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Analysis of trade-offs in agricultural systems: current status and way forward☆

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Trade-off analysis has become an increasingly important approach for evaluating system level outcomes of agricultural production and for prioritizing and targeting management interventions in multifunctional agricultural landscapes. We review the state-of-the-art for trade-off analysis, assessing different techniques by exploring a concrete example of trade-offs around the use of crop residues in smallholder farming systems. The techniques for performing trade-off analyses have developed substantially in recent years aided by mathematical advancement, increased computing power, and emerging insights into systems behaviour. Combining different techniques allows the assessment of aspects of system behaviour via various perspectives, thereby generating complementary knowledge. However, this does not solve the fundamental challenge: trade-off analyses without substantial stakeholder engagement often have limited practical utility for informing practical decision-making. We suggest ways to integrate approaches and improve the potential for societal impact of future trade-off analyses.

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Introduction

Trade-offs, by which we mean exchanges that occur as compromises, are ubiquitous when land is managed with multiple objectives. Trade-offs become particularly acute when resources are constrained and when the stakeholders' goals conflict [1]. In agriculture, trade-offs may arise at all hierarchical levels, from the crop (such as grain versus crop residue), the animal (milk versus meat production), the field (grain production versus nitrate leaching and water quality), the farm (production of one crop versus another), to the landscape and above (agricultural production versus land for nature). Individual farmers face trade-offs between maximizing short-term production and ensuring sustainable long-term production. Within landscapes, trade-offs may arise between individuals' competing uses of land. Thus, trade-offs occur within agricultural systems, between agricultural and broader environmental or socio-cultural objectives, across time and spatial scales, and between actors. Understanding the system dynamics that produce and alter the nature of trade-offs is central to achieving a sustainable and food secure future.

Trade-off analysis has emerged as one approach to assessing farming system dynamics. The number of scientific papers using the term 'trade-off analysis' increased by more than a magnitude from 104 in 1992 to 1644 in 2012. Though the concept of trade-offs and their opposite; synergies, lies at the heart of several current agricultural research for development initiatives [2,3], methods to analyse trade-offs within agro-ecosystems and the wider landscape are only nascent [4]. We review the state-of-the-art for trade-off analyses by focusing on one concrete example that is highly controversial, the trade-offs in the use of crop residues for different purposes in smallholder farming systems. We highlight innovations and constraints for analysing trade-offs, and suggest approaches aimed to increase the utility of this type of research.

Trade-off analysis: the case of crop residues in mixed smallholder farming systems in developing countries

Trade-offs are quantified through the analysis of system-level inputs and outputs such as crop production, household labour use, or environmental impacts such as water use (for a set of examples across different integration levels see Table 1). In this paper we will illustrate the methods used to analyse and quantify trade-offs by elaborating one concrete example, the use of crop residues within mixed smallholder farming systems in developing countries (example no. 5 in Table 1). Smallholder

Table 1

Examples of trade-offs in agricultural systems

Example	Indicators	Nature of trade-off	Alleviation possible?
Ammonium volatilization versus denitrification or nitrate leaching [41]	Ammonia and nitrous oxide emissions and nitrate-N concentration in groundwater	Pollution swapping (air quality versus climate change versus water quality); field production scale	Optimize timing and rate of N application for crop growth, avoid excess mineral N in soil
Farm scale production versus environmental impact [42,43]	Farm level grain yield, farm level greenhouse gas emissions, nitrate-N concentration in groundwater	Agriculture versus the environment; across spatial scales: field to landscape	Agro-ecological intensification, effective application of N fertilizers to increase crop recovery efficiency
Long-term soil fertility improvement through green manure agroforestry species versus immediate food production	Soil fertility (soil C content) after 5 years of green manure treatment versus immediate food production	Immediate food and cash needs versus long-term sustainability of production; across temporal scales	Use of external inputs, to intensify food production on a smaller land area
Croppers versus cattle owners versus wildlife in East Africa [31]	Cropped areas, household income, food insecurity	Limited availability of land; across spatial scales	Income diversification, preservation of wildlife and cattle movement corridors
Allocation of crop residues to fodder for cattle versus mulch for soil and water conservation [5]	Milk production versus crop production	Limited availability of organic resources; farm scale	Input use to increase amounts of crop residue produced
Sale of labour causing delay in own crop management versus use labour for own production	Labour sold versus crop production and household food self-sufficiency	Seasonality resulting in immediate cash or food needs versus household food-self sufficiency; at farm scale	

crop–livestock systems are characterized by the interdependence of crop production and livestock husbandry [5] and form the basis of the livelihood of two-thirds of the population in developing countries [6]. The crop–livestock combination offers farmers a more diverse source of food and income [7,8]. Despite such complementarities, the limited availability of fodder in these systems often results in internal competition for the use of crop residues. They can be used as feed to sustain livestock productivity, as mulch/soil amendment to sustain crop productivity, and fuel and construction material. How farmers use crop residues depends on individual preferences and the biophysical and socio-economic conditions [9,10].

