustainable farming; to show strengths and weaknesses in system stability, risk management, grey energy, and animal welfare.	Farm entrepreneur.
Sustainability Assessment of Food and Agriculture (SAFA) (FAO and SAFA 2013*a*, 2013*b*, 2014)	Framework for assessment along food and agricultural (F&A) value chains—focused on supply-chain enterprises; governance, environmental, economic, and social dimensions with 21 themes and 58 sub-themes encompassing 118 indicators; global applicability.	To provide a common language for sustainability; to harmonize sustainability approaches within F&A value chain through a focus on indicators in an easy-to-use standardized scoring system.	Companies, organizations, and stakeholders; governments; expert input not required.
Sustainability Assessment of Farming and the Environment (SAFE) (Van Cauwenbergh et al. 2007; Sauvenier et al. 2005)	Protocol for assessment that defines dimensions, themes, and subthemes, using 97 indicators related to multiple spatial scales of agro-ecosystems, relative to target or reference values.	To evaluate sustainability in agriculture by identifying goals, principles (functionality), criteria (component objectives or target states), and indicators (PC&I theory).	Scientists as intermediary to policy makers and farmers.

Table 5. The approaches within the reviewed agricultural sustainability assessment frameworks (ASAF) address agricultural sustainability concerns differently through a diverse information sources. They identify landscape patterns and ecosystem processes to varying degrees across similar spatial and temporal extents.

Name	Sources of information	Approach	Efforts to identify agro-ecosystem processes or patterns	Spatial and temporal scales	Type of guidance provided	Locations of application
APOIA-Novo-Rural	Biophysical sampling, farm records with farmer consultation, GPS/satellite imagery.	Calculation of impact indices through weighted transformation factors; then converted to utility values by best fit equation; relative to pre-determined targets (normalized on 0–1 scale); aggregation within dimensions, and overall sustainability index resulting from averaging each dimensional index.	Landscape ecology dimension contains indicators of spatial characteristics; impact indices intended to synthesize status and trend for each indicator.	Farm/rural establishment and higher (landscape, region).	Assessor enters data with farmer(s); computer aggregates standard list of indicators; highlights management alternatives to correct low values.	South America (primarily Brazil); adaptable.
BioSTAR	Data from models, GIS, biophysical sampling, surveys, government records, and scientific literature.	Systems-based, hierarchical characterization of indicators into subtheme scores; can use aggregation of indicators or multi-criteria analysis or spatial optimization to compare alternative scenarios based on Multi-Attribute Decision Support; non-dynamical; ratio-normalized indicators.	Scenarios of feedstock production and management practices across fuelsheds to determine effects on environmental, social, and economic conditions.	Farming systems, fuel shed, culmination of 5-year experiment for case study, repetition of assessment encouraged.	Information on 7-step framework; context-based suite of indicators can be used to compare management practices.	Tennessee and Iowa, USA; adaptable.
IDEA	Farm records, farmer declarations, and interviews.	Each indicator has a max score, adding up to 100 in each subtheme; key constraints identified; lowest of theme score used as final score, allows trade-offs/compensation of indicators.	Indicator themes include crop and animal diversity, spatial organization, resource protection, and accessibility of space; recognizes lack of simple indicators for socio-territorial functions.	Farm/farm family.	Assessor completes evaluation and describes results; indicators not flexible.	Case study in France, many assessments completed; intended for EU; adaptable.
MESMIS	Biophysical sampling, socio-economic surveys, farm records, census data, and modelling.	Systematic, holistic, participatory; mixed multi-criteria analysis; iterative application to monitor progress relative to reference/baseline.	System attributes apply to ecosystems: productivity, stability, reliability, resilience, adaptability, equity, and self-reliance.	Field/farm/village over two or more cropping cycles.	Selection of site-specific indicators with stakeholder input.	Central and South America; adaptable.
MMF	Sampling, surveys, census data, GIS, and modeling.	Indicators derived in analysis phase, quantified using multiple goal linear programing nested by the scale of analysis; alternative policy or management options evaluated via scenario that show optimizing or constraining specific indicators.	System attributes apply to ecosystems: productivity, stability, reliability, resilience, and adaptability.	Farm household, community, (sub)region.	Selection of site- and scale-specific indicators with stakeholder input.	Case studies in Mexico, Mali; adaptable.
PG	Farm records, via interview questions about “key activities” (indicators).	Each indicator receives a score 1–5 or n/a; sub-theme score calculated by averaging the indicator scores.	Services (public goods) from landscape aesthetic; biodiversity, soil functionality, and other themes.	Farm.	Assessor conducts interview with farmer to develop scores for indicators; indicators not flexible.	England.

Table 5 (*concluded*).

