Methods for Environment – Productivity Trade-off Analysis in Agricultural Systems

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Summary

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 and the strengths and weakness of the different techniques available. The techniques for performing trade-off analyses, including mathematical programming and participatory approaches, have developed substantially in recent years aided by mathematical advancement, increased computing power, and emerging insights into systems behaviour. The strengths and weaknesses of the different approaches are identified and discussed, and we make suggestions for a tiered approach for situations with different data availability.

1. Introduction

Trade-offs, by which we mean exchanges that occur as compromises, are ubiquitous when land is managed with multiple goals in mind. Trade-offs may become particularly acute when resources are constrained and when the goals of different stakeholders conflict (Giller et al., 2011). In agriculture, trade-offs may arise at all hierarchical levels, from the crop (such as grain vs. crop residue), the animal (milk vs. meat production), the field (grain production vs. nitrate leaching and water quality), the farm (production of one crop vs. another), to the landscape and above (agricultural production vs. land for nature). An individual farmer may face trade-offs between maximising short-term production and ensuring sustainable production in the long-term. Within landscapes, trade-offs may arise between different individuals for competing uses of land. Thus trade-offs exist both 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 change the nature of the trade-offs are central to achieving a sustainable and food secure future.

In this chapter we focus on how the complex relationships between the management of farming systems and its consequences for production and the environment, here represented by greenhouse gas emissions, can be analysed and how trade-offs and possible synergies can be quantified. For example, an important hypothesis is that by increasing soil carbon sequestration in agricultural systems, farmers can generate a significant share of total emission reductions required in the next few decades to avoid catastrophic levels of climate change. At the same time, increasing soil carbon sequestration also increases soil organic matter, which is fundamental to improving the productivity and resilience of cropping and livestock production systems, and thereby a potential win-win situation is identified. However, it is debatable whether these win-win situations also exist in reality. An important constraint for the above-mentioned hypothesis is the lack of organic matter like crop residues on many smallholder mixed crop-livestock systems to serve both as feed for livestock and as input into the soil to be able to increase soil organic matter contents. This organic matter could be produced through for example the use of mineral fertilizer or intensification of livestock production, but both of these have negative consequences for greenhouse gas emissions, probably offsetting the gains made in soil organic matter storage. It seems therefore likely that to achieve maximum impact on smallholders food production and food security environmental indicators have to be compromised. However, good quantitative insight in these possible compromises is still lacking.

Trade-off analysis has emerged as one approach to assessing farming system dynamics from a multi-dimensional perspective. Though the concept of trade-offs and their opposite; synergies, lies at the heart of several current agricultural research for development initiatives (Vermeulen et al., 2011; DeFries and Rosenzweig, 2010), methods to analyse trade-offs within agro-ecosystems and the wider landscape are only nascent initiatives (Foley et al., 2011). We review the state-of-the-art for trade-off analyses, highlighting important innovations and constraints, and discuss the strengths and weaknesses of the different approaches used in the current literature.

2. The nature of trade-off analysis

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 greenhouse gas emissions. The desired outcomes that different actors in and beyond the landscape may want to achieve need to be defined at different time scales and different spatial scales. Understanding these desired outcomes or objectives of different stakeholders is a necessary first step in trade-off analysis. We illustrate the key concepts and processes of trade-off analysis with a simple example that has only two objectives: farm-scale production and an environmental impact, greenhouse gas emissions. Once the objectives have been defined, the next step is to identify meaningful indicators that describe these objectives. The indicators form the basis for characterizing the relationships between objectives (Fig. 1). The shape of the trade-off curve gives important information on the severity of the trade-off of interest. Is it simply a straight line, or it the curve convex (i.e. the lower curve, which means strong trade-offs exist between the indicators) or concave (i.e. the upper curve, which means the indicators are independent of each other and the trade-offs between the indicators are quite 'soft') (Figure 1A).The shape of the trade-off curve represents different functional relationships and can be assessed by evaluating farm management options; in our example, each point could represent a method and level of mineral fertilizer application (Figure 1B). The position of each option in the trade-off space refers to its outcomes in terms of the two indicators, productivity and environmental impact. Based on this information, a "best" trade-off curve can be drawn (Fig. 1C). In trade-off analyses the researcher will be interested in which system management options or interventions result in which type of outcome of the different objectives (Figure 3D).

