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Analysis

Quantifying ecosystem services trade-offs from agricultural practices

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ABSTRACT

The concept of ecosystem services (ESS) is widely used to highlight the interdependencies between agricultural and environmental systems. However, few studies have attempted to quantify the potential of agriculture to produce multiple ESS, and to estimate the possibilities for joint production of marketed and non-marketed ESS. A quantification of the trade-offs between non-marketed ESS and production of farm commodities (marketed ESS) may help to better target agricultural policies.

We use a well-established biophysical farm-systems model (APSIM) to estimate how alternative farm management practices affect the joint production of ESS on mixed crop-livestock farms in the wheatbelt of Western Australia. Our analysis quantifies the trade-offs between the supply of agricultural commodities (crop yields and livestock weight gain) and non-marketed ESS (groundcover, soil carbon, nitrogen supply, and water regulation). Win–win trade-offs between marketed and non-marketed ESS become apparent when the value of agricultural commodity production is monetised. This study shows that, in our study regions, increasing crop residue retention can jointly increase production value and improve ESS provision of groundcover, soil carbon and nitrogen supply. Conversely, increasing the use of perennial pastures in the farming mix results in negative trade-offs between production values and non-marketed ESS.

1. Introduction

Modern agricultural management practices can affect ecosystem conditions through impacts on, for example, soil erosion, water quality, or greenhouse gas emissions. Given the dependence of agriculture on agri-environmental systems, it is important to understand the relationships between agricultural production and ecosystem changes. The ecosystem services (ESS) framework is now widely used as a way to understand how agricultural practices may impact ecosystems, and vice versa (Gomez-Baggethun et al., 2010). The seminal work by Daily (1997) defined ESS as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life." The interdependencies between ESS and agriculture are complex. On the input side, many ESS (e.g. pollination by insects or soil fertility) provide direct production benefits to agriculture (Zhang et al., 2007). On the output side, agriculture supplies a range of "provisioning" ESS (e.g. fuel and fibre) that are traded in commodity markets. Agriculture may further sustain "supporting" services and "regulating" ESS (e.g. water purification and soil nutrient renewal) (MEA, 2005; Swinton et al., 2006). The ESS framework has been put forward as an approach to characterise options for improved environmental management in agriculture (Pittock et al., 2012). In this paper, we use the ESS framework to identify win–win possibilities between agricultural practices and ESS, building on the approach taken by Robertson et al. (2009).

Departments of Agriculture around the globe acknowledge the relevance of the ESS concept to policy development. In December 2008, the United States Department of Agriculture established an Office of Ecosystem Services and Markets (now "Office of Environmental Markets") to catalyse the development of markets for ecosystem services in agriculture. The 2013 reform of the European Common Agricultural Policy proposes an increased budget for direct payments for ESS provision by agriculture (Plieninger et al., 2012). The Australian Department of Agriculture Fisheries and Forestry also recognises the benefits of using an ESS approach for constructive dialogue between scientists, communities and government decision makers (Cork et al., 2012). The Australian Federal Government introduced financial support for the adoption of best management practices in their Carbon Farming Futures Program — for example through tax offsets for conservation tillage and funding for regional natural resource management plans (DCCEE, 2012). To aid effective development of these kinds of policies, it is important to understand how ESS respond to changes in agricultural practices (Dale and Polasky, 2007; Seppelt et al., 2011).

Various authors (e.g. Heal and Small, 2002; Power, 2010; Swinton et al., 2006; Zhang et al., 2007) have provided excellent qualitative discussions about the ecosystem processes and services on which agriculture depends. Works by, for example, Heal and Small (2002: p1365) and

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Antle and Stoorvogel (2006) have suggested conceptual frameworks to analyse the relationship between agriculture and ecosystem services. Several authors (e.g. Pilgrim et al., 2010; Swinton et al., 2007: 251; Zhang et al., 2007: 258) have, however, noted the lack of studies that quantify the trade-offs that exist between production of alternative ESS and marketed farm products. Sauer and Wossink (2013) and Cong et al. (2014) recently noted the lack of empirical studies that have quantified the joint provision of ESS on farms. Such analyses are needed to estimate how ESS can be jointly produced in agricultural systems and to aid the development of agri-environmental management policies (Balmford et al., 2012; Turpin et al., 2010; Wossink and Swinton, 2007).

In their review of ESS studies, Seppelt et al. (2011) identified the lack in (evidence-based) simulation models to assess ESS provision, and the limited analyses of (uncertainty in) trade-offs between ESS. In this paper, we address this knowledge gap by demonstrating an approach to quantify the trade-offs between agricultural provisioning services, and other ecosystem services. Based on the Agricultural Production System Simulator (APSIM) we estimate the joint production of marketed ESS (agricultural commodities: grain crop yields and livestock weight gain) and non-marketed ecosystem service outputs (groundcover, soil carbon, nutrient supply, soil water drainage), that can be achieved through on-farm management actions. Whereas Robertson et al. (2009) looked at a general crop-rotation mix, our analysis focuses on the production of ESS under two of several land management practices that are actively promoted as sustainable management practices by natural resource management organisations in Australia: stubble retention and including pasture phases in crop rotations (Barson et al., 2011, 2012). Our study thus pertains to the reality being faced by farmers in our study region. We will present the trade-off results as “production possibility frontiers” to identify opportunities for “win–win” scenarios where agricultural production values and non-marketed ESS are jointly produced. Furthermore, we examine the variability around the trade-off curves, which was not addressed in (Robertson et al., 2009). Our approach is demonstrated for two representative mixed crop-livestock farming systems in Western Australia.