Name	Sources of information	Approach	Efforts to identify agro-ecosystem processes or patterns	Spatial and temporal scales	Type of guidance provided	Locations of application
RISE	Farm records, farmer interview, regional data, assessor observations, and scoring of indicator values.	System-oriented, holistic; each indicator is a driving force/state (on opposing scales of 0–100), influenced by life cycle assessment methods.	Focused on status and monitoring of changes to status; parameters broadly address stocks and flows of resources.	Farm, 1 year.	Assessor determines suitable measurement from list of core indicators and preferred data.	Global; adaptable.
SAFA	Primary, secondary, proxy, and estimated data; company records, biophysical sampling, inspection, and interviews.	Hierarchical indicator aggregation; 5-step rating system, indicators are weighted depending on number of indicators per sub-theme and the indicator type.	Focused on status relative to pre-stated ideals.	Adaptable to all F&A enterprise contexts and sizes, 1 year generally.	Flexible indicator suite from default list, based on context and entity type; flexible assessor roles.	Global application promoted.
SAFE	Standardized logbooks of farm records, questionnaire, regional models, biophysical sampling, indicator species, and GIS.	Content-based (multi-component), multi-criteria, holistic; relative and absolute targets; integration at each hierarchical level using fuzzy models; weighted average of normalized indicators within each subtheme gives a sustainability index for the theme, dimension, and overall.	Supply and buffer function of agro-ecosystems, based on stocks and flows of resources; services, ecosystem integrity; land use pattern.	Parcel, farm, and higher (landscape, region, state); case specific temporal scale generally 1 year.	Systematic procedure for selection of core indicators, temporal and spatial scales, and reference values.	Belgium; adaptable.

an ex post assessment tool that engages stakeholders with site-specific indicator data. While updated recently, SEEBalance (Saling et al. 2005) remains focused on product/supply-chain assessment for use within BASF commercial entities; SMART-Farm Tool (Schader et al. 2016) is a tool for implementing SAFA (retained). We excluded frameworks that are limited to a single agricultural sector (e.g., MOTIFS (Monitoring Tool for Integrated Farm Sustainability) applies only to dairy farms; de Mey et al. 2011), emphasize one dimension (e.g., EFA (Ecological Focus Area) Calculator; Tzilivakis et al. 2016), or are limited to the regional or higher spatial extent (e.g., Dantsis et al. 2010). ASAF that rely exclusively on modeled indicator data to develop ex ante scenarios are not reviewed here (e.g., SEAMLESS-Integrated Framework, Ewert et al. 2009; MODAM, Sattler et al. 2010).

We present a qualitative review of several ASAF based on initial published description and updated versions where applicable. A comparison of applications of these frameworks in a given case study (as in De Olde et al. 2017*a*, 2016; Graymore et al. 2008) or examination of publications following a framework's application to separate case studies (e.g., MESMIS reviewed by Astier et al. (2012); SMART-Farm Tool reviewed by Schader et al. (2016)) was beyond the scope of the present research and not strictly necessary to explore useful features for assessment of agricultural landscapes. We describe nine ASAF in Tables 4 and 5 representing different combinations of approaches to the assessment process. To varying degrees, the frameworks reviewed here address agricultural sustainability concerns related to landscape patterns and processes that can be important for making decisions regarding agricultural management practices and for monitoring progress toward better socio-economic and environmental conditions. In the following sections we compare features of the selected frameworks: APOIA-NovoRural (Rodrigues et al. 2010), BioSTAR (Bioenergy Sustainability Target Assessment Resource: Parish et al. 2016; Pollesch 2016), IDEA (Indicateurs de Durabilité des Exploitations Agricoles: Zahm et al. 2008), MESMIS (which derives its acronym in Spanish: Framework for Assessing the Sustainability of Natural Resource Management Systems: Astier et al. 2011; López-Ridaura et al. 2002), MMF (Multi-scale Methodological Framework (López-Ridaura et al. 2005*a*; Astier et al. 2011), PG (Public Goods: Gerrard et al. 2012), RISE (Response-Inducing Sustainability Evaluation: Häni et al. 2003; Grenz et al. 2011; Bern University of Applied Sciences 2017), SAFA (Sustainability Assessment of Food and Agriculture: FAO and SAFA 2013*a*, 2013*b*; 2014), and SAFE (Sustainability Assessment of Farming and the Environment: Sauvenier et al. 2005; Van Cauwenbergh et al. 2007).

Findings

Goals, stakeholders, and end-users

The objectives, priorities, and resources of stakeholders vary considerably, and any single framework satisfies these diverse needs to different degrees (Schader et al. 2014). The frameworks we examined have a variety of goals within the realm of evaluating sustainability of agricultural systems. For example, MESMIS, SAFE, and SAFA entail methods for describing management entities such as a farm, business, or public resource, and for selecting appropriate indicator suites from extensive lists of indicators. In contrast, IDEA, PG, and BioSTAR have more specific assessment objectives and are somewhat less flexible for adapting to multiple farm system types. IDEA focuses on farms/farm families in the European Union with a fixed list of indicators. PG was developed for farms in a stewardship program with policy-defined regional targets, while BioSTAR can be applied in a variety of contexts with an indicator suite focused on effects of bioenergy production within a specified fuel shed. APOIA-NovoRural focuses on rural activities rather than farm systems per se. The MMF focuses on peasant systems, emphasizing site- and scale-specific indicators.

Some of the frameworks are explicitly designed for the goal of self-assessment, internal communication, or self-improvement of sustainability within agricultural entities (IDEA, SAFA, MESMIS, RISE). However, with the exception of SAFA, the listed frameworks are not specifically intended for a farmer to use for self-assessment without the assistance of one or more trained assessors. The designers of SMART (Sustainability Monitoring and Assessment Routine: Schader et al. 2016)—a protocol for SAFA—go as far as stating that it is not recommended for "extension" purposes. Some frameworks are operationalized in protocols geared for specific policy development, monitoring, or compliance. IDEA references requirements of the EU Common Agriculture Policy, while PG assesses provisioning of public goods from farms enrolled in England's Organic Entry Level Stewardship program.

