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Review

Evaluating agricultural trade-offs in the age of sustainable development☆

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ABSTRACT

A vibrant, resilient and productive agricultural sector is fundamental to achieving the Sustainable Development Goals. Bringing about such a transformation requires optimizing a range of agronomic, environmental and socio-economic outcomes from agricultural systems – from crop yields, to biodiversity, to human nutrition. However, these outcomes are not independent of each other – they interact in both positive and negative ways, creating the potential for synergies and trade-offs. Consequently, transforming the agricultural sector for the age of sustainable development requires tracking these interactions, assessing if objectives are being achieved and allowing for adaptive management within the diverse agricultural systems that make up global agriculture. This paper reviews the field of agricultural trade-off analysis, which has emerged to better understand these interactions – from field to farm, region to continent. Taking a "cradle-to-grave" approach, we distill agricultural trade-off analysis into four steps: 1) characterizing the decision setting and identifying the context-specific indicators needed to assess agricultural sustainability, 2) selecting the methods for generating indicator values across different scales, 3) deciding on the means of evaluating and communicating the trade-off options with stakeholders and decision-makers, and 4) improving uptake of trade-off analysis outputs by decision-makers. Given the breadth of the Sustainable Development Goals and the importance of agriculture to many of them, we assess notions of human well-being beyond income or direct health concerns (e.g. related to gender, equality, nutrition), as well as diverse environmental indicators ranging from soil health to biodiversity to climate forcing. Looking forward, areas of future work include integrating the four steps into a single modeling platform and connecting tools across scales and disciplines to facilitate trade-off analysis. Likewise, enhancing the policy relevance of agricultural trade-off analysis requires improving scientist-stakeholder engagement in the research process. Only then can this field proactively address trade-off issues that are integral to sustainably intensifying local and global agriculture – a critical step toward successfully implementing the Sustainable Development Goals.

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1. Introduction

Agriculture plays a central role in sustainable development. Its fundamental position as the supplier of human nutrition shapes the global economy and society's relationship with the natural world. It is thus central to achieving a suite of Sustainable Development Goals (SDGs) agreed to by the United Nations in 2015 (United Nations, 2015), ranging from ending hunger and poverty, to improving human well-being and reducing environmental impacts (United Nations Economic and Social Council, 2016). Already, over a third of the world's land surface and nearly three quarters of its freshwater resources are devoted to agriculture (Dobermann et al., 2013; HLPE, 2013; Pretty et al., 2006). It is both an important driver of global climate change, as a result of land-use change and greenhouse gas emissions (Smith et al., 2014), and one of the sectors most vulnerable to its impacts (Vermeulen et al., 2012). Moreover, approximately three quarters of the world's poorest people live in rural areas, where farming is the main source of employment and income (World Bank, 2007; IFAD, 2011). With growing global population and affluence, the pressure on agricultural and natural systems increases. As a result of these growing pressures, humans now expect agriculture to supply not only nutritious food but also employment, energy resources, clean water, biodiversity conservation and more. This situation makes it essential to navigate and manage the trade-offs between potential benefits and negative impacts that can arise as food production interacts with other aspects of sustainable agricultural systems (Millenium Ecosystem Assessment, 2005; Tilman et al., 2009; Godfray et al., 2010; Tilman and Clark, 2014).

Concepts such as sustainable agricultural intensification (Garnett and Godfray, 2012) and climate-smart agriculture (Lipper et al., 2014) are rallying cries to the challenge of achieving the multiple goals of increasing agricultural productivity and rural livelihoods while minimizing negative environmental effects. As pointed out by Garnett and Godfray (2012), sustainable agricultural intensification is not a particular set of practices but instead provides a conceptual framework for guiding discussions on achieving balanced outcomes of intensification. Thus, there can be multiple alternative pathways to sustainable agricultural systems whose suitability and outcomes vary depending on agro-ecological zone, farming system, cultural preferences, institutions and policies, among other factors. Each of these pathways results in a different suite and/or degree of environment and socioeconomic trade-offs and synergies that must be recognized and addressed.

The successful transformation of the agricultural sector to meet these multiple goals, therefore, requires the ability to track multiple outcomes, assess whether identified goals are being met or compromised, and allow for guided course corrections. In an effort to make these interactions explicit, trade-off analysis for agricultural systems has emerged as an increasingly important field of study. This paper attempts to synthesize the central components of the literature on agricultural trade-off analysis and provide guidance on next steps for research in this area.

Trade-off analysis developed out of cost-benefit-analysis (CBA) and was first applied to agriculture during the Green Revolution in the 1970s to evaluate the economic impacts of emerging agricultural technologies (Alston et al., 1995). These approaches focused on maximizing financial margins in agriculture. As researchers began to broaden their focus to issues of sustainability in the 1980s and 1990s, it became apparent that the CBA paradigm was insufficient to address the multiple monetary and non-monetary goals of sustainability. Early applications of trade-off analysis in agricultural sustainability assessments coupled biophysical data and models with economic models to generate a more inclusive approach to evaluating agricultural sustainability (Antle and Capalbo, 1991; Antle and Pingali, 1994; Pingali and Rosegrant, 1995; Crissman et al., 1998). These early studies assessed the economic, environmental and health trade-offs of pesticide use. Since then, the use of trade-off analysis to assess agricultural sustainability has steadily grown as a field of study, expanding beyond agronomic and economic outcomes at the field and farm level, to incorporate environmental and social outcomes at regional and continental scales (e.g. Weersink et al., 2002; Chen et al., 2008).

A range of tools provide means to assess the trade-offs and synergies that arise from agricultural intensification. This review builds on previous introductions to trade-off analysis in agricultural systems by moving beyond considerations of any one specific technique (e.g. Crissman et al., 2001) or scale of analysis (Dale et al., 2013; Klapwijk et al., 2014). The scope of this review encompasses more inclusive notions of human well-being beyond income or direct health concerns (e.g. to gender, equality, nutrition), as well as extending consideration of environmental aspects from a historic focus on soil health to issues of biodiversity, climate forcing and landscape-level processes. Moreover, we consider how information derived from trade-off analysis can be visualized and communicated effectively to guide agricultural development – a key challenge of making this research relevant at the science-policy interface. In short, we attempt to provide a comprehensive review of the parameters, tools, and outreach methods that constitute the various stages of trade-off analysis. With the international community now focused on how to implement the SDGs across local, national and global scales, it is more important than ever to understand how trade-off analysis can help decision-makers develop balanced approaches that take the links between the SDGs into account (Le Blanc, 2015). This integrated approach is particularly relevant for agriculture, as efforts to make this sector more economically, environmentally and socially sustainable are critical to the success of a majority of the SDGs (Canavan et al., 2016).

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We organize the paper by distilling the agricultural trade-off analysis process into the following steps: 1) understanding the decision context and identifying the indicators needed to assess agricultural sustainability in a particular setting, 2) selecting the methods for generating indicator values across different scales, 3) deciding on the means of evaluating and communicating the trade-offs with stakeholders and decision-makers, and 4) improving uptake of trade-off analysis outputs by decision-makers. Considering these steps helps us to identify and highlight gaps in data sources, assessment tools, and communication of more systematic, yet targeted, assessments of the sustainability of agricultural intensification.

2. Understanding the decision context and selecting indicators

Several studies have presented frameworks for assessing trade-offs and synergies associated with agricultural intensification (Crissman et al., 1998; Lee and Barrett, 2000; López-Ridaura et al., 2002).

While many of the approaches to trade-off analysis are common across situations, there is no 'one size fits all' approach to sustainable agricultural intensification. Each decision context involves a unique combination of local parameters, circumstances and actors that define the scope and final outcomes of the analysis (Efroymson et al., 2013). Understanding the specific context sets the boundaries of what is socially, politically, economically, and ecologically feasible and desirable in the system and is essential to defining the primary sustainability objective. Co-developing, with stakeholders, a common conceptual model at the outset of the process is an important (and too often skipped) first step in trade-off analysis. This conceptual model should describe the socio-economic, institutional and agro-ecological context; capture the essential dynamics, drivers and feedbacks of the system; and elicit stakeholder values, preferences and assumptions (Giller et al., 2011). Important stakeholders in this process include policy-makers, farmers, landowners, consumers, environmentalists (as well as other interest groups) and scientists representing a variety of disciplines. The goal of the process is to define the key indicators to be analyzed, ensuring that they are meaningful to end-users and cover the multiple dimensions of sustainability relevant to this particular context (Dale et al., 2015).

Indicators are the fundamental units of agricultural trade-off analysis (ISPC, 2014) and should convey reliable information relevant for assessment and decision-making. Indicators can be direct, single-factor measurements (e.g. crop yields), modeled estimates requiring data and statistical relationships from several measurements (e.g. watershed soil erosion), or composites of several underlying indices (e.g. Women's Empowerment in Agriculture Index – Alkire et al., 2013). Criteria to consider in selecting indicators include 1) confidence that the links between the indicator and what it purports to represent are well-understood, unambiguous and sensitive, 2) reliability and accuracy of the information conveyed, and 3) the ease and cost of monitoring the indicator over time (Pannell and Glenn, 2000). Furthermore indicators should be sensitive to both natural and anthropogenic stresses to the system, anticipatory of impending changes, and predictive of changes that can be averted with management action (Dale and Beyeler, 2001). Many indicators have been proposed to measure the agricultural, environmental and human livelihoods aspects associated with agricultural intensification, of which several have been included in the list of indicators proposed by the United Nations to measure progress on the SDGs (United Nations Economic and Social Council, 2016). The most commonly used indicators for assessing various aspects of sustainability associated with agricultural systems are listed in Table 1 (López-Ridaura et al., 2002; Speelman et al., 2007; ISPC, 2014; Zurek et al., 2015; Smith et al., 2016).