The presence and significance of trade-offs in crop residue use are highly debated and extensively researched [11]. Trade-offs from crop residue use encompass consequences related to different time scales (short versus long term productivity effects), spatial scales and levels (livestock access to crop residues on fields owned different farmers within the community [12]), gender (who collects and sells crop residues and controls the cash income) and environment (effects on soil carbon [13] and pressure on grassland areas [12]).

Methods to analyse and quantify trade-offs

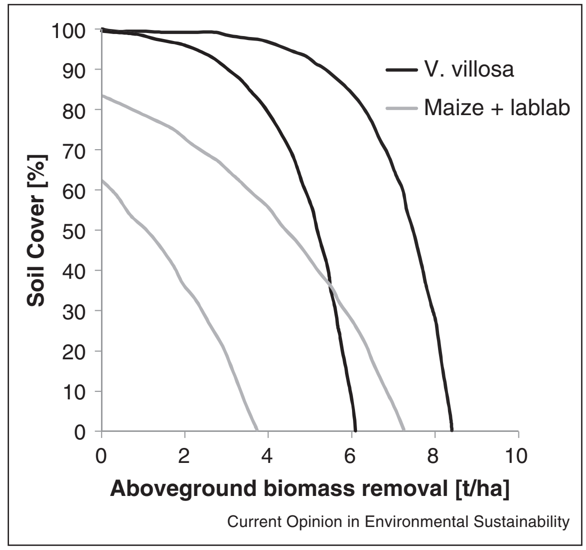
Many methods have been developed to analyse trade-offs. Through the crop residue lens, we assess four widely applied approaches: firstly, participatory methods; secondly, empirical analyses; thirdly, optimization models; and finally, simulation models. These four approaches overlap often and can generate complementary knowledge. Consequently, trade-off analyses will often utilize a mixture of methods simultaneously and/or iteratively.

The concept of *participatory research* originally highlighted the need to include the active involvement of those who are the subject of research and/or for whom the research may lead to outcome changes. More recently, the notion has expanded to acknowledge that change in researchers' assumptions and perceptions may be required to create outcomes that are attractive to farmers [14••]. Participatory approaches, such as fuzzy cognitive mapping [15•], resource flow mapping, games and role-playing are powerful ways to identify actor-relevant objectives and indicators, although the scope of farmer knowledge and perceptions within scientific research can be constraining in some situations, particularly in times of rapid change [16]. Participatory approaches usually generate qualitative data and so are not well suited for quantifying trade-offs. However, they provide critically important information that can be used to inform quantitative tools, for example, through the development of participatory scenarios [3,17,18•] and the identification of key objectives of the stakeholders. In the case of crop residue use it is important to identify the relative importance of livestock versus crop productivity for the farmer, the importance of crop residues for fuel and construction and the possible use of crop residues for sale. The researcher might stress, for example, the important role of crop residues as an element in the conservation agriculture package, but if the farmer assigns more importance to livestock productivity and well-performing livestock as a social symbol, interventions promoting conservation agriculture might fail [11]. Systematically linking development pathways with biophysical and socio-economic processes and characteristics across scales and integration levels is key for the assessment of how different policy options can influence future land use development, food production and the possibilities for sustainable development [18•,19,20], and rapid developments take place to do this in a participatory manner. An example of this is the scenario work performed by the Climate Change, Agriculture, and Food Security Program of the Consultative Group on International Agricultural Research (CCAFS) in East Africa [20,21]. For the region four different development pathways were defined: firstly, 'Sleeping Lions', representing regional fragmentation and reactive governance; secondly, 'Lone Leopards', representing continued fragmentation but proactive governance; thirdly, 'Herd of Zebra', strong regional integration but reactive governance; and finally, 'Industrious Ants', strong regional integration and proactive governance. The likely effects of these scenarios on key indicators were assessed; trade-offs and possibilities for synergies, depending on the scenario investigated, were identified between different indicators (e.g. gross domestic product, crop yields, food security and environmental indicators like forest cover and biodiversity). Such a participatory approach to scenario development makes sure that indicators are captured that stakeholders perceive as essential and thereby strongly increases the relevance of the analyses performed.