Although stakeholder contribution to assessment decisions (which could include indicator information from farmers or managers) was a criterion for inclusion in the review, methods for stakeholder engagement vary. BioSTAR and MMF explicitly aim to engage stakeholders in the community, beyond farm owners/managers, whereas generally the other assessments reviewed here do not. ASAF emphasize the presentation and usefulness of the assessment results for farmers and resource managers to different degrees. APOIA-NovoRural, RISE, and SAFA produce reports for individual farmer/operators specifically. Most assessments focus on comparing a farm's conditions to policy targets, and do not prioritize monitoring of progress to the manager's (farm system) goals. The assessor is generally a third party such as a research group, certification company, extension agent, or government that could then share and interpret results for the farmer, policy makers, or other stakeholders.

Spatial and temporal boundaries

We are especially interested in ASAF that are relevant to the farm system as a component within the broader context of agricultural landscapes. Several frameworks are explicitly applicable to multiple spatial extents (SAFA, MESMIS, MMF, SAFE, BioSTAR), which include farm systems. In contrast IDEA, RISE, and PG are specifically applicable to a farm system but would be difficult to expand to broader levels of organization because the methods of obtaining indicator data emphasize farmer records that are not likely to encompass landscape parameters. RISE has reported assessments of groups of farm systems (Bern University of Applied Sciences 2017) but does not extend this to a synthesis of landscape sustainability characteristics explicitly. SAFA provides specific guidelines for determining system boundaries through inclusion/exclusion recommendations from a supply-chain perspective. SAFE and BioSTAR highlight the need to establish system boundaries beyond the farm system such as watersheds, communities, and (or) fuel sheds, based on a product's life cycle. Developers of APOIA-NovoRural describe the target system as a farm or rural establishment (that may include a collection of farms) and have applied it at different spatial scales in an effort to assess linkages beyond individual farm or business entities (Rodrigues et al. 2010). MMF is designed explicitly for multi-scale analysis from smallholdings to regions, however, unique indicators are derived for each scale.

Indicators selected for use within a sustainability assessment relate to how system boundaries are defined both generally (i.e., an area of interest) and specifically for each indicator. Inclusion or exclusion of components of an agricultural landscape must be made explicit for each assessment. Indicators that document patterns and transformations across landscapes (e.g., local land use/land cover change, employment patterns) have received less attention than static observations for assessment indicators, likely because such indicator values are more difficult to obtain. The challenge of including patterns and processes within indicator-based ASAF has been recognized and is partially addressed in later version of MESMIS (Astier et al. 2012). APOIA-NovoRural addresses spatial patterns within the landscape-ecology dimension by using satellite imagery for land-use categorization and calculation of diversity indices. An emphasis on landscape patterns and processes requires a flexible approach to defining system boundaries since the scope of each indicator may be unique. For example, soil organic matter (SOM, e.g., as % carbon) varies among fields and management practices, thus a single status "snapshot" value is minimally informative of the farm system or landscape. Instead the difference in SOM through time or between management regimes is more useful but requires sampling techniques to ensure reliable and representative data for changes over time in average field or landscape values. If the value stabilizes or increases, one may infer maintenance or even improvement of soil quality in that location over the specified time. Additionally, neither the single SOM value, nor the change in value for a single point, depends on the spatial extent of the system. In contrast, if we wish to monitor soil carbon sequestration potential of a farm system, agricultural landscape, or alternative management practice, then we must define the spatial extent of farm system boundaries since the metric is sensitive to areal units. Similarly, economic indicators might require explicitly defined system boundaries (e.g., a municipality, county, or state government) to monitor cash or credit flows, and this boundary may be independent of the bio-physical farm system or landscape boundary.

To gauge the sustainability of trends, flows, or processes of an agricultural landscape, some temporal scope must be defined. Of the protocols we reviewed in detail, few recommend using data from multiple cropping seasons (with the exception of MESMIS and BioSTAR). Others recognize the need to aggregate certain types of primary data to an annual average. It is not always clear what temporal boundaries are established by the assessment, but generally only one year is covered by a given procedure. Snapshot data of farm production practices (for example, arrangement of fallow plots, age and distribution of perennial patches, crop rotations, and livestock density) can provide contextual information for assessments but are more useful if a farm is monitored for several years so that trends in specific land-use changes and their functions can be examined (e.g., Hiernaux et al. 2009). Frameworks that help identify changes in indicator values through time are needed if the objective is to capture landscape patterns and processes. BioSTAR has been designed to take on this challenge (Pollesch 2016) by addressing aggregation methods explicitly and providing a means to robustly combine information when appropriate and to compare conditions against baselines and targets.