Table 1

Some of the most common agricultural, environmental and socioeconomic indicators proposed for assessing trade-offs and synergies in agricultural systems. Included for each indicator are examples of units as well as the SDGs targets that are most relevant.

Agriculture indicators	**SDG target**
Yield *(e.g. kg product/ha)*	2.3 Double agricultural productivity and incomes
Yield gap *(e.g. attainable yield – actual yield; kg product/ha)*	2.3 Double agricultural productivity and incomes
Input efficiency *(e.g. kg grain/kg N)*	2.4 Sustainable agriculture
Labor productivity *(e.g. kg product/labor time (days or hours))*	2.3 Double agricultural productivity and incomes
Cropping intensity (*e.g. crop rotations/year*)	2.3 Double agricultural productivity and incomes
Fodder production (*e.g. tons/year*)	2.3 Double agricultural productivity and incomes
Input use intensity (*e.g. kg pesticides/ha*)	2.3 Double agricultural productivity and incomes; 2.4 Sustainable agriculture
Stocking rate (*e.g. animals/ha*)	2.3 Double agricultural productivity and incomes; 2.4 Sustainable agriculture

Environment Indicators	**SDG target**
Soil quality	
• Soil carbon *(e.g. % soil organic matter)*	2.4 Sustainable agriculture; 13.2 Integrate climate measures into national policy; 15.3 Reverse land degradation
• Soil erosion(*e.g. kg/ha*)	2.4 Sustainable agriculture; 15.3 Reverse land degradation
• Nutrient balance *(e.g. N applied/N harvested)*	2.4 Sustainable agriculture; 6.3 Improve water quality; 6.6 Protect aquatic ecosystems; 13.2 Integrate climate measures into national policy; 14.1 Reduce marine pollution
• Soil fertility (*e.g. pH*)	2.4 Sustainable agriculture; 15.3 Reverse land degradation
Biodiversity	15.1 Protect terrestrial ecosystems 15.2 Sustainable forest management 15.5 Halt biodiversity loss
• Population size (*e.g. number of individuals*)	
• Species richness (*e.g. number of rare species*)	
• Habitat area (*e.g. wetland extent*)	
Greenhouse gas emissions (*e.g.* $t\ CO_2$ *eq.*)	2.4 Sustainable agriculture; 13.2 Integrate climate measures into national policy
Water quality (*e.g. mg pollutant/ml*)	6.3 Improve water quality; 6.6 Protect aquatic ecosystems
Water quantity (*e.g.* m^3)	6.4 Increase water use efficiency; 6.6 Protect aquatic ecosystems
Land cover type/change (*e.g. % converted*)	15.1 Protect terrestrial ecosystems; 15.5 Halt biodiversity loss

Human well-being indicators	**SDG target**
Agricultural income (*e.g. $/ha*)	2.3 Double agricultural productivity and incomes
Poverty *(e.g. % population below poverty line)*	1.1 End extreme poverty i.e. <$1.25/day 1.2 Reduce poverty by half according to national definitions
Employment (*e.g. on–and off–farm employment rate*)	8.5 Employment for all
Food Security	
• Food availability *(e.g. calories/head)*	2.1 End hunger; 2.3 Double agricultural productivity and incomes
• Food access *(e.g. % income spent on food)*	2.1 End hunger
• Dietary intake *(e.g. calories/head)*	2.1 End hunger; 2.2 End malnutrition
• Food utilization (*e.g. % food waste*)	12.3 Halve global food waste
Nutrition *(e.g. % stunting, % obesity)*	2.1 End hunger; 2.2 End malnutrition
Empowerment *(e.g. Women's Empowerment in Agriculture Index)*	5.5 Ensure equal opportunity for women

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Stakeholder objectives and concerns often shift with spatial scale from local to global, shaping which trade-offs are examined and which indicators are important at each scale. At the scale of an individual crop field, stakeholders are primarily focused on maximizing yields and minimizing negative environmental repercussions from agronomic activities (crop type, fertilizer application, pesticide use, tillage, irrigation, harvest). In addition to these field-scale priorities, farm-scale goals are often a balance of productivity, income, and social goals of a household (multi-crop yields, nutrient balances, labor demands, food security, income stability, nutrition). Maximizing utility at this scale therefore encompasses a broader array of outcomes than simply profit maximization – health outcomes, cultural preferences, and agro-ecological conditions (to name a few) are also stakeholder priorities (Rufino et al., 2011). Moving to the regional scale, questions regarding the optimal spatial arrangement of land use (e.g. placement of reserves or vegetative buffers) and interactive impacts of multiple independent decisions by landholders become most relevant to a wider population of stakeholders (e.g. the downstream effects of land-use management decisions on water quality, local biodiversity loss, and local food security). Finally, at the global scale the focus of analysis shifts to the distribution of benefits (e.g. national food security) and impacts (e.g. global biodiversity loss, climate change) of agricultural production across countries and continents, with market forces (including international trade), and national and international policy efforts frequently exerting important influence. Consequently, the spatial scale of interest greatly influences indicator choice and stakeholder involvement.

Ecological and biophysical processes are linked across scales and are hierarchically-nested within one another (Dale and Polasky, 2007), as are social and economic ones. It is important to focus the analysis at the scale at which the phenomenon of interest occurs, as insights from one scale cannot necessarily be translated to other scales (Turner et al., 2001). Hierarchy theory also reveals that it is important to consider contextual information at least one scale above and one scale below that of the main focus (O'Neill et al., 1986). The broader scale in which the study is situated (e.g. a watershed or political jurisdiction) sets both the biophysical and socio-economic context and constraints of the system, while the finer scale processes (e.g. soil nutrient budgets or economic motives) can be the drivers of change (Turner et al., 2001). It is also important to recognize that although some indicators can be useful at multiple scales, their unit of measurement and interpretation may change between scales, e.g. soil organic matter at the field or farm scale may be indicative of soil quality for farmers, while at larger scales it may be an important indicator of carbon sequestration for national and global climate mitigation efforts. In order to be useful, indicators need to be formulated in ways that convey the type of information, at the appropriate scale, that decision-makers need to draw conclusions (Zurek et al., 2015). For example, when making management decisions regarding the protection or clearing of a forest, a climate scientist might be interested in the amount of carbon stored in a forest, while a farming household may be interested in provisioning services from the forest like fuelwood, medicinal plants, or drinking water, each requiring a different set of indicators to inform their respective decisions.

3. Estimating indicator values

The numerical value of a chosen indicator can be estimated in a variety of ways. Arguably the most robust (and thus desirable) approach is direct measurement via primary data collection in the field. The

Table 2

List of commonly used models for estimating indicators values and performing trade-off analysis by scale and their capacity to evaluate important agricultural (blue), human well-being (orange) and environmental (green) indicators. Red boxes indicate major gaps across models and scales. This list is not meant to be comprehensive but rather an illustration of the diversity of models available for generating indicator values for the purposes of trade-off analysis. The "yield" indicator refers to crop and livestock production.

Scale	Model	*Yield (crop and/or livestock)*	*Labor productivity*	*Cropping frequency*	*Income / poverty*	*Assets*	*Food security*	*Nutrition*	*Health*	*Gender equity*	*Empowerment*	*Soil organic matter*	*Soil nutrients*	*Soil erosion*	*GHG emissions*	*Water quality*	*Water quantity*	*Resilience*	*Biodiversity*	*Land cover*	*Energy production*
Field	RUMINANT*	X											X		X						
	FIELD	X										X		X							
	LIVSIM*	X																			
	HEAPSIM*												X								
	SWAT	X										X	X		X						
	RSIM	X											X		X						
	LPJ	X											X		X						
	FieldIMAGES	X			X							X	X	X			X				
	EPIC/DSSAT/APSIM	X										X	X	X	X	X	X				
Farm	FarmDESIGN	X			X							X	X	X			X				
	FarmIMAGES	X			X							X	X	X			X				
Region	BLOSM	X			X									X		X	X			X	X
	CSAP	X			X		X	X				X	X				X				
	TOA–MD	X			X			X	X	X		X	X		X		X				
	TOA–ME	X			X				X			X			X	X					
	InVEST	X			X									X	X	X	X			X	X
	APEX	X										X	X	X	X	X	X				
	SWAT	X											X	X		X	X				
	LandscapeIMAGES	X			X									X					X		
Continental	GLOBIOM	X		X				X					X		X		X		X	X	X
	MODE	X			X	X									X					X	
	IMPACT	X					X						X				X				
	GAEZ	X										X	X	X	X		X		X	X	X
	IMAGE	X		X	X		X	X	X			X	X	X	X	X	X		X	X	X