Quantitative assessment of trade-offs requires *empirical* or experimental approaches to generate data on the behaviour of the system under different conditions. Trade-off curves can be drawn on the basis of experimental measurements of indicators, such as the removal of plant biomass for fodder and the resulting soil cover, which is a good proxy for control of soil erosion (Figure 1) [22], thereby illustrating the different shapes of a trade-off at field level. Empirical approaches are powerful in the sense that outcomes of various system choices can be explored using the existing variability in system configuration and performance. However, the inference space of the analysis is constrained to the data set collected and is therefore not suitable to predict outcomes outside the ranges of the original data. So, for example, in many smallholder farming systems most crop residues will be fed to the cattle [5]. Therefore, based on existing information, it can be difficult to assess the trade-off curve between crop and livestock productivity, as limited observations will be presented where crop residues are used as soil amendment to varying degrees.

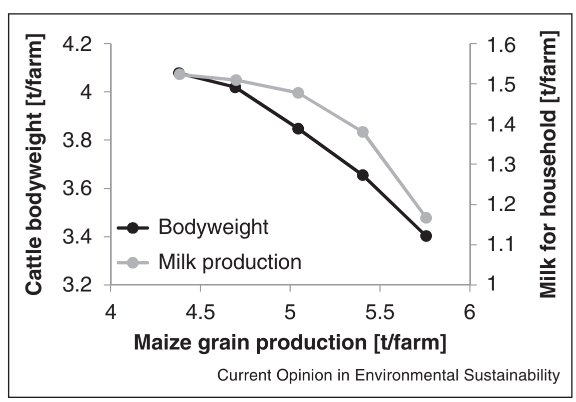
In contrast, *simulation models* can be used to explore options that are not observed in reality. In the example of crop residue use in smallholder farms, simulation models have been used to quantify the shape of the trade-off curve between crop and livestock production when different percentages (varying between 0% and 100%) of the crop residues were retained in the field (Figure 2). These results were subsequently used to quantify the amounts of crop residues that could be used for soil amendment without affecting livestock productivity [23]. Simulation models also allow the dynamic nature of trade-offs to be explored, where outcomes can differ in the short-term or long-term [24]. At community level, multiple agent models set up for a system in central-eastern Zimbabwe have been used to quantify the consequences for crop and livestock productivity if

Figure 1



Relationships between biomass removal and soil cover for two different types of crop residues (Vicia villosa, and maize together with lablab) in Madagascar. Upper and lower range of uncertainty are shown, based on [22].

Figure 2



Trade off in animal or crop productivity with crop productivity against animal live weight per farm and versus milk produced for the household. Data shown are the average values for the 12-year of simulation for a farming system in central-eastern Zimbabwe. Based on [24].

Table 2

Strengths and weaknesses of the different approaches for analysing trade-offs in agricultural systems ('Act' is the actual or current state in the scientific literature, 'Pot' is the potential usefulness of a technique to assess a certain aspect of trade-off analyses)

	Research approach							
	Participatory		Empirical		Simulation		Optimization	
Aspect	Act	Pot	Act	Pot	Act	Pot	Act	Pot
Integration of interdisciplinary content	–	+	–	+	–	+	–	–
Assessment across different time horizons	–	+	–	–	+	+	+	+
Assessment across spatial scales and integration levels	–	+	–	+	+/–	+/–	+/–	+
Takes into account qualitative information	+	+	–	+	–	–	–	–
Appropriate representation of uncertainty	–	+	–	+	–	+	–	+
Identification of possibilities to alleviate the observed trade-offs	–	–	–	–	+	+	+	+
Ability to deal with real-life system complexity	+	+	+	+	–	–	–	–
Applicability to real-life decision-making	+	+	+	+	–	–	+/–	+/–

non-livestock owners would continue to let livestock graze their crop residues or if they would stop that practice [12]. In this system the trade-off is between the different land users in one community. In such a case participatory methods are again essential to capture the objectives of the different land users, and the social arrangements accompanying the different practices (e.g. when non-livestock owners let livestock graze their crop residues, they will be allowed to use oxen of livestock owners for land preparation in the following year [12]).