Once the best (observed or inferred) trade-off curve has been identified, various system management options or interventions can be studied with respect to the extent to which they contribute to the desired objectives (Fig. 1D). This analysis determines whether so-called 'win-win' solutions are possible, i.e. solutions where the performance of the system with regard to both objectives can be improved or whether improvement in one objective automatically leads to decrease in system performance for another objective (Fig. 1E). Identification of possible threshold values can be done once the shape of the trade-off curve is known. For example, do productivity thresholds exist above which the environmental impact increases rapidly? In some situations, it may be possible to alter the nature of the trade-off between production and environmental impact through the exploration of new management interventions (Fig. 1F), thereby redefining the "best" trade-off curve.

3. Research approaches and tools

Trade-offs are typically much more complex with more dimensions and objectives than indicated by the simple two-dimensional example presented in the previous section. A wide variety of tools and approaches have been developed to account for diverse situations. With the range of methods available, the most suitable approach depends on the nature and scale of the problem to be addressed, the trade-offs involved, and the indicators available . We assess five widely applied approaches: (i) participatory methods; (ii) empirical analyses; (iii) econometric tools; (iv) optimization models; and (v) simulation models. These five approaches overlap often and can help generate complementary knowledge. Consequently, trade-off analyses will often utilise several methods simultaneously 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. In recent times, the notion has expanded to acknowledge that change in researchers' assumptions and perceptions may be required to achieve desired outcomes that are attractive to farmers (Crane, 2010). Participatory approaches, such as fuzzy cognitive mapping (Murungweni et al., 2011), 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 (Van Asten et al., 2009). There are many examples of participatory approaches (Gonsalves, 2013) that could be or are used to assess trade-offs. Participatory approaches usually generate qualitative data and so while they may not be well suited for quantifying trade-offs, they provide critically important information that can be used to inform quantitative tools, for example through the development of participatory scenarios (DeFries and Rosenzweig, 2010; Claessens et al., 2012). However, despite the participatory nature of these approaches, the assessment of trade-offs often remains researcher-driven.

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 (Naudin et al., 2012). Statistical techniques such as data envelope analysis (Fraser and Cordina, 1999) or boundary line analysis (Fermont et al., 2009) can be used to quantify best possible trade-offs between indicators in empirical datasets (e.g. Fig 1C). Related to these empirical approaches are **econometric tools**, in which large datasets form the basis of statistical coefficients that define input-output relationships of system level outcomes (e.g., Antle and Capalbo, 2001). Developments combine biophysical and socio-economic aspects of the system, and use farm level response to quantify consequences at a regional level (Antle and Stoorvogel, 2006). Empirical and econometric 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.
Empirical approaches cannot be used to assess indicators that are difficult to measure directly; therefore, they are often combined with **simulation models** to obtain an overview of overall system performance. Simulation models allow the dynamic nature of trade-offs to be explored, where outcomes can differ in the short- or long-term (Zingore et al., 2009). System performance, expressed quantitatively in terms of outcomes, represented by different indicators, can be used as input for **optimization** approaches such as mathematical programming (MP). MP finds 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 (e.g. Hazell and Norton, 1986) and is among the most extensively used trade-off application in land use studies (e.g. Janssen and Van Ittersum, 2007), despite the inherent limitation of the approach that land users do not always behave according to economic rationality and optimize their behaviour. Techniques have been developed recently to solve non-linear MP problems and integrate across levels, linking farms and regions through markets and environmental feedbacks (e.g. Laborte et al., 2007; Roetter et al., 2007; Louhichi et al., 2010).