Dimensions, themes, and indicators

Environment, social, and economic dimensions are defined similarly in each of the frameworks we reviewed. SAFA recognizes governance as a separate dimension. APOIA-NovoRural distinguishes landscape ecology and environmental quality dimensions and further defines a management or administration dimension instead of governance. Although different terminologies exist, there are similar themes and subthemes across frameworks generally representing air, soil, water, energy, (bio)diversity, productivity, profitability, employment, food security, and social acceptability. However, each of the reviewed frameworks recommends unique indicator sets to the extent that information is available for the particular case, and groups the subthemes and indicators somewhat differently. Depending on the framework, the suite of indicators may be modified to varying degrees based on the context of the system being assessed. MESMIS, MMF, and SAFA assessments rely on a customized set of indicators based on farm or company characteristics. BioSTAR provides a checklist of indicators to be considered for each case. De Olde et al. (2017*a*) provide a detailed analysis of the degree to which some farm-level assessment tools overlap after aligning terminology and demonstrate that the differences in thematic coverage and indicators influence the overall conclusion of each assessment.

Irrespective of differences in terminology and thematic categorization, the reviewed ASAF obtain indicator values via a mix of census information, observations, sampling, model estimates, farmer records, and farmer or other stakeholder declarations in surveys or interviews. Thus there is a need to synthesize diverse types of data (Pollesch and Dale 2015). Some indicators rely on yes/no responses to a stated condition (e.g., formal involvement in any agri-environmental programs (PG), or existence of a mission statement (SAFA)); others rely on classifying inputs or outputs on a relative scale. For example, a RISE assessor converts primary indicator values to fit a 0–100 scale for each indicator. Within the reviewed set, a few frameworks require indicators that are on-site measurements of physical conditions, and some protocols try to avoid this requirement (e.g., PG). Others emphasize high-quality quantitative information as primary data (especially measured and estimated physical data, as in BioSTAR and APOIA-NovoRural) thus providing a systematic option for ranking scenarios or scoring indicators during the aggregation procedure. Such data are advantageous for analysis of landscape patterns and processes in which spatial scaling (up or down) is facilitated by quantitative and areal units. In some protocols the assessor is given significant responsibility for making judgements regarding data input, including rating or ranking the primary data and determining the direction of the impacts (e.g., RISE) or obtaining data from modeling tools (e.g., MESMIS, BioSTAR).

Methodological approaches

We intentionally reviewed ASAF that each use a somewhat different combination of methodological and analytical approaches to complete an assessment. MESMIS emphasizes a whole-system approach that is focused on informing management decisions, while SAFA highlights strengths and weakness in sustainability of product life cycles. SAFE offers a multi-criteria component-based approach in contrast to MESMIS' multi-criteria systems approach and relies on fuzzy logic models rather than a qualitative ranking as in BioSTAR. Yet each framework strives to be holistic and multidimensional. RISE uses a driving force-state-response approach applied to direct measures of many indicators, a method that originated in sustainable development research efforts (OECD 2001). Likewise, APOIA-NovoRural emphasizes biophysical sampling and remote sensed indicators, which are normalized and combined via utility functions into composite indices. MESMIS, SAFE, SAFA, and BioSTAR emphasize the importance of contextualizing the system being assessed to choose appropriate indicators. With the exception of MESMIS, the frameworks we examined use unique, hierarchical, aggregation techniques to remove indicator-specific units and visualize sustainability at the thematic or dimensional level—most often as radar plots. Generally, the frameworks do not provide specific management recommendations that would improve an indicator's "score" for a given farm system. This sometimes falls within the purview of the assessor but most frequently is not made explicit in the assessment. Exceptions are illustrated by APOIA-NovoRural, which formulates an environmental management report highlighting technology options for abatement of environmental impacts, and RISE in which a trained assessor discusses indicator scores and potential solutions to poor scores with the farmer.

Opportunities and challenges in addressing landscape concepts in ASAF

Generally, these ASAF fall short of encompassing many concerns related to agricultural landscape patterns and processes, which is an admittedly difficult task. Most ASAF we reviewed represent the concept of agro-ecosystem services by including, for example, indicators of biodiversity, soil and water quality, and to a lesser extent, greenhouse gas emissions. SAFE offers an indicator suite based on agro-ecosystem functions defined in de Groot et al. (2002) that can be expanded from the parcel or farm to the watershed. MESMIS additionally addresses seven sustainability attributes of Natural Resource Management Systems that are applicable to ecosystems (productivity, stability, reliability, resilience, adaptability, equity, and self-reliance) but does not recommend specific indicators for landscape patterns. IDEA explicitly excludes what the authors term "territorial functions [or] services rendered to landscape[s]," yet the protocol addresses biodiversity, spatial organization, and human development with indicators that other assessments use to imply ecosystem processes (Zahm et al. 2008). In contrast, APOIA-NovoRural explicitly examines "landscape ecology" as a theme, but the implications for understanding pattern and process are not clear in that the aggregation approach taken may negate the spatial relevance of landscape indicators.

A key challenge is to develop indicators that represent landscape characteristics that are important to stakeholders and adequately capture the changes of those characteristics that occur as a result of agricultural management practices. One way to document trends in indicators is to repeat assessments of "status" periodically, in which each farm or case study provides its own baseline. However, for assessing landscapes in which key components, processes, and even boundaries may be variable through time, an alternative approach may be needed. For example, baselines and target values for indicators could be identified in the literature or historical records so that trends towards or away from goals may be highlighted even within a single assessment cycle. Sustainability assessment designers should acknowledge that it is possible to have apparent improvements in agroecosystem indicators that do not reflect improvement in landscape function. For example, an increase to a diversity index based on remote sensed land-use or land-cover change could reflect significant ecosystem disruption that is neither environmentally beneficial nor reflective of stable agricultural productivity or more resilient markets. A diversity index could increase as a result of the introduction of exotic or invasive species, the abandonment of cropland because of salt intrusion, or subsidized fallowing. Such complexities require expert interpretation, especially by stakeholders with local knowledge. Experts may be formally trained or may rely on acquired, informal knowledge systems. Reliance on expert interpretations on a case-by-case basis necessitates a larger investment in time (and likely money), a consideration that must be balanced against the intended purpose of the assessment.