Optimization approaches such as mathematical programming (MP) (e.g. [25,26]) or multi-objective evolutionary algorithms, for example, [27•,28,29] find the best possible trade-off through multi-criteria analysis and can assess whether this trade-off curve can be alleviated through new interventions. MP has a long history [25] and is among the most extensively used trade-off application in land use studies [26]. The inherent limitation of the approach that land users do not always behave according to economic rationality and optimize their behaviour. Naudin and co-workers [30] have used MP to optimize land use management options that would maximize the availability of crop residue use for conservation agricultural practices while not affecting livestock productivity adversely. They identified optimal land use allocation strategies for a system in Madagascar that result in increases in both crop and livestock productivity compared to the current land use management system, thereby identifying a possible synergy between the two production components, despite crop residues being limiting in the system.

Improving the utility of trade-off analysis

The various approaches to trade-off analysis have key strengths and weaknesses. For example, participatory approaches are needed in many cases to be able to define meaningful objectives and indicators but are not suitable to quantify reliably the trade-offs associated with possible interventions. Empirical and econometric approaches can be used to quantify the current state of the overall agricultural system, although in many cases simulation models are needed to quantify indicators that are difficult to measure. For example, the effects of management on longer term productivity and to explore options outside the existing system configurations and boundaries (Tables 1 and 2). Optimization can be used to assess the potential for synergies and alleviation of trade-offs, but has limited applicability when socio-cultural traditions and rules play a key role, for example, in the example of the croppers versus cattle owners versus wildlife in East Africa (Table 1, [31]). So it is clear that for trade-off analyses combinations of approaches are needed. Combining approaches provides opportunities for a realistic, relevant and integrated assessment of systems (see Table 2 for an overall assessment). Examples of such integrated approaches are multi-criteria analysis in which participatory and optimization methods are combined: the weighting of the individual criteria in goal programming models is done together with the stakeholders, and by changing these weights together with the stakeholder a trade-off analysis is performed (e.g. [32]). A participatory approach would increase the relevance of the analyses performed by capturing those indicators that stakeholders perceive as essential.

Combining techniques, however, does not solve one of the major problems still associated with trade-off analysis, and systems modelling in general. Many perceive the practical relevance of models as being too limited. An unbalanced attention for model development rather than model application is often blamed for this [33••,34–37]. But this view seems overly simplistic. Even with active participation of farmers in model development and use, through action research to facilitate co-learning and co-innovation, trade-off analysis may not sufficiently or appropriately take into account the diversity in resource availability, the objectives of its diverse end-users, or the broader institutional and policy environment within which they function [14••].

How to capitalize on the joint benefits of quantitative and qualitative approaches, while keeping in mind the relevant questions for complex agricultural systems, remains a challenge. One option is to use trade-off analysis for 'discussion support', rather than decision support (see e.g. [33••,34,38]). Different members in a community may have conflicting objectives (and will value objectives differently). But the power of models is to be able to explore 'What ifs' and to enable actors to engage in a deeper discussion of trade-offs [39]. This is, for example, the case of the study in Zimbabwe on the consequences of the use of crop residues produced by non-livestock owners by livestock. Another example of a successful 'discussion support' application is, where policy makers used trade-off analysis to evaluate options and implement an appropriate alternative [14••]. A second, more ambitious approach is to ensure that the modelling or mapping methods are developed in participatory approaches and that interventions focusing on productivity and profitability are evaluated in its larger societal setting together with stakeholders. Similar approaches can be used for formalized representations of role games, companion modelling and multi-agent games (e.g. [40]). This links up very much with the 'knowledge into action' literature (e.g. [39]) and social learning [17], which stress the importance of co-production of knowledge with ultimate end-users to create demand-driven rather than supply-driven information. Again, as shown by the crop residue example, a thorough understanding of trade-offs between farmers within a community goes beyond a simple assessment of productivity [12], and needs to take into account the social rules and social networks active within a community to make a realistic assessment of the overall trade-offs present. This reinforces a systems perspective within which the key factors and objectives are identified and evaluated, going often beyond what technical approaches can deliver, and requires development of robust partnerships between researchers and stakeholders (i.e. producers, traders, consumers, ecologists and policy makers) as a prerequisite for increasing the impact of trade-off analysis research.

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