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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