Some progress in assessing agriculture-related changes to landscapes could be made by inclusion of specific types of indicators. For example, indicators that monitor rates (material and energy flows; e.g., denitrification, water table depletion, soil loss or gain, nutrient input relative to production) are relevant to farm management decisions and the underlying data may be available from empirical measurements or modeling techniques. Including data about landscape patterns and ecosystem processes would add complexity to ASAF, thus tools that facilitate data collection, management, and visualization are important. Trained assessors and software support may help accommodate additional levels of data complexity that may be required for landscape assessment, though at some additional expense of time and cost. Some attributes of landscapes such as patchiness and degree of heterogeneity can be quantified or estimated to the appropriate resolution through GIS modeling and remote sensing, use of indicator-species assessments, and even qualitatively from farmer records and crowd-sourced information. Important socio-economic processes can also impact agro-ecosystem patterns, including migration, governance of natural and manmade resources (e.g., irrigation and other infrastructure), local exchanges of agricultural products and sub-products, human welfare, and security (Saqalli et al. 2011).

There is often a major gap between farm-level and regional indicator data. For example, government census data that applies to a county or municipality (i.e., on the order of thousands of square kilometers) may be inadequate to address stakeholder concerns related to water resource access at farm, community, or local watershed scales (on the order of hundreds of hectares) but useful in providing context for the landscape and revealing potential resource constraints and opportunities. On the other hand, sampling a sufficient number of farm households and community representatives to understand drivers of priority water resource concerns is likely to be time-consuming and expensive and raises questions about data reliability and reproducibility. Thus, investments are needed to develop realistic indicators of relevant agricultural landscape processes that include multiple farm systems, natural resources, and non-agricultural activities. In contrast to predicted or modeled data that can often be scaled, pre-existing observational data (such as census data) may be aggregated to the regional or broader spatial scale. Time and costs required for making new, protocol-specific observations will certainly limit options for indicator data. Significant research may be required to determine which proxies can best represent difficult to obtain indicators in assessment of agricultural landscapes including defining the level of resolution necessary to adequately inform farm and landscape management decisions and modeling approaches that allow reliable estimates of indicators. Citizen science may play a role in filling such data gaps (Wallace et al. 2016; Yu et al. 2017). It is worthwhile to note that comprehensive coverage of landscape components within selected indicators is not the goal because such extensive data can inhibit interpretation by stakeholders (De Olde et al. 2018). Rather, a minimum number of easily monitored indicators, sufficient for making decisions regarding identified stakeholder priorities, should be the focus (e.g., Graymore et al. 2008; Dale et al. 2013*b*).

If decision support for agriculture practices is a key objective of the ASAF, it is imperative to provide a synthesis of the results to the stakeholders and decision makers. Some ASAF produce outputs that illustrate a sustainability status through simplified graphics or maps while others require users to have substantial training to interpret the results and relate them to management practices. In some instances, multiple frameworks may be needed to communicate progress toward landscape objectives. Another option is provided by scenario-based assessment that can demonstrate potential outcomes of policy or practices to stakeholders facing agricultural management decisions.

Modeling in ASAF

Models used to project or explore a wide array of environmental management decisions are available. Scenario-based assessments often employ modeling techniques and emphasize policy impacts and risk analysis in management of, for example, invasive species (Keller et al. 2008), protected sites (Marnika et al. 2015), regions (Gutzler et al. 2015), and continents (Helming et al. 2011). Scenarios can be developed through various methods based on actual or target conditions and modeled outcomes in which specific parameters have been systematically manipulated. ASAF that allow for ex ante exploration (if not predictions per se) of possible management scenarios can be made compatible with ex post analysis through careful selection of indicators, as in MMF and BioStar. Musumba et al. (2017) provide a further example of combining observed and predicted data in an indicator-based assessment for multiple scales, as applied to research for sustainable development. This combined functionality in ASAF could help stakeholders envision practical agricultural options by illustrating how management choices influence indicators. Under such an application, scenarios could demonstrate the degree to which management choices facilitate progress toward specific indicator targets for agricultural landscapes. Trade-offs between competing objectives that influence management decisions can be simplified and illustrated (Tittonell et al. 2015) relative to multi-dimensional sustainability goals with the help of scenario comparisons. Care must be taken to present scenario procedures in an understandable, transparent way so that diverse stakeholders with informal training maintain trust in the assessment.