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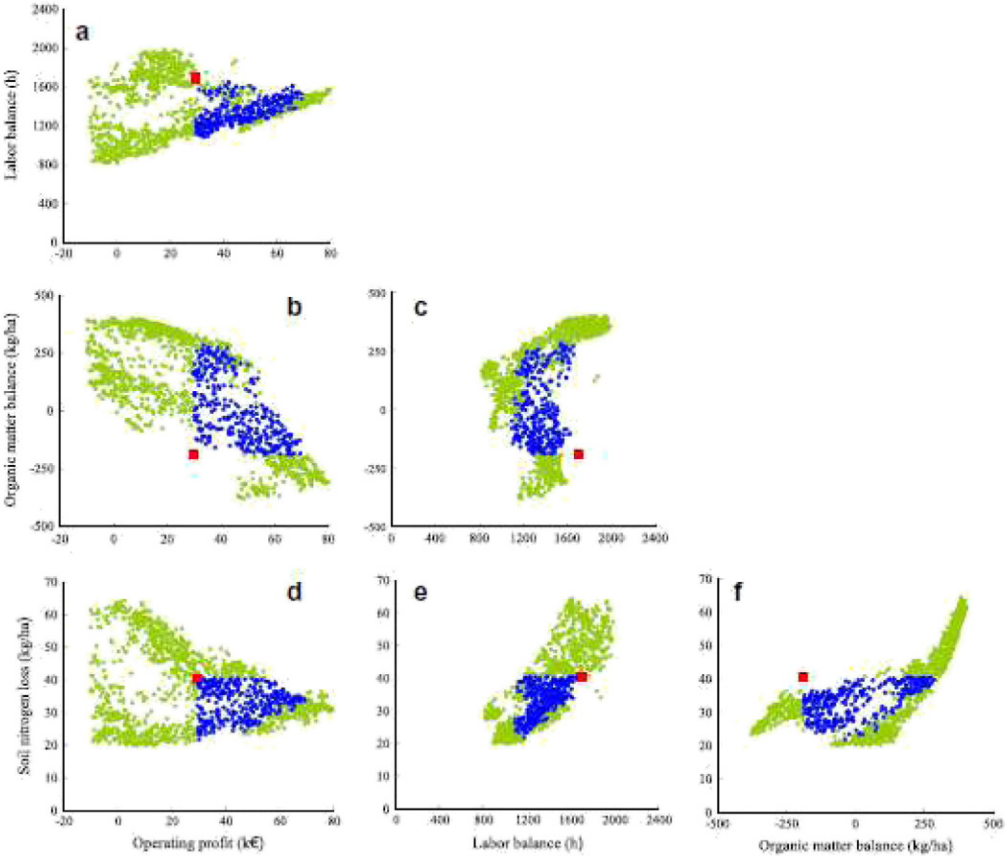
Box 1
Trade-off analysis at the farm scale.

FarmDESIGN, a bio-economic model, uses a multi-objective optimization algorithm to identify an optimal arrangement of elements on a farm (Groot et al., 2012a, 2012b). In this application, Groot et al. use data from a farm in Oostkapelle, Netherlands, to generate Pareto-optimal alternative farm designs based on four objectives; maximize operating profit, minimize labor balance, maximize organic matter balance, and minimize soil nitrogen losses. The initial farm endowment is used as the baseline, and outcomes that outperform it are mapped along a Pareto frontier (for description of Pareto-optimal solutions see Section 4.1 Optimization). The red square indicates the original farm configuration, the green dots are configurations that perform equal to or better than any other configuration for one or more objectives, and the blue dots are solutions that outperform the original endowment in all objectives.



Source: Groot et al. (2012a, 2012b)

costs of data collection, however, can be prohibitively high, especially for large-scale, multiple-indicator assessments (Carletto et al., 2015a). Another approach is to compile secondary data from the literature or data-repositories for the domains of interest. A major challenge is that the data from the different sources are rarely coincident spatially or temporally for a specific site. For example, one project may have an agronomic focus and collect crop yield and field management data at the end of season, another may be ecosystem-focused collecting data on soils and biodiversity mid-season, while a third socio-economic focused project may implement a household survey that collects data on household demographics, income and nutrition for a subset of the households or household members of special interest – making robust trade-off analysis using secondary data a challenge. Although recent studies are moving toward more comprehensive assessments collecting data from all domains and many indicators (Parish et al., 2016; Scholes et al., 2013; Díaz et al., 2015), there are still few holistic datasets that can be used to link the indicators across the multiple domains of sustainability (Sachs et al., 2010: Barrett et al., 2002). This need is particularly pressing given the wide array of SDG targets and the many links between them (Le Blanc, 2015).

Where primary or secondary data is unavailable, scientists have relied on expert elicitation, proxies, and models to fill data and indicator gaps (Antle, 2011; Claessens et al., 2012). Proxy indicators, such as estimates of the duration of green leaf area from remote sensing imagery to estimate carbon fluxes, provide an approximation. However, unless validated in each new situation, inaccuracies and biases may be incorporated as the proxy is scaled up or applied to a new location (Riley, 2001; Bockstaller et al., 2009). Likewise there can be increased uncertainty and loss of critical information arising from spatially interpolating or extrapolating data (e.g. point counts of birds to regional population estimates) to try and match the scale and resolution of other datasets (Turner et al., 2001).

Modeling approaches for estimating indicator values fall into the following categories: empirical, and process-based biophysical and economic models (Crissman et al., 1998; Antle and Capalbo, 2001; Tittonell, 2013). Empirical approaches rely on using observed relationships from a sample of in-situ measurements to describe expected changes in the system (Adams et al., 2013). However, when taking direct measurements is not feasible or costly, process-based biophysical or economic models can be used. Process-based models, which rely on

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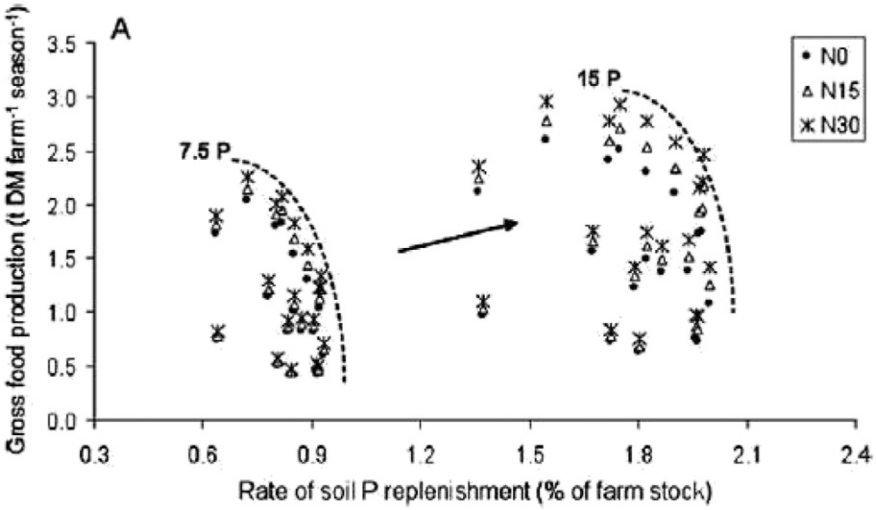
Box 2
Using multiple models for trade-off analysis at the farm scale.

The Nutrient Use in Animal and Cropping Systems - Efficiencies and Scales (NUANCES) framework is used to analyze processes that occur at the farm level and simulates short and long-term trade-offs around soil fertility (Giller et al., 2011). The trade-offs can range from labor use versus soil fertility to agricultural income and soil nutrient loss. The framework is a set of linked sub-system models or modules that include FIELD module that links the crop and soil models, LIVSIM that simulates animal production of meat, milk, manure etc., and HEAPSIM model that examines nutrient dynamics through manure and organic residue management. The farmer typologies based on resource endowment are simulated using Farm-scale Resource Management SIMulator (FARMSIM).
NUANCES has been used to analyze the implications of different resource allocation decisions at the farmer level and assess trade-offs. For example in a study in Western Kenya using survey data on labor availability and nutrient recycling at the farm level, repeated 10 year explorations concluded that small farms could achieve a substantial increase in total food production if they used at least 15 kg of phosphorus and 30 kg of nitrogen per farm per season (Tittonell et al., 2009; Giller et al., 2011)



Simulation results from the 10-year scenario of N and P fertilizer use: Gross food production plotted against the rate of farm-scale soil P replenishment with mineral fertilizer when 7.5 and 15 kg P per season are used in a case study farm, without or with the application of N at 15 and 30 kg farm per season. Dashed lines delineate P-limitation for farm productivity (Tittonell et al., 2009 in Giller et al., 2011)

empirical or theoretical relationships, can be used to simulate ecological, biophysical and socio-economic processes from which indicator values can be derived to describe a system's behavior. Economic process-based models are based on fundamental concepts such as supply and demand and utility maximization, which are then applied to a particular case to generate indicator values specific to it. Due to the complexity and multi-faceted nature of agricultural systems, analyzing trade-offs associated with different management practices tends to require models that combine a number of approaches and use output from other models as inputs to others. An example of such integrated approaches are “bio-economic models” that combine elements of both process-based biophysical models and economic behavioral models (Janssen and van Ittersum, 2007; Havlík et al., 2014).

