

Modelling trade-offs between ecosystem services and agricultural production in Western Australia

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Abstract: The concept of ecosystem services (ES) is widely used to highlight the interdependencies between agricultural and environmental systems. Many ES provide direct production benefits to agriculture—even those that are not directly producing agricultural commodities, such as pollination, water regulation, and soil retention. Farm management practices may produce ES or ‘disservices’, such as nutrient pollution or greenhouse gas emissions. Few studies have attempted to *quantify* the potential of agriculture to produce multiple ES, and to estimate the possibilities for joint production of marketed and non-marketed ES. A quantification of the trade-offs between ES provision and production of farm commodities can help to better target agricultural policies.

We use a well-established biophysical farm-systems model (APSIM) to estimate how ES can be jointly produced on mixed crop-livestock farms in the wheatbelt of Western Australia. We focus our assessment on the joint supply of agricultural commodities (crop yields and livestock weight gain) and non-commodity ES (groundcover, soil carbon, nitrogen supply, and water regulation). Our analysis fills the knowledge gaps identified by scholars such as Pilgrim et al. [2010], Turpin et al. [2010], and Wossink and Swinton [2007], by estimating quantitatively how ecosystem services can be jointly produced in an agricultural system, and by quantifying the trade-offs between the services provided. The analysis shows that, in general, win-win situations can be achieved between increasing the production value of marketed agricultural commodities, and improved ES provision in our case study region. In order to better reflect the non-marketed ES values in decision making, further economic valuation research is essential.

Keywords: Agriculture; APSIM; Conservation Practices; Ecosystem Services;

1 INTRODUCTION

Agricultural production on arable and pastoral lands depends critically on the condition of agro-ecosystems. It is therefore important to understand how ecosystem changes may affect agricultural production. The ecosystem services (ES) framework is now widely used as a way to communicate agriculture’s dependence on the environment [Gomez-Baggethun et al. 2010]. ES are defined as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life” [Daily 1997]. Many ES (e.g. pollination by insects or soil fertility) provide direct production benefits to agriculture. Agriculture also supplies a range of ‘provisioning’ ES (e.g. fuel and fibre) that are traded in agricultural commodity markets. Agriculture may further sustain ‘supporting’ services and ‘regulating’ ES (e.g. water purification and soil nutrient renewal) [MEA 2005]. However, agricultural practices can also negatively

affect ecosystems ('disservices'), for example through soil erosion, sedimentation of waterways or greenhouse gas emissions.

Agricultural policies are increasingly being targeted at paying farmers for environmental management activities [see, e.g. the European Common Agricultural Policy; European Commission 2005, or the Australian Carbon Farming Initiative; Parliament of the Commonwealth of Australia 2011]. To aid effective policy development, it is important to understand the contribution of agricultural practices to different ES, which in turn affect agricultural productivity [Dale and Polasky 2007]. In order to maximise synergies between agricultural practices and ES provision, we need to identify which agricultural production activities directly enhance (non-production-related) ES, and vice versa ('win-win' situations).

Various authors [e.g. Power 2010, Swinton et al. 2006, Zhang et al. 2007] have provided excellent *qualitative* discussions of the ecosystem processes and services on which agriculture might depend, but few studies have attempted to quantify the trade-offs that exist between production of alternative ES and marketed farm products [Pilgrim et al. 2010, Swinton et al. 2006]. In this paper, we quantify the joint production of agricultural commodities (crop yields and livestock weight gain) and non-commodity outputs (groundcover, soil carbon, nutrient supply, water regulation), that can be achieved through on-farm environmental management actions. The assessment uses the Agricultural Production System Simulator (APSIM) to estimate ES and production for a representative mixed crop-livestock farming system in the wheatbelt of Western Australia.