The ESS framework is briefly discussed in the context of agriculture in the next section, followed by an explanation of our modelling approach and case study regions in Section 3. The results of the analysis are presented in Section 4, which are subsequently discussed in the concluding Section 5.

2. Ecosystem Services and Agriculture

The concept of ESS highlights the long-term role that healthy ecosystems play in the sustainable provision of human wellbeing, economic development and poverty alleviation across the globe (Turner and Daily, 2008). ESS provide direct and indirect benefits to people. The Millennium Ecosystem Assessment (MEA, 2005) identified four classes of ESS:

1. Provisioning services = the products (goods) directly obtained from ecosystems (e.g. food, water, fuel, genetic resources;
2. Supporting services = services that are necessary for the production of all other ecosystem services (e.g. soil formation, nutrient cycling, production of oxygen);
3. Regulating services = the benefits obtained from the regulation of ecosystem processes (e.g. climate regulation, water purification);
4. Cultural services = the nonmaterial benefits people obtain from ecosystems through e.g. spiritual enrichment, recreation, and aesthetic experiences.

The term ESS is sometimes separated into “good” and “services” to reflect the fact that ecosystems provide products and processes that can deliver both tangible and intangible benefits to humans. Some researchers have advocated a distinction between ecosystem services (processes and functions) that can be seen as intermediate ESS, and the provision of final services that can (actively or passively) be used to produce human well-being (Boyd and Banzhaf, 2007; Fisher and Turner, 2008). This distinction may be useful from an accounting or economic valuation perspective (Balmford et al., 2011; Brouwer et al., 2013). However, in this paper we follow the more holistic understanding of ecosystem services to encompass the multiple aspects of ecosystems (processes and direct benefits — Balmford et al., 2011) that contribute to making human life both possible and worth living (Fisher and Turner, 2008; UK NEA, 2011).

There is a large body of research that discusses the general trade-offs between ESS provision and their notional relationships with agro-ecosystems (see, e.g., Bennett et al., 2009; Heal and Small, 2002; Plieninger et al., 2012; Rodríguez et al., 2006; Swinton et al., 2007; Zhang et al., 2007). Most of this work proposes typologies for ESS and remains limited to a theoretical discussion of possible trade-offs between ESS, as briefly summarised in this section.

Agro-ecosystems are both providers and consumers of ESS (Fig. 1). Agricultural production relies on a wide variety of supporting and regulating services. For example, the biophysical capacity of agricultural systems is (at least partly) determined by beneficial ecosystem processes such as biological control and climate regulation (Balmford et al., 2011). Agro-ecosystems also provides humans with direct commodities, such as food, forage, bioenergy and pharmaceuticals that are essential to human wellbeing (Power, 2010).

In addition to direct provision of agricultural commodities (marketed ESS), agricultural systems can produce supporting, regulating, and cultural (non-marketed) services, depending on what land management practices are undertaken. For example, perennial vegetation can regulate water, soil, and nutrient retention on paddocks. Conservation tillage practices or cover crops can increase soil organic matter, which helps water storage and reduces soil erosion. Retaining crop residues can reduce soil erosion and increase soil carbon sequestration, which assist in climate change mitigation. Understanding the trade-offs between the market values of agricultural provisioning services and non-marketed ESS will help us to make more informed decisions about the sustainability of agricultural practices (Dale and Polasky, 2007).

3. Methods

3.1. Trade-Off Analysis

Maximising production values in agriculture has historically resulted in environmental degradation (Pittock et al., 2012). However, it may be possible to achieve “win–win” situations between agricultural provisioning services that generate marketable commodities, and other ESS by adopting management practices such as increasing pasture phases or stubble retention. The trade-offs between marketed production and non-marketed ESS can be presented as “production possibility frontiers” (PPFs — Fig. 2). When the output of agricultural commodities and another ecosystem service can be jointly increased from the same resource base we are in a “win–win” situation (Fig. 2a) where producers have a private incentive to produce the (non-marketed) ESS. However, when there are “win–lose” trade-offs between (marketed) provisional services and non-marketed ESS (Fig. 2b), profit-maximizing farmers have no private incentive to produce the (non-marketed) ESS (Swinton et al., 2007). In that case, external incentives are required to stimulate adoption of alternative farm practices (Weersink et al., 2002).

3.2. Study Regions

How ecosystems and crop production respond to farming practices varies widely by agro-climatic regions. The focus of this study is on broad-acre farming[1] in the wheatbelt of Western Australia (WA). This

[1] Broad-acre farming is a term used to indicate large-scale operations, mostly for grain crops or extensive livestock operations in Australia.