Many models span disciplines and scales to generate indicator values (see Table 2 for some examples of the most commonly used ones). At the field scale, biophysical process-based models that simulate crop or livestock yields like Decision Support System Agrotechnology Transfer (DSSAT) (Jones et al., 2003), Agricultural Production Systems sIMulator (APSIM) (Keating et al., 2003), Environmental Policy Integrated Climate (EPIC) (Williams and Singh, 1995) and RUMINANT (Herrero et al., 2013), tend to dominate. They have more recently been expanded to estimate other field-level environmental indicators, such as soil health, greenhouse gas emissions, and erosion. At the farm scale, human well-being indicators such as agricultural income and poverty can be estimated from economic models along with the agricultural production and environmental indicators accumulated from the field scale. At the regional scale, process-based models often predominate because of their ability to simulate biophysical processes across large areas: for example, the Soil Water Assessment Tool (SWAT) (Arnold et al., 1998) simulates water quantity, quality and sedimentation in agricultural landscapes that result from different land use and management practices; the Integrated Valuation of Ecosystems Services and Trade-offs Tool (InVEST) is a suite of models that can estimate carbon sequestration, pollination services, timber production, scenic value, and other ecosystem services in mixed-use landscapes (Tallis and Polasky, 2009a, 2009b). Economic models can be used at the regional level to simulate the adoption of particular technologies by farmers and its heterogeneous impacts on natural resources and human well-being (e.g. the Trade-off Analysis Multi-Dimensional, or TOA-MD, model), or at the global scale to account for the interconnectedness of regions through trade (e.g. Global Biosphere Management Model – GLOBIOM).

As demand increases for trade-off analysis to address an ever-greater number of sustainability dimensions, users and modelers have responded by coupling existing models in order to generate a wider range of indicator values. For example, many farm, regional, and global models (e.g. FarmDESIGN, FarmIMAGES, GLOBIOM – Groot et al., 2012a, 2012b; Dogliotti et al., 2005; Valin et al., 2013a, 2013b) rely on inputs of crop yields from field-scale models to estimate income, nutrition or food security outcomes. Crop models like DSSAT have evolved and been linked to biogeochemical models such as CENTURY to integrate soil carbon and nitrogen (Parton, 1996) and DayCENT to estimate greenhouse gas emissions (Parton et al., 1998).

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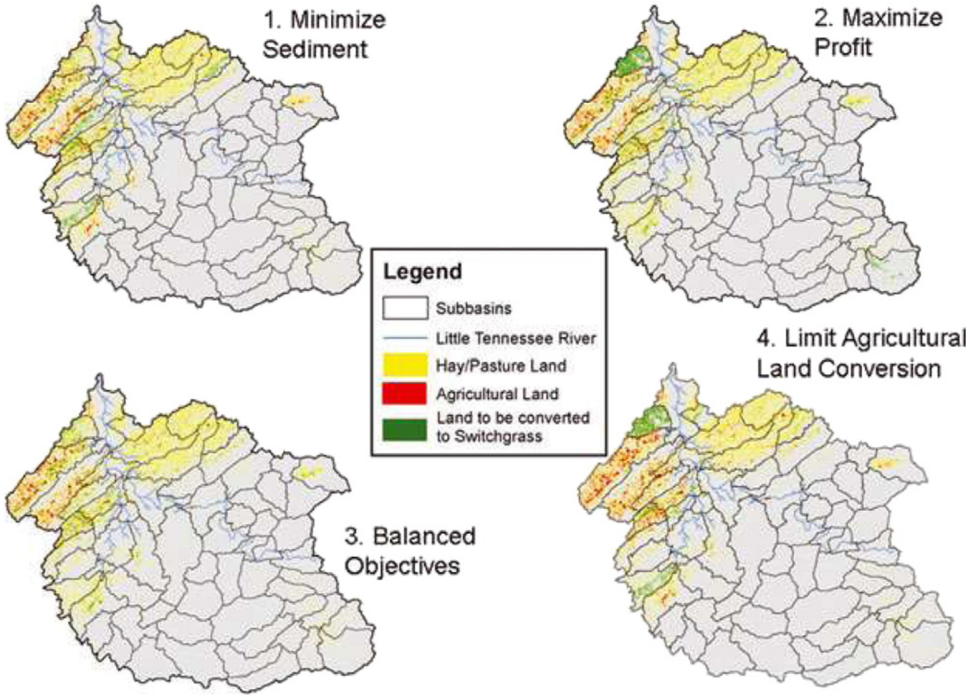
Box 3
Trade-off analysis at the regional scale.

The Biomass Location for Optimal Sustainability Model (BLOSM) is a bio-economic model that explores potential configurations for perennial bioenergy crops across a watershed to simultaneously meet agreed upon production goals while considering environmental and economic objectives. Parish et al. (2012) used BLOSM to assess trade-offs among four sustainability objectives (three water quality indicators and profit) for a targeted increase in production of biomass from perennial switchgrass planted on pasturelands and croplands in the Lower Little Tennessee Watershed. BLOSM used economic results from the county-based Policy Analysis System (POLYSYS) model in conjunction with sub-basin crop yields derived on an empirical grid of yield potential to (1) maximize farmer profits across the watershed, and (2) simulate the effects on water quality and quantity as estimated by the Soil and Water Assessment Tool (SWAT). BLOSM identified where the crop could be sown to achieve yield targets while maximizing the sustainability objectives both individually and collectively. Outputs from the model demonstrate that achieving a given sustainability objective or set of objectives depends on where the crop is planted and what it replaces (see figure below). Examination of potential changes in water quantity from switchgrass plantings across the 64 sub-basins of the Lower Little Tennessee Watershed showed that a combined economic and environmental optimization approach can achieve multiple objectives simultaneously when a small proportion (1.3%) of the watershed is planted with perennial switchgrass (Parish et al., 2012). BLOSM could be adapted to estimate progress toward other aspects of sustainability.



Projected agricultural land-use configurations for the Lower Little Tennessee watershed under four switchgrass planting scenarios run with BLOSM was applied to the Lower Little Tennessee watershed to look at the following objectives: (a) minimizing sediment concentrations; (b) maximizing overall economic profit; (c) maximizing three water-quality objectives and economic profit to the extent possible using a 'balanced' weighting approach; and (d) using the 'balanced' approach with the additional constraint of limiting agricultural land conversion to 25% of the total land area. Adapted from Parish et al. (2012)

Nevertheless, many models still do not include key process representations and programming features that are critical to linking across scales and other models. In order to achieve this linkage, models and platforms need to 1) be developed in programing languages that can be integrated across systems; 2) enable easy 'plug-in' of new components that does not alter the operation of the entire system, 3) facilitate code development and sharing, and collaborations among research groups; and 4) enable model inter-comparisons (Jones et al., 2001; Adam et al., 2016; Antle et al., 2015). These aspects would not only generate information on the complex interactions within agricultural systems and how they change under different management strategies but would provide a structured manner to link and integrate knowledge across disciplinary boundaries in order to address multiple facets of sustainability.

Table 2 shows obvious gaps in the indicator values generated by models. In particular, human well-being indicators such as nutrition, gender equity, and empowerment are poorly represented. Even where these indicators are simulated, they are often oversimplified. For example, though nutrition is listed as an output of several models, it is usually generated from an algorithm converting food produced into calories or nutrients consumed – an assumption that may or may not be valid in evaluating actual food intake and nutrition (Carletto et al., 2015b).

4. Assessing trade-offs

Once indicator values have been estimated, the trade-offs among them can be assessed. Evaluating trade-offs generally involves the comparison of indicators and the changes in indicator values under different

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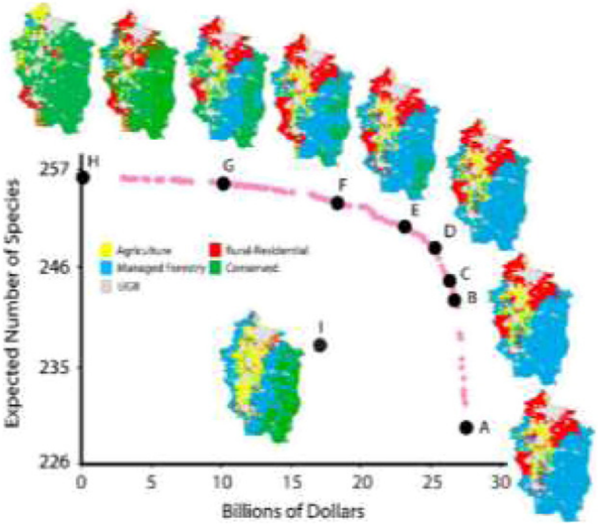
Box 4
Mixing and matching tools for trade-off analysis.

Polasky et al. (2008) integrate both spatially explicit biological and economic models and apply an optimization approach to analyze the consequences of alternative spatial land-use configurations on both biodiversity conservation and economic objectives in the Willamette Basin in Oregon, USA. To do this, they develop a species-specific biological model that evaluates how well a set of native species can be sustained on a landscape given a spatially explicit pattern of land use and species habitat requirement, resulting in a "biological score" for each potential landscape configuration. The economic value of a discrete landscape configuration is estimated by a set of models that predict the likely economic returns for each land parcel under nine different land uses: including agriculture (pasture, row-crop, orchard/vineyard, forestry and rural residential use).