Some efforts have been directed towards developing modeling approaches that can be used for assessments at different biophysical extents through the quantification of indicators across various spatial scales, notably field, farm, and region. For example, Landscape IMAGES (Interactive Multi-goal Agricultural Landscape Generation and Evaluation System) uses a genetic algorithm to search for large numbers of alternative, acceptable landscape configurations and allows the quantification of agronomic, economic, and environmental indicators and their trade-offs (Groot et al. 2007*a*, 2007*b*). Delmotte et al. (2016, 2017) developed a suite of modelling techniques (linear programming, multi-agent models, land-use change models) to conduct participatory assessment of scenarios of agricultural change to quantify indicators at different spatial scales. Baudron et al. (2015) used soft-coupling of several scale-specific models including simple agent- and multi-agent-based models to assess trade-offs at different spatial scales (plot, farm, territory) within a region in relation to crop biomass management and regional productivity responses to management patterns. Saqalli et al. (2011) applied the Common Resources Management Agent-based System to simulate likely agro-ecological and socio-economic outcomes of agricultural intensification interventions at the farm to village level. The benefits of cover crop use for managing fertilizer costs and nutrient export in an agricultural watershed were estimated by a simple land-use change and farmer implementation rate model (Eichler Inwood 2016).

Methodological approaches and tools used to develop scenarios can also inform the selection of specific indicators for sustainability assessment of agricultural landscapes. Approaches include optimization and simulation models at different scales as well as soft-coupling scale-specific models in which landscape processes and patterns can be explicitly addressed. Simulations within ex ante analyses for ASAF could be used to identify indicators that are sensitive to context-specific farm and landscape management options early on in an assessment process, thus streamlining a complex agricultural landscape assessment.

Recommendations

Several recommendations for agricultural assessment frameworks are provided below based on this review (Table 6). Principles underlying sustainability goals for agricultural landscapes include the following: continual learning and adaptive management; consideration of multiple spatial scales, temporal scales, stakeholders, and functions; participatory frameworks for monitoring change; resilience; and increased stakeholder capacity, which pertain broadly to many development processes (Sayer et al. 2013). Recognizing the relationships between sustainability goals, landscape components, and indicators can help identify potential co-benefits and trade-offs between management choices that affect agricultural landscapes (Gerdessen and Pascucci 2013; López-Ridaura et al. 2002, 2005*a*, 2005*b*). The science of landscape ecology provides methods for addressing complexities such as spatial heterogeneity (Dale et al. 2013*a*) as a part of assessing sustainability. Furthermore, a landscape approach is well-suited to addressing diverse stakeholder needs because it includes an "iterative, flexible, ongoing process of negotiations, decision-making and reevaluation, informed by science but shaped by human values and aspirations" (Sayer et al. 2013). Such approaches generally recognize the need to evaluate dynamic conditions including rates of change, trends, and thresholds or tipping points in indicators.

A flexible ASAF that can be adapted to a broad spectrum of agricultural landscapes is useful for monitoring changes through

Table 6. Recommended features for a sustainability assessment framework applied to agricultural landscapes.

Framework feature	Detail
Agricultural landscape perspective	Identifies indicators of patterns and processes beyond the boundaries of a single farm or field; intended for repeat applications at multi-year intervals to monitor trends in indicators within each of the social, economic, and environment dimensions.
Systems approach for integrated assessment	Considers interactions across farm systems and agro-ecosystems, rather than product life-cycle or business enterprise focused; across environmental, social, and economic dimensions.
Participatory and iterative	Early and regular involvement of stakeholders via a transparent and collaborative process to select indicators and embed feedback to improve use for repeat assessments; easy-to-understand summaries and assessment results for diverse audiences while retaining individual indicator information and links to management practices; inclusion of local knowledge systems to support adaptive management.
Flexible indicator suite	Guidance to select a core set of indicator themes containing site-specific indicators that can accommodate additional indicators as systems evolve and (or) data availability changes.
Adaptable	Relevant to a variety of farm system types and landscapes in any socio-economic and bio-physical locale; becoming context-specific as stakeholder goals are addressed.
Communicative	Timely and effectively sharing of assessment results that illustrate relationships between management decisions, ecosystem services, and socio-economic activities including trade-offs among the selected indicators.