Inverse modelling techniques use non-linear **simulation models** directly to perform multi-objective optimization without the intermediate step of MP. Furthermore, with the identification of the appropriate model outputs, system behaviour across different temporal and spatial scales can be assessed and feedbacks taken into account, often a weak part of MP models. The complexity of agro-ecosystems and the large number of potential indicators can hamper efficient applications of this computationally intensive method. But advances in computer power have resulted in several applications in farming systems research, going from farm to landscape (Groot et al., 2012; Groot et al., 2007; Tittonell et al., 2007).

The various approaches to trade-off analysis each have key strengths and weaknesses and combining approaches may provide enhanced opportunities for a realistic, relevant and integrated assessment of systems (Table 1). 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 effects of management on longer term productivity and to explore options beyond the existing system configurations and boundaries (Table 1). Optimization can 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 vs. cattle owners vs. wildlife in East Africa (Thornton et al., 2006). So it is clear that for trade-off analyses combinations of techniques are needed. 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. Romero and Rehman, 2003).

4. A tiered approach

For fully integrated trade-off analyses it is clear from the discussion above that different approaches should be combined. However, in many cases data availability will not allow for such elaborate analyses. The techniques discussed in the previous section are not only different in the strengths and weakness, but, related to that, also different in their data demands. Typically, empirical and econometric approaches are highly data demanding, whereas participatory approaches can already give essential information about system functioning after only a few well designed discussion panels and targeted questionnaires. Simulation and optimization models can be, in terms of data demand, anywhere in between these extremes. Their data demand is highly determined by model setup and model complexity.

An example of a tiered approach in which the researchers moves from quick initial data analyses to more complex, data demanding, modelling exercises is the four step approach used by Van Noordwijk and his team at ICRAF (Meine van Noordwijk, personal communication). Step 1 is the collection of system characterization data and the analyses of these data to explore whether trade-offs can be identified, for example between an environmental indicator like soil carbon and the net present value of the land. The next step is to look at these variables form a dynamic perspective and to identify opportunities for interventions by analysing the opportunity costs of different management options present in the landscape. This step already asks for much more detailed data than step 1. In this example this analysis can be used to identify the price of emission reduction potentials. The consequences of the identified intervention options for the different land users and the environment can be explored by using dynamic land use models in the third step. In the last step agent based models and participatory modelling exercises are used to analyse the opinions of and interactions between different actors in the landscape to get an integrated analysis of both the environmental and socio-economic factors and actors working and living within the landscape. This approach of using these four steps is an interesting example of how the strengths of different trade-off analysis methods can be combined, and how such an analysis can move stepwise towards more complex and data-demanding exercises.

All in all it is not straightforward to give concrete advice that relates purpose of analysis to the technique and approach to be used. It is embedded in the 'art' of modelling and trade off analyses that researchers are likely to make personal choices regarding complexity and analysis approach, although this is sometimes difficult to reconcile with the 'objectivity' that we try to pursue in scientific research. However, we do think some general indications can be given. If the purpose is to assess the overall potential for system improvement and the room for manoeuvre to increase efficiencies and profitability while not having negative effects on environmental indicators, then optimization approaches are the most logical approach to take. If the purpose is to analyse short and longer term consequences of certain interventions, and the trade-offs between different objectives over different time scales, then simulation modelling is an obvious candidate to use, potentially in combination with some sort of multi-objective non-linear optimisation or inverse modelling approach. Both optimization and simulation are typically used for scientifically oriented studies, but to have real-life impact that takes into account the complexities of how agricultural systems function and the large diversity of drivers and options that exist in agricultural land use, especially in developing countries, it is likely that a variety of approaches needs to be used, both quantitative and qualitative ones (e.g. Murungweni et al., 2013). The setup of these tools, the identification of indicators and use and presentation of analysis results need to be determined using participatory approaches where key stakeholders are involved and drive decisions from the beginning of the project. This might lead to less value in terms of scientific novelty of the study, but will increase its practical relevance on the ground. It is ironic, with the topic of this chapter in mind, to realize that in many cases there might be a trade-off between scientific impact and societal impact.