Combining results from the biological and economic models, they use a heuristic optimization approach to search for efficient land-use patterns; the result is a set of Pareto efficiency solutions, which maximize the biological score and economic returns. Using this combined approach the analysis found limited trade-offs between biodiversity conservation and economic returns when proper attention is given to spatial management. An optimal land-use pattern was found that could sustain an expected value of 248 species (97% of the highest biological score found for the landscape) and $25.4 billion in economic returns (92% of the maximum economic score) from the landscape. In contrast, an estimate of the 1990 land-use pattern sustains an expected value of 238 species and generates $17.1 billion in economic returns, significantly lower values on both dimensions than what is feasible. This approach could be extended to other objectives including ecosystem services provision from a given landscape (e.g. carbon sequestration, erosion, pollination, water yield) by integrating outputs from process-based models such as SWAT or those in InVEST.



Land-use patterns associated with specific points along the efficiency frontier and the current landscape. Each land-use pattern shown outside of the efficiency frontier corresponds to a lettered point on the frontier. The current land-use pattern is also shown. Compared to the current landscape, points on the efficiency frontier have less agriculture and more rural- residential use. There is a shift from predominantly managed forest toward conservation land as the biological objective is emphasized more relative to the economic objective.
Source: Polasky et al., 2008.

scenarios (Fisher et al., 2011; Villa et al., 2014). The models presented in Table 2 could, in principle, be used for trade-off analysis, as they are able to provide values for more than one indicator. However, only a few of the models have built-in platforms to evaluate or visualize multiple indicator outputs for trade-offs assessments (see Boxes 1, 2, 3). Therefore additional techniques are necessary and often include the use of optimization approaches and algorithms for scenario comparison of indicator values through tables and visualizations (e.g. see Boxes 4).

4.1. Optimization

Optimization approaches are widely used in trade-off analysis, particularly where land-use allocation is a critical part of agricultural systems (Tittonell, 2013; Klapwijk et al., 2014). Multi-objective optimization in particular could be a valuable technique for SDG implementation in the agricultural sector by helping decision-makers identify options that maximize the likelihood of simultaneously achieving multiple SDGs (for example, see Box 3). A range of techniques are available for optimization, from algorithms of a finite number of steps, to iterative methods that converge to a solution, and heuristics that provide more approximate solutions (Loucks et al., 2005). These techniques often require aggregating the indicator values and objectives of interest into a single function via a process of weighting and normalization (Groot et al., 2011). Criteria for aggregation function selection have only recently been assessed (Pollesch and Dale, 2015). Weighting can introduce additional complexity and bias and can increase the opaqueness of trade-off analysis by embedding into the process the implicit preferences of a particular set of stakeholders conducting the analysis – all factors that reduce the potential utility of this work for decision-makers. By contrast, Pareto-optimization does not require such a priori weighting. Pareto-optimal set solutions, solutions where any one indicator cannot be improved further without compromising performance of other indicators, are a way to identify a set of mathematically equivalent solutions from a large number of options (Box 1 and as illustrated

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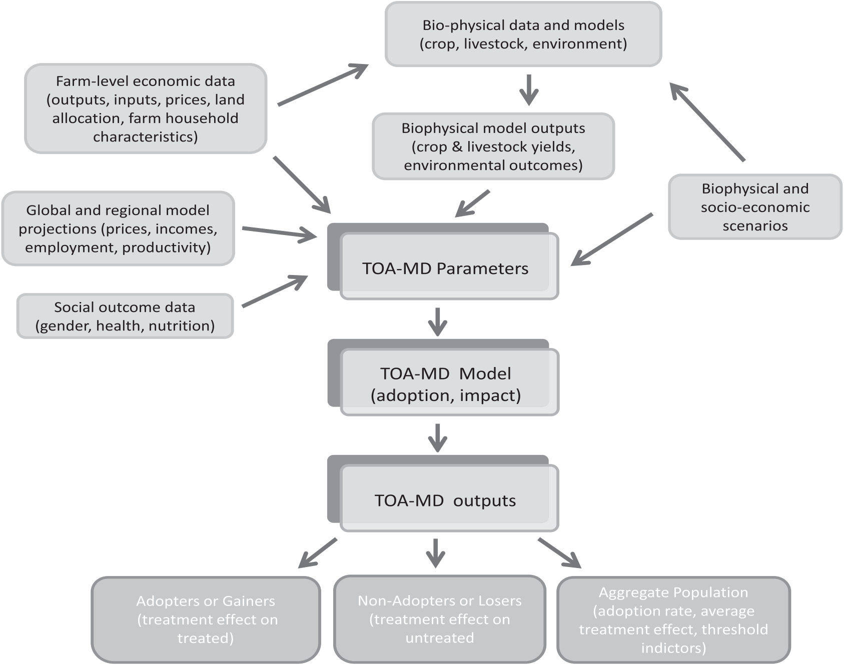
Box 5
Parsimonious trade-off analysis model.

The Trade-off Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) is an economic model that is based on a statistical framework of econometric policy evaluation. It is distinct from other farming system models because it is based on a parsimonious statistical representation of a heterogeneous population of farm households, rather than being a highly detailed and parameter-intensive model of one or a few representative farms. TOA-MD is a generic whole farm household framework that can integrate economic data and behavioral models with data from bio-physical farming system models, environmental process models, or field observations from randomized trials or surveys. TOA-MD can be used for several types of analysis: to estimate an adoption rate and impacts of a new technology (Antle, 2011; Homann-Kee Tui et al., 2014); to simulate the supply of ecosystem services (Immerzeel et al., 2008; Antle et al., 2010); and to assess vulnerability to climate change and other environmental changes, and benefits of adaptive responses to those changes (Claessens et al., 2012; Rosenzweig and Hillel, 2015). Impacts are analyzed as the "treatment effects" for those who gain from a change (adopters), those who do not gain (non-adopters) and the full population. TOA-MD is being used in the Agricultural Model Inter-comparison and Improvement project's (AgMIP) regional integrated assessment methodology that combines outputs from global economic models, downscaled climate data, and global and regional socio-economic scenarios with regionally parameterized crop and livestock models, to assess climate impacts and adaptations (Antle et al., 2015).



in Lautenbach et al., 2013). This is frequently done using evolutionary algorithms, which, through iterating a cycle of small modifications and then discarding those which do not lead to improvements, ultimately identify a suite of management options that are Pareto-optimal, i.e. that do not perform worse than any other solution for all the indicators (Groot et al., 2010). From this solution set, a Pareto-efficiency frontier can be drawn by establishing the envelop which includes the pairwise combination of all indicators for all scenarios (Box 4, also Tittonell et al., 2007). Such Pareto-efficiency frontier can then be overlain with sets of utility isoclines that represent the preferences of different stakeholders for particular pairwise combinations of indicators (Cavender-Bares et al., 2015).

4.2. Scenarios

Scenarios describe sets of plausible and internally consistent possible futures that may consist of a discrete set of agriculture and land-management options (Fisher et al., 2011; Valin et al., 2013a, 2013b), or sets of a priori defined shifts in key drivers such as agricultural commodity prices (Valdivia et al., 2012) or climate forcings (Parry et al., 2004; Lin et al., 2007; Havlík et al., 2014) identified by scientists and other stakeholders at the outset of the process. Direct comparison is often made between modeled indicator values based on a current baseline or business-as-usual scenario, and values from one or more alternative future scenarios. Ideally scenarios are developed in collaboration with relevant stakeholders to ensure that they are realistic and represent a number of shared or contested visions of future land management and intensification (Vervoort et al., 2014). The process of scenario development is interdisciplinary and involves: 1) developing narratives of present or future changes around identified drivers of change and plausible intervention pathways (defined collaboratively with stakeholders); and 2) translating these narratives into quantitative data to parameterize models (Valdivia et al., 2015). For example, this process is used to generate data in the TOA-MD model for a counterfactual farming system (Antle et al., 2015).