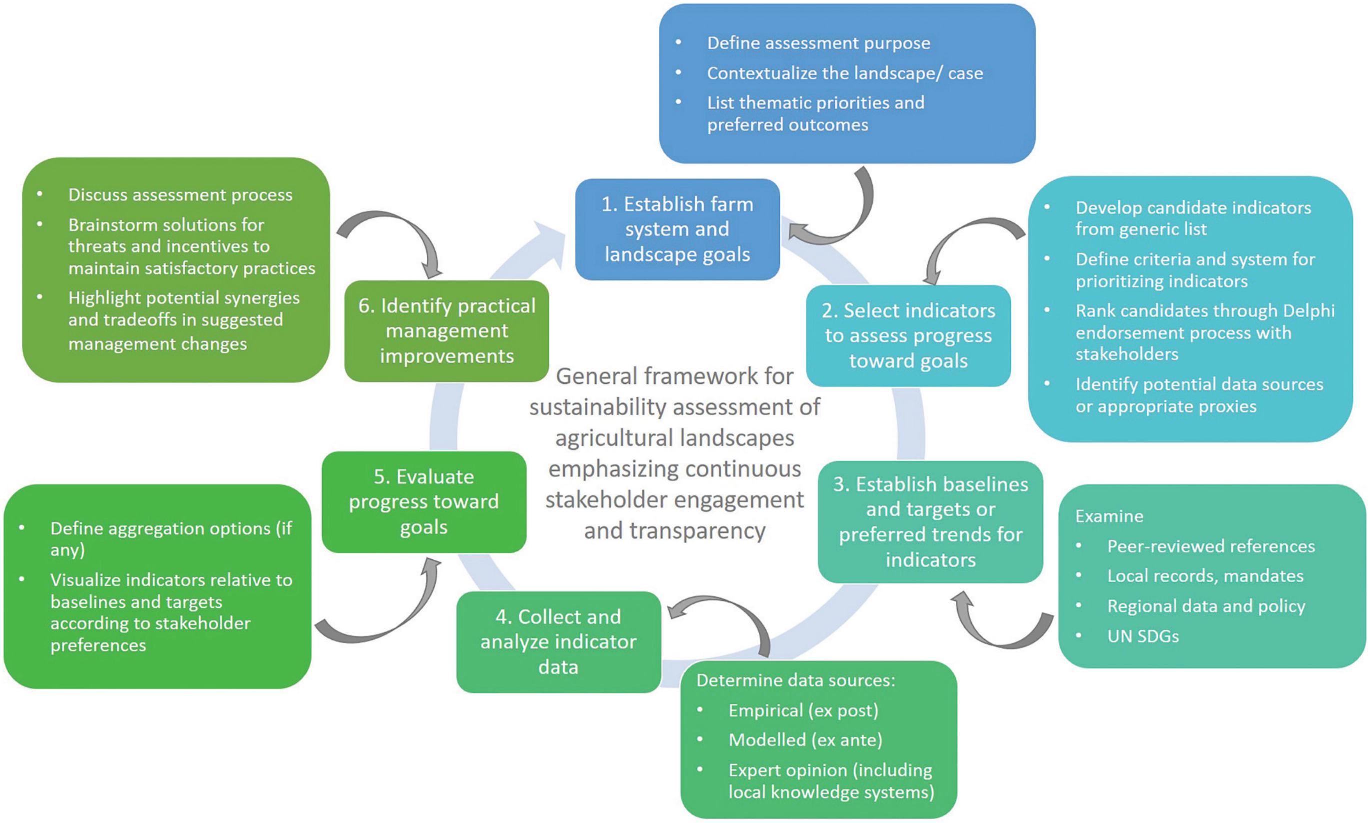
time and comparing progress toward sustainability across a variety of systems. Shifts in agricultural management such as adding perennial crops or livestock, accessing an alternative market, or using different tillage equipment as it affects system functioning may be difficult to predict. The ASAF should be relevant as stakeholders acquire new information, use new technology or crop varieties, and consider different management options since a key objective is to support decision making. Thus, sustainability assessment designed for a highly specific context or product may not capture the inherent heterogeneity and variability of farm systems and agricultural landscapes. A major challenge remains balancing contextual specificity of individual farms with the generally applicable concerns of agricultural landscapes. An ideal framework would be capable of documenting trends in individual indicators as the agricultural landscape changes. The use of the same framework would therefore result in potentially different lists of indicators depending on the context (López-Ridaura et al. 2002; FAO and SAFA 2013*a*). The framework and potential indicators should be developed, tested, and adapted through case studies.

Frameworks should be suitable for the system under assessment. Gasparatos and Scolobig (2012) list priorities for choosing assessment tools based on the desired perspective or features of the tool, the reference or target indicator values, and stakeholder values. Other important factors include the needs and objective for performing the assessment, context of the system being assessed, and early stakeholder input on protocol choice (Coteur et al. 2016; Dale et al. 2015; De Olde et al. 2017*a*, 2017*b*). In our view, it is essential to have existing working relationships between extension or research organizations and other stakeholders to facilitate incorporation of farmers' interests, capacity, and cooperation. In addition, a fluid mechanism for communication in the inhabitants' native language and expert translations into the language of the framework or protocol may be an important component to obtain useful data for assessing farm systems within agricultural landscapes and to transmit learnings back to stakeholders. We expect varying levels of quality with different types of social, economic, and environmental indicator data, but a minimum amount of standardized information is needed at the appropriate resolution, including farm household data. Additionally, having a sense of farm and landscape improvement goals and management records provides useful context for selecting an appropriate assessment framework and subsequently, useful indicators.

Research on the derivation of relevant indicators has generally concluded that sustainability assessment requires characterizing a farm system and stakeholder concerns prior to developing indicator lists or weighting factors and aggregation techniques (Dale et al. 2015; FAO and SAFA 2013*b*; López-Ridaura et al. 2002). However, in the realm of sustainable intensification of agriculture, there may be sufficient overlap between the particular objectives of the ASAF (baseline and monitoring of progress toward target values related to SDGs) and stakeholder concerns (welfare and profitability, practicality) so that a general framework can be designed for multiple contexts and may include a checklist of broadly relevant indicators a priori. A framework that provides guidance on identifying indicators of patterns and processes that occur at farm system to community and landscape levels, in addition to the socio-economic and bio-physical distinctions of farms, households or communities, would apply to a wide array of systems. An example general framework for sustainability assessment of agricultural landscapes is illustrated in Fig. 3, which builds from López-Ridaura (2005), Dale et al. (2015), and De Olde et al. (2017*a*).