The ES framework is briefly discussed in the next section, followed by an explanation of our modelling approach and scenarios 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 IN AGRICULTURE

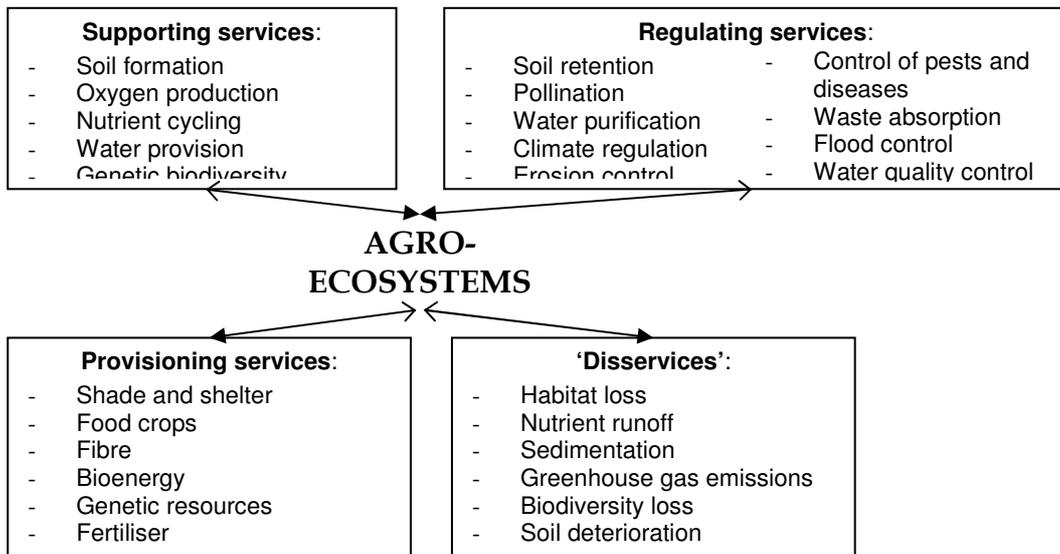
The concept of ES highlights the long-term role that healthy ecosystems play in the sustainable provision of human wellbeing, economic development and poverty alleviation across the globe [Turner and Daily 2008]. The Millennium Ecosystem Assessment [MEA 2005] identified four classes of ES:

1. Supporting services = services that are necessary for the production of all other ecosystem services (e.g. primary production, production of oxygen)
2. Provisioning services = the products people obtain from ecosystems (e.g. food, water, fuel)
3. Regulating services = the benefits people obtain 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

Agro-ecosystems are both providers and consumers of ES (Figure 1). Agricultural ecosystems provide humans with food, forage, bioenergy and pharmaceuticals that are essential to human wellbeing [Power 2010]. Agricultural production relies on a wide variety of supporting and regulating services. For example, pollination and soil fertility determine the underlying biophysical capacity of agricultural systems [Zhang et al. 2007].

Agricultural systems can also produce supporting and regulating 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 reduce soil erosion. Legume intensification can maintain soil fertility by reducing nutrient losses. Retaining crop residues can reduce soil erosion and increase soil carbon sequestration-which assist in climate change mitigation.

Preliminary assessments indicate that the value of ES to agriculture is enormous and often underappreciated [Power 2010]. There is a need to quantify how farm practices affect ES, and how ES affect agricultural production. Understanding



possibilities of agricultural lands to produce multiple ES is necessary to make more informed decisions about the sustainability of agricultural practices [Dale and Polasky 2007]. In this paper, we quantify some of the trade-offs that may occur between agricultural provisioning services, and other ecosystem services and disservices.

Figure 1. Relationships between agro-ecosystems and ecosystem services

3 METHODS

3.1 Trade-off analysis

We need to understand the trade-offs between marketed products and non-marketed ES to determine the need for agricultural policy intervention [Weersink et al. 2002, Wossink and Swinton 2007]. The two-dimensional trade-offs between ES can be presented as 'production possibility frontiers' (PPFs-Figure 2). When the output of agricultural commodities and an ES can be jointly increased from the same resource base (*complementary products*; Figure 2a), producers have a private incentive to produce the (non-marketed) ES. However, when there are 'win-lose' trade-offs between agricultural production and a non-marketed ES (*competitive products*; Figure 2b), profit-maximizing farmers have no private incentive to produce the ES [Swinton et al. 2007]. In that case, external incentives are required to stimulate adoption of alternative farm practices [Weersink et al. 2002].