At the regional scale and larger, most models require spatially explicit LULC maps as a key component of the scenario. In addition to hand-made maps produced through stakeholder consultation, there are a number of modeling approaches that can be used to generate new LULC maps to represent scenarios. Many well-known models (CLUE, DINAMICA, Land use change modeler) are dynamic, spatially explicit and use an inductive pattern approach, whereby the new LULC is modeled empirically using past LULC or land use/cover spatial distribution. Other models, such as GLOBIOM, project future LULC as part of the

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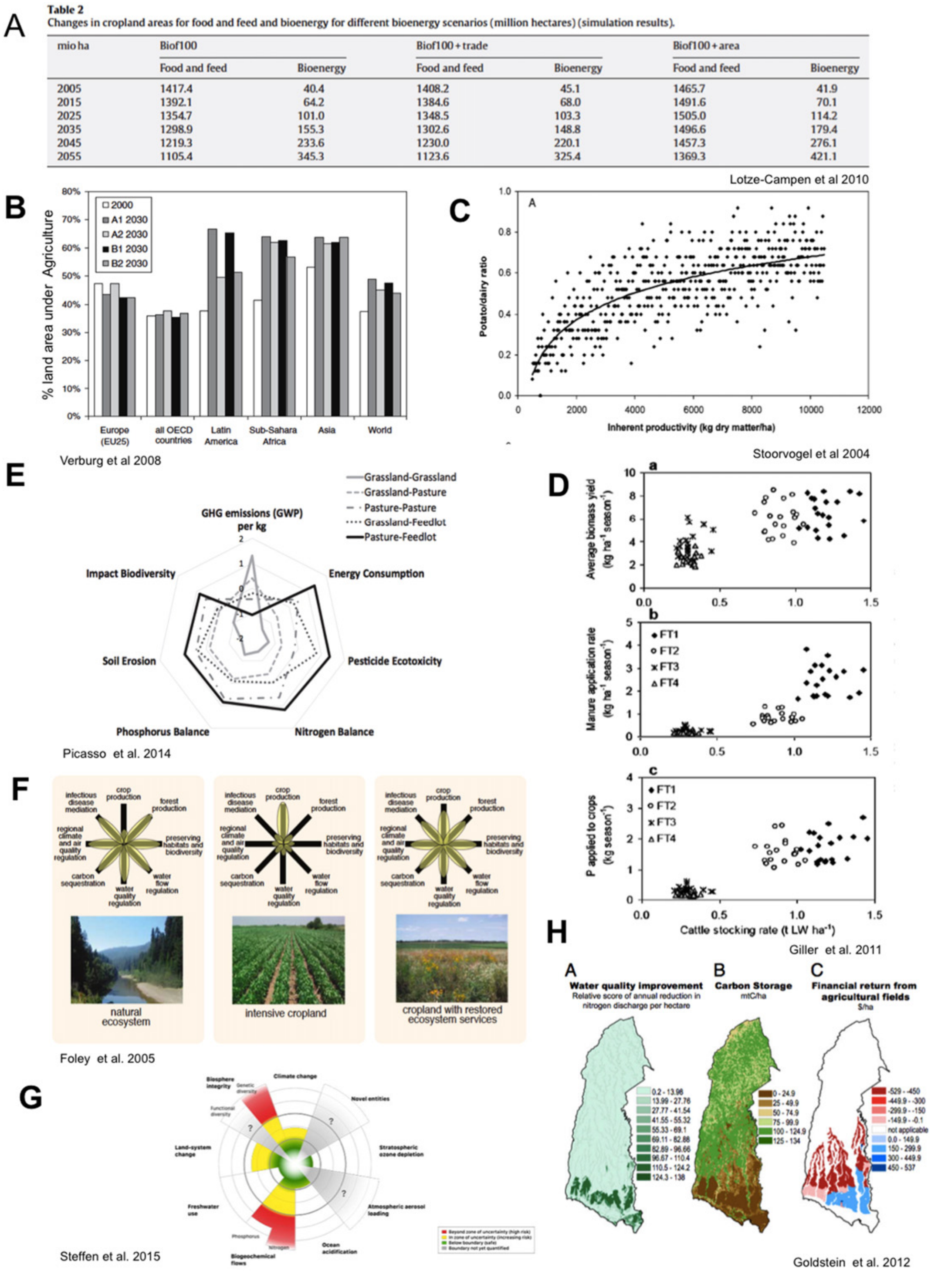

Table 2
Changes in cropland areas for food and feed and bioenergy for different bioenergy scenarios (million hectares) (simulation results).

mio ha	Biof100		Biof100 + trade		Biof100 + area	
	Food and feed	Bioenergy	Food and feed	Bioenergy	Food and feed	Bioenergy
2005	1417.4	40.4	1408.2	45.1	1465.7	41.9
2015	1392.1	64.2	1384.6	68.0	1491.6	70.1
2025	1354.7	101.0	1348.5	103.3	1505.0	114.2
2035	1298.9	155.3	1302.6	148.8	1496.6	179.4
2045	1219.3	233.6	1230.0	220.1	1457.3	276.1
2055	1105.4	345.3	1123.6	325.4	1369.3	421.1

Fig. 1. Various visualization approaches to illustrate trade-offs among indicators of alternative agricultural scenarios: tabular matrices (A), bar charts (B), scatterplots (C), matrix of scatterplots (D), spider diagrams (E), radial diagrams (F), petal diagrams (G), spatially explicit maps (H).

market equilibrium solution, based on the relative profitability of alternative land uses.

Scenario analysis and optimization are not mutually exclusive. They can be combined to evaluate trade-offs. For example, FarmIMAGES can be used to combine the production activities at the field with the farm scale to produce optimal combinations of labor, land, mechanization, and irrigation technology while taking into account the farm resource endowments (Dogliotti et al., 2005). Once the optimal output is obtained, FarmIMAGES incorporates scenario analysis across competing objectives. An income-oriented scenario can be implemented in which family income is maximized 'without' and then 'with' environmental restrictions. Scenarios can also be set that focus on farm size, labor endowment as man-hours per farm per year, percentage of irrigation area, and type and level of mechanization employed on the farm (Dogliotti et al., 2006). These scenario outputs are visually presented to show the trade-offs of interest.

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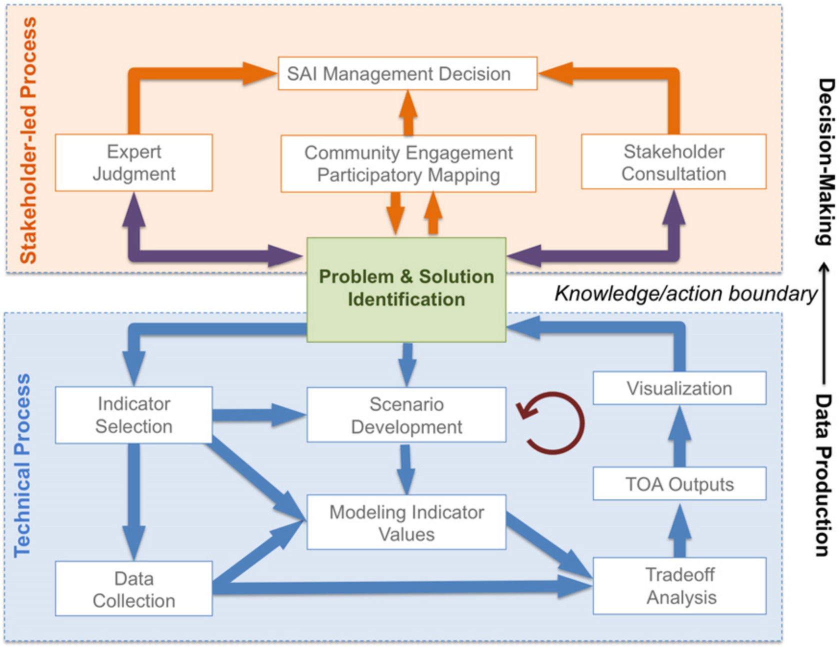
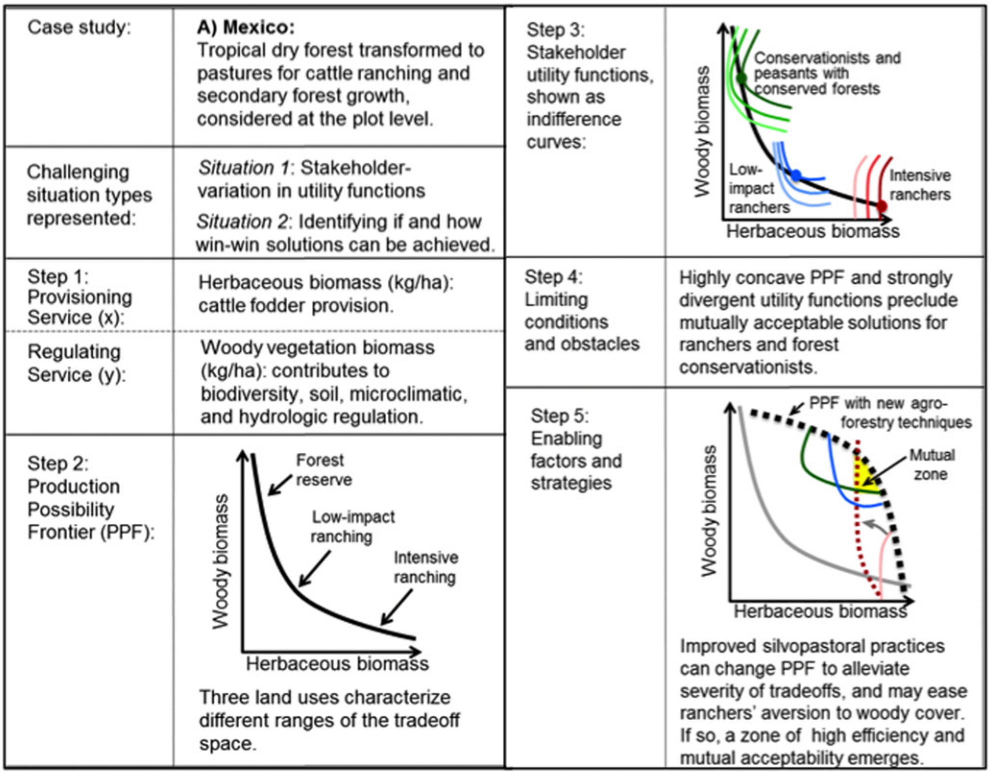


Fig. 2. Conceptual framework for stakeholder engagement and trade-off analysis (TOA). The top box focuses on stakeholder-led processes whereby the decision context/goals for sustainable agricultural intensification (SAI) and potential solution-sets are identified through a stakeholder engagement with experts, local communities, institutions and scientists. Outputs of this process are then fed into the lower box translating stakeholder preferences into scenarios, identifying appropriate indicators, data and models to carry out the trade-off analysis, which is then transformed into contextually-relevant visualizations and conveyed back to stakeholders for review and adaptation. This can be an iterative process, as signified by the curved arrow, with multiple rounds of scenario co-production, analysis and review via stakeholder consultation until realistic scenarios and trade-off results are found.