We recommend an assessment framework that is system-based, rather than focusing on a product or single component, and reflects a transparent process involving early and continuous input by stakeholders (Fig. 3). Ideally, embedding a framework in the decision-making processes of stakeholders from field to landscape makes such an approach be more effective by increasing knowledge exchange and trust between stakeholder groups. A coordinator initiates an assessment process in which landscape goals and context (Step 1) are determined via interactions with diverse stakeholders. The goals and context then provide guidance on identifying those indicators stakeholders find informative, often based on a checklist of recommended indicators (Step 2). The baseline and target values (or preferred trends when endpoints are unknown) are determined to track changes in selected indicator values over time. Indicators may be based on empirical, secondary or modelling data, expert opinion, sampling, or surveys, and may include some combination of bio-physical observations, census data, remote-sensing, and digital modeling resources, and farmer and other stakeholder declarations and records. The indicators should be widely recognized and broadly applicable (i.e., highly specialized or uncommon equipment, analyses, or expertise as a requirement for establishing indicator values are discouraged) and somewhat customizable to the context of each farm system and agricultural landscape. Infor-

Fig. 3. Six-step framework for sustainability assessment of agricultural landscapes using a transparent process with ongoing stakeholder involvement as organized and implemented by the coordinator of the assessment. Built upon López-Ridaura (2005), Dale et al. (2015), and De Olde et al. (2017*a*).



mation requirements for the indicator values should optimize use of existing data and incorporate knowledge exchange and local knowledge systems (see Fazey et al. 2013; Buytaert et al. 2014) when possible. We suggest including some indicators that could serve as proxies for functional relationships within farm systems and landscapes only when a thorough understanding of the system components is available. The goal of the selected indicator suite should be sufficient rather than exhaustive coverage of agricultural landscape components to illustrate important and manageable interactions.

The indicator data should be assembled (Step 3 of Fig. 3), and then requirements for further data collection should be identified in consultation with stakeholders (Step 4). Progress toward goals can be evaluated relative to baseline and target values that are established based on stakeholder input and published references (Step 5). In the evaluation step, indicators are often summarized within themes, and several aggregation techniques are available for this step (Pollesch and Dale 2015). Outputs from the evaluation step should provide intuitive visualizations of dimension and theme-level aggregations where appropriate. The assessment results should enable review of individual indicator values such that practical management alternatives can be linked to specific indicator improvements. Based on the evaluation, better management practices can be proposed through discussion among stakeholders (Step 6). Once alternative practices have been implemented, the framework can be applied again so that progress toward indicator targets and sustainability objectives is monitored. These recommendations are being tested in a case study sustainability assessment of the Yaqui Valley, Mexico, agricultural landscape (Eichler Inwood 2018).

An important role of an agricultural landscape sustainability assessment is communicating the complexity of functions and services related to agricultural landscapes in the form of assessment output and results that are easy to interpret. Avoiding assessment results in the form of composite indices alone—which may be useful for high level overviews—and instead striving for transparent, individual indicators helps maintain relevance to actual management practices. Ratings or rankings of indicators on an intuitive unit (such as percentages, as in IDEA) and with minimal assessor influence could help maintain transparency in the farm system assessment process and at the same time improve capabilities for self-assessment. Similarly, limiting indicators to those that can be affected by farm or resource (e.g., watershed) management decisions improves relevance of the framework. By re-applying the same set of customized indicators through time—as in MESMIS—stakeholders could visualize progress towards sustainability goals, using their system's baseline status as well as similar local systems as references. The ability to add indicators as systems or priorities change, as provided by the SAFA procedure, would increase the long-term usefulness of a framework. Such a framework would reduce effort and maximize information transferability—two important considerations for research and extension agencies targeting sustainability improvements.

Conclusion

Continued research is needed to fill gaps in information about the relationships among management practices, farm systems, ecosystem processes, and agricultural landscapes at multiple scales. The relationships are critical to support informed decisions by actors ranging from farm operators to regional and national governance units. Experimental or context-specific data are more often available for farm systems whereas general information on market, ecosystem, and social conditions is typically available at the scale of state, regional, or national governance systems. Assessing progress and comparing indicators of sustainability can be challenging owing to the different scales associated with different data sets.

Our qualitative analysis of sustainability assessment frameworks provides recommendations to improve assessments of agricultural landscapes. Development of effective indicators for characteristics and processes important to agricultural landscapes may be facilitated by linking publicly available geo-referenced databases to software and modeling tools to streamline the contextualization process and provide capability for scenario building. Such linkages could support more reliable, affordable, and transparent assessments. For example, linking existing models of soil loss, water-nutrient transport, and greenhouse gas emissions with socio-economic data on markets, migration, land-use change, and information about dynamic social networks could help identify improved practices for production and transport of agricultural goods. Synthesis of stakeholder input, observed indicator values, and location and rates of adoption of improved practices should result in a dynamic assessment process that improves with each use by including regular communication and feedback amongst participating stakeholders. The knowledge exchange occurring within a participatory assessment process itself is likely to improve awareness of management actions that affect landscapes, in addition to outputs and recommendations resulting from application of any given assessment framework. Our work does not attempt to quantify differences in these approaches as applied to specific landscapes—an exercise that may help identify the relative advantages of the different ASAF reviewed and the specific indicators they employ. Continued collaboration among assessment developers will help identify operationally effective procedures to understand changing patterns and processes as measured by indicators of progress toward sustainability in farm systems and agricultural landscapes.

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