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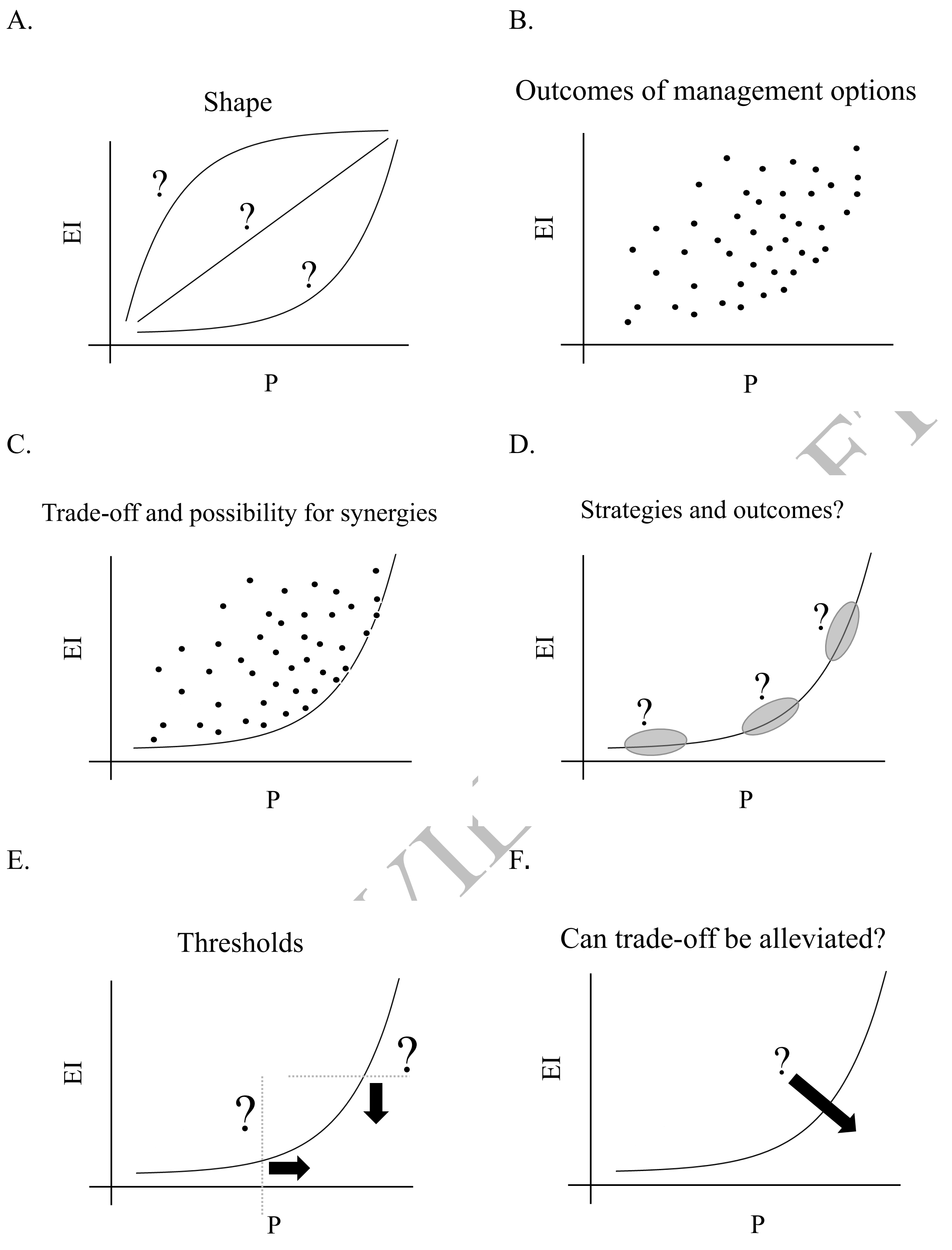

Figure 1. Key-concepts of trade-offs and their analysis for a simple two objective example (for explanation see text). EI stands for Environmental Impact and P stands for Production

Table 1: 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									
	Empirical		Econometric		Simulation		Optimization		Participatory	
Aspect	Act	Pot	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	+	+	+	+	-	-	+/-	+/-	+	+