4.3. Linking trade-off analysis to market processes

A major conceptual and analytical challenge is to evaluate how trade-offs at the farm or (sub-national) regional levels will affect or be affected by local or national economic changes. Changes in prices and incomes in particular, can have important effects on both demand and supply of agricultural commodities and on the economic well-being of farm households as well as other members of society. Large-scale, aggregate economic models at the national or global scale can simulate how major changes, such as technology, policy or climate, can impact



Case study:	**A) Mexico:** Tropical dry forest transformed to pastures for cattle ranching and secondary forest growth, considered at the plot level.
Challenging situation types represented:	*Situation 1*: Stakeholder-variation in utility functions *Situation 2*: Identifying if and how win-win solutions can be achieved.
Step 1: Provisioning Service (x):	Herbaceous biomass (kg/ha): cattle fodder provision.
Regulating Service (y):	Woody vegetation biomass (kg/ha): contributes to biodiversity, soil, microclimatic, and hydrologic regulation.
Step 2: Production Possibility Frontier (PPF):	Three land uses characterize different ranges of the tradeoff space.
Step 3: Stakeholder utility functions, shown as indifference curves:	
Step 4: Limiting conditions and obstacles	Highly concave PPF and strongly divergent utility functions preclude mutually acceptable solutions for ranchers and forest conservationists.
Step 5: Enabling factors and strategies	Improved silvopastoral practices can change PPF to alleviate severity of tradeoffs, and may ease ranchers' aversion to woody cover. If so, a zone of high efficiency and mutual acceptability emerges.

Fig. 3. Graphical use of Pareto-efficiency curves under alternative scenarios in combination with utility curves to elicit stakeholder preferences within a participatory setting to move toward consensus on more sustainable agricultural practices (adapted from King et al., 2015).

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prices and incomes. However, these outputs are also aggregated to provide meaningful assessments of distributional impacts, e.g., impacts on poverty rates, food security or climate vulnerability of poor households. Research shows that integrating these economic impacts into trade-off analysis can significantly influence the results, as well as stakeholder decision-making. Thus, establishing linkages between disaggregated analyses, such as household or regional models that do not represent markets, and more aggregate market analyses is essential. In one of the first studies to make this linkage, Valdivia et al. (2012) show how a regional farming system model can be coupled with a market equilibrium model to jointly simulate the impacts of market changes, such as a shift in supply and reduced maize prices caused by development policies, and trade-offs between poverty and system sustainability (the TOA-MD model, see Box 5).

A number of advances are needed in order to facilitate such cross-scale analyses. First, there are very few systematic comparisons of global economic models (see Nelson et al., 2014), so it is difficult for researchers at the national or sub-national level to know which model to use. This challenge is compounded by the fact that recent global economic model inter-comparisons show a high level of disagreement between models. Second, global model outputs are not routinely made available for other modelers to use. Third, the global economic modeling community, in contrast to the global climate modeling community, has not yet established a set of standard "reference scenarios" spanning a meaningful range of plausible futures that regional research teams could use and link to their analyses. The AgMIP initiative on "coordinated global and regional assessment" aims to address these challenges (Rosenzweig et al., 2016).

4.4. Visualization

Presenting the information relevant to trade-off analysis in an easy-to-interpret format is critical for effective communication of results. Well-designed visualizations of multiple indicator values can be a powerful and intuitive means of conveying large amounts of complex data, facilitating deeper understanding of the interactions among indicators to support better decision-making. Visualizations can be effective for highlighting similarities and divergences in indicator values and temporal or spatial patterns among scenarios that are not as easily perceived when reviewing the raw data (Miettinen, 2014). However, most models that produce indicator values do not automatically generate a visual representation, creating the need for researchers to select an appropriate visualization technique. The choice of visualization approach depends on a number of factors including the type of trade-off scenarios being evaluated, the number of scenarios considered, the number of indicators in question, and the intended audience.

Estimates of indicator values can be presented as absolute values, relative values with reference to a baseline or desired value, or weighted values based on stakeholder preferences. Often indicator values are rescaled to allow comparison across social, economic and environmental dimensions. Depending on the number of indicators considered, different visualization techniques can be used to compare across indicators.

In Fig. 1 we assemble a selection of visualization approaches that have been used to illustrate trade-offs in agriculture. One of the most visually appealing and intuitive approaches is the petal diagram (Fig. 1F), which adjusts the length of each petal to reflect normalized indicator values. Foley et al. (2005) provide one of the most widely cited examples of this technique, comparing the provision of seven ecosystem services across natural ecosystems, intensive cropland and diversified farming. Another highly cited example is from Steffen et al. 2015 – using a variant of the petal diagram, a radial plot, to show the impact of current anthropogenic activities on nine planetary boundaries, from climate change to biodiversity loss (Fig. 1G). It is also possible to enhance this technique by overlaying indicator values from multiple scenarios onto the same axes, creating a spider diagram (Picasso et al., 2014; Fig. 1E). This technique can be useful for demonstrating the strengths and weakness of one scenario versus another. While these approaches have a strong intuitive appeal, they have been criticized for their low-data content (e.g. lack of error estimates) and the inherent difficulty in interpreting normalized differences in indicator values (Miettinen, 2014).

Other approaches incorporate raw data into a visualization, which can provide stakeholders with more accurate information on the reliability of the results. Classic examples include bar charts or scatterplots where each scenario can be denoted with unique colour or symbol identifiers (Fig. 1B, C and D). While scatterplots are limited to trade-offs between two indicators and thus may only be useful when there are just a few indicators of interest, bar charts or tables (Fig. 1A) can display multiple indicator outputs across all scenarios and can easily incorporate error estimates. For example, Verburg et al. (2008) (Fig. 1B) display the outcomes of four global economic scenarios on demand for agricultural land, with the largest demand occurring in Latin America, sub-Saharan Africa and Asia in a scenario representing an unregulated global economy. A drawback of these more data-heavy approaches is that it can be challenging for stakeholders to distill key outcomes or important trends from large amounts of information (Miettinen, 2014). Consequently, these graphics are perhaps best suited for technical audiences that are already familiar with these types of visualizations.

Maps displaying indicator outputs have been another visualization approach that is increasing in use with the widespread adoption of Geographic Information Systems (GIS) (Groot et al., 2007; Bekele et al., 2013). Beyond portraying the initial and expected land-use pattern of a set of scenarios (e.g. Verburg et al., 2008), mapping indicator values can be extremely useful for understanding spatial dynamics of tradeoffs and identifying "hotspots" or "coldspots" across a region (Goldstein et al., 2012; Fig. 1H). They can also be used to show changes from a common baseline. For example, Goldstein et al. (2012) use a matrix of maps to display the relative change in carbon storage, water quality and financial returns from agriculture between a business-as-usual and six alternative land-use scenarios, visualizing where on these landscape changes occur. One challenge with maps, however, is the difficulty to express more than one indicator or trade-off per map. This can lead to an unwieldy number of maps to evaluate trade-offs within a single scenario and across multiple scenarios. Thus, when communicating trade-off results using maps with decision-makers, care should be taken to select a small number of maps which convey the key information necessary, complemented with other visualization techniques allowing for easier cross-indicator or cross-scenario assessments.

Finally, estimates of uncertainty are crucial when assessing trade-offs or selecting between alternatives. They provide a measure of confidence in the results. Policy makers are often risk-averse and prefer options that demonstrate low risk (high certainty) despite only marginal gains, over high gain options with low certainty. While estimates of standard deviations, confidence intervals or standard errors are more easily included in tabular or bar charts, they are often lacking from star-plots, petal diagrams, trade-off frontiers or maps due to the difficulty of portraying them in the diagrams. Researchers should continue to work with stakeholders to find creative means to communicate trade-offs and uncertainty in ways that are simple yet powerfully convey the key messages and allow decision-makers to draw reliable conclusions.

5. Using trade-off analysis to improve decision-making

Despite a significant number of studies evaluating agricultural trade-offs, the routine application of these tools to actual decision-making has been limited (though see Clark et al., 2011 for several notable exceptions). As McCown (2002) points out, scientists frequently assume that decision-makers will automatically apply whatever result is produced by science because of the formal logic and reduction of uncertainty that models can provide to the otherwise extremely complex nature of agricultural systems. The low rate of uptake of trade-off analysis results is due to several factors: 1) lack of participation of the appropriate stakeholders in the research design and process, 2) the often generic recommendations that bypass traditional decision-making processes, and 3) lack of a clear end-user or stakeholder groups for the outputs of trade-off analysis. In short, tools frequently fail to bridge the knowledge/action boundary – a mismatch between science producer and user goals – frequently referred to as a lack of tool "contextualization" (Sterk et al., 2011).

Several terms have been used to characterize what is missing from the relationship between the producer of information and its intended user: 'mutual understanding' (McCown, 2002), 'receptivity' (McIntosh et al., 2007), or 'systems integration' (Kristjanson et al., 2009). These problems point to a lack of recognition and understanding of the views of stakeholders outside the academic community, as well as a lack of interest or know-how from scientists in building partnerships with relevant stakeholders. The poor engagement of stakeholders often leads to tools that prescribe action instead of facilitating learning. This dynamic stems partly from power asymmetries, with scientific knowledge often carrying outsized influence compared to local knowledge (Kristjanson et al., 2009), making it a challenge for multiple legitimate views of reality to be included in the decision-making process (McIntosh et al., 2007).

To address this challenge, some argue that scientists first need to be clear as to what end the knowledge created is being applied: is it simply to advance basic scientific understanding without any obvious application? Or is it for more practical purposes of decision- and negotiation-support? Each application and set of stakeholders has different requirements for knowledge to be influential, all involving a combination of credibility, saliency and legitimacy (e.g. how and where were the data collected, who collected it, who was consulted, whose voices are at the table, and how are decisions being made, Clark et al., 2011). Tools must also integrate multiple forms of knowledge to be effective – tailoring the recommendations derived from the generalized knowledge of research to the context-specific knowledge of practice (Clark et al., 2011).

An important challenge of agricultural trade-off analysis is selecting and mobilizing a diverse and appropriate range of stakeholders to include in the process (Sterk et al., 2011). Clark et al. (2011) propose several criteria for stakeholder selection, including: whose behavior is the knowledge in question trying to change? Who has an incentive to block any action based on this knowledge? And who is best placed to certify the credibility of the knowledge created by these identified stakeholders? Facilitating this dialogue requires trusted people, organizations and objects (such as maps, reports and policy briefs) that can act as conduits between stakeholders, known as "boundary-spanning" entities or "stepping stones", to support collaboration at the interface of different communities (Kristjanson et al., 2009). Without such trusted entities, it can be challenging for stakeholders from different perspectives to discuss the problem or goals of the process in a genuine manner.

Approaches exist to improve the producer/user relationship and increase the likelihood that model outputs are applied in decision-making (summarized in Fig. 2). As discussed at the beginning of the paper, the first step in trade-off analysis is identification of the problem, the context in which it occurs and goals of the process. It is critical that problems and systems be defined collaboratively with and by stakeholders so that the tools (and ultimately the outputs) produced respond to user needs and are built on a sound and common understanding of the system's dynamics (Kristjanson et al., 2009; Dale et al., 2016). For this process to occur, scientists, and particularly those working at the knowledge/action boundary (e.g. working directly with farmers in the field, or with NGOs on agricultural development tools), need to expand beyond their traditional roles as knowledge creators by applying 'soft skills' of "facilitation, synthesis, stakeholder engagement, monitoring and evaluation, impact assessment – in the use of tools and processes that will lead to faster and broader outcomes and impacts" (Kristjanson et al., 2009). In other words, as much attention needs to be devoted to embedding this work in the relevant social context and mapping models onto pre-existing user knowledge and practices (Sterk et al., 2011), as to selecting indicators and running models. One promising strategy for creating a shared vision around a problem to be addressed is via 'social learning'. Social learning brings together a diverse set of stakeholders to share and co-create knowledge around a common issue by collaborative and iterative priority setting, analysis, and discussion of results – as portrayed in the middle box of Fig. 2 "Problem & Solution Identification". This process allows for the integration of diverse knowledge and value systems at many different levels (Kristjanson et al., 2014).

King et al. (2015) developed a framework that integrates stakeholder preferences within an analysis of trade-offs between ecosystem services. Using this framework, they examine the trade-offs between protecting tropical dry forest areas (which provide woody biomass, biodiversity, soil, climatic and hydrologic regulation) versus transforming them into pastures for cattle ranching (providing herbaceous biomass, which serves as cattle fodder) in Mexico (Fig. 3). Various stakeholder preferences were mapped onto a Pareto-efficiency frontier of woody versus herbaceous biomass in order to identify stakeholders' preferences for parts of the frontier and where overlap existed (i.e. possible consensus on a particular desired state and course of action). Not surprisingly, conservationists preferred an outcome where most of the tropical dry forest area was preserved, while intensive ranchers preferred one where pasture dominated. The realization that no mutually acceptable outcomes existed along the efficiency frontier forced the group to consider alternative management practices, such as improved agroforestry practices, which changed the shape of the efficiency frontier to allow for more woody and herbaceous biomass co-production, thereby creating a set of outcomes acceptable to most stakeholders. This type of study is an excellent example of how producers' knowledge and users' preferences can be aggregated and translated into a compelling visual illustration.

6. Future work

In addition to improving scientist-stakeholder engagement in the research process, a key area of future work is integrating the steps of indicator selection, value estimation and trade-off assessment into a single modeling platform to facilitate trade-off analysis, while maintaining a level of modularity to allow users to select the most appropriate tool at each step. This is primarily a computer programming issue that can be readily overcome with license sharing agreements and data alignment between the various tools.

In addition, integration of models across scales is important in capturing the embedded hierarchical nature of many of the processes that feed into trade-off analysis. As mentioned earlier, ecological and biophysical processes are linked across hierarchically nested scales. Most models in use and reviewed here still focus on, and are built to address, processes at a single scale. Promising new model frameworks or platforms that have made scale an organizing principle include the SEAMLESS-IF (Van Ittersum et al., 2008) and COMPASS (Groot et al., 2012a, b) that aggregate model outputs at lower scales to use as inputs at higher scales – a bottom-up approach. Other models deal with issues of scale via a more top-down approach, by having sub-models that operate at different spatial and temporal resolutions (e.g., Dale et al., 2006; Valin et al., 2014).

In order to bridge scales, additional research is needed to understand how processes are linked across scales and can be accurately represented in or across modeling frameworks, as well as commitment from model developers to facilitate this process. Developers of next generation models should consider using open platform software, with clear documentation and data available, and models tailored to end users. In addition to the continued development of large-scale models powered by super-computers (e.g. Earth System Models) efforts should focus on 'plug and play' approaches to model components where possible (Janssen et al., 2015). Together these approaches will greatly

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increase the flexibility and inter-operability of models, allowing individuals to modify, combine and adopt tools for local contexts. Though developing cross-disciplinary and cross-scale models is a challenging endeavor, their results are frequently much richer and more relevant to stakeholders across a range of disciplines.

Crowdsourcing – the outsourcing of data collection to large groups of stakeholders (often farmers) – has also emerged as a potentially important method for amassing more accurate data (Fritz et al., 2015) and creating stakeholder buy-in for agricultural trade-off analysis. For example, crowdsourcing information from farmers using their mobile phones on the performance and preference of new seed types could provide a trove of data to help accelerate and refine the seed development process, as well as help plant breeders better understand the actual seed diversity needs of farmers – and ultimately what trade-offs are important to them (van Etten, 2011). Scenario building among different stakeholders (Herrero et al., 2014; Vervoort et al., 2014) and education simulation tools that allow for role-playing (García-Barrios et al., 2008; Costanza et al., 2014) are also important for engaging stakeholders and can increase a stakeholder's creativity in finding solutions to the trade-offs that arise in agricultural intensification, positively influencing future behavior. These tools should be further developed and employed to ensure that trade-off analysis best responds to stakeholder needs.

These technical improvements will mean little if there is no open and meaningful dialogue between researchers, decision-makers and stakeholders. Improved exchange between scientists and decision-makers can work toward ensuring that trade-off analysis addresses issues that actually matter for sustainably intensifying local and global agriculture – a critical step in the implementation of the Sustainable Development Goals.

7. Conclusion

Agriculture lies at the heart of sustainable development. It is precisely because of its centrality to many of the newly defined Sustainable Development Goals that the potential for synergies and trade-offs arises. Trade-off analysis provides an important toolkit to better understand and manage the myriad interactions between agronomic, environmental and socioeconomic outcomes associated with the agricultural sector. By tracking these interactions, trade-off analysis enables adaptive management across the range of diverse agricultural systems that make up global agriculture. In this paper, we take a more expansive view than previous work, distilling the trade-off analysis process into four distinct steps, spanning indicator selection and generation, to the communication and eventual uptake of outputs. Each step requires different sets of tools and engages different areas of academic expertise. Key areas of future work require combining these steps into a common platform to improve practicability, and further integrating tools across scales and disciplines. Linked to these steps is the need to continuously improve stakeholder engagement in order to ensure the viability of trade-off analysis as a policy tool in the age of sustainable development. This paper shows a way forward to achieving these goals.

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