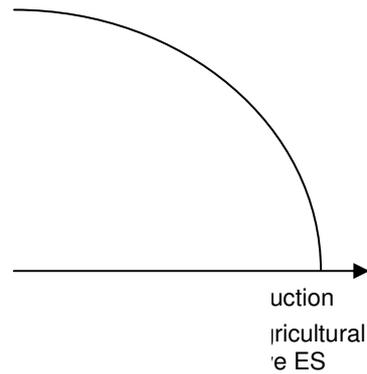


Figure 2. Example production possibilities frontiers (PPFs) for agricultural production and ecosystem services [source: Wossink and Swinton 2007]
(A PPF shows the combinations of output that can be produced if all of the available factor resources are used efficiently)

3.3 Study area

Farming practices, and the production of ES, vary widely by agro-climatic regions. Our analysis will be conducted in multiple Australian farm regions, to account for differences in climate, farm systems and soils. The results reported in this paper are for the central wheatbelt of Western Australia (Cunderdin—Figure 3).

The region has predominantly loamy sandy soils, and receives an average annual rainfall of 350–400mm. The weather is characteristic of the Mediterranean climate in south-western Australia with long, hot and dry summers and cool, wet winters. Principal land use is rain-fed broad-acre (mixed grain and livestock) farming.

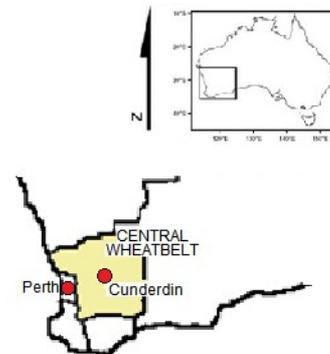


Figure 3. Location of study area

3.2 The APSIM model

We use the Agricultural Production System Simulator [APSIM-Keating et al. 2003] to estimate how ES can be jointly produced for a representative paddock in the wheatbelt of Western Australia. APSIM consists of separate modules that simulate components such as wheat and barley production, lucerne production, soil carbon stock, soil water balance (SOILWAT2), surface residues (RESIDUE2), and soil nitrogen (SOILN2). A manager module controls farming activities like sowing and harvesting crops, tillage and fertilising [Keating et al. 2003, Probert et al. 1998, Verburg et al. 2007]. The APSIM model is widely used and has been validated by several authors [e.g. Probert et al. 1998].

APSIM version 7.2 was configured to simulate annual output for crop grain yields, grazed pasture biomass, and ES indicators on a paddock scale. Values were reported as annual totals or averages as appropriate for the indicator (Section 3.4). The simulations were conducted for loamy sand-soils, using a 120-year historical climate record for Cunderdin (1889–2010). The model accounts for links between processes, such as nitrogen fixation by legumes and the provision of nitrogen for crop and pasture growth; and the positive relationships (in this semi-arid study region) between retention of crop residues (which conserve soil water) and crop and pasture growth. However, there are some feedback loops between changes in ES and agricultural production that are not yet included in the model. For example, there is no direct impact from an increase in soil organic carbon on processes influenced by soil structure, such as water infiltration [Robertson et al. 2009].

3.4 Scenarios and indicators

The analysed scenarios and indicators were selected to present practices that are typically advocated to improve agricultural environmental management [e.g. Power 2010]. The first scenario consists of a stepwise increase of perennial pastures in the crop-pasture mix, at 50 per cent crop residue retention. An increase in annual or perennial pastures can have several positive effects on ES, e.g. (i) regulating capture, infiltration, retention and flow of water; (ii) reducing erosion rates; and (iii) increasing nitrogen retention and input via legume fixation. This scenario moves from continuous cropping of wheat and barley (0LWB), to lucerne–wheat–barley rotations with increasing length of the lucerne phase (1-9LWB); to continuous pasture (10L).

In the second scenario, we decreased the proportion of crop residue (stubble) removed from the paddock after harvesting in 25% increments from no (0%) stubble retention to full (100%) stubble retention. Incorporating crop residues can, e.g. (i) improve soil fertility through maintaining soil organic matter; (ii) reduce soil carbon losses; and (iv) increase water capture and retention in soils. The scenario was run for different crop-pasture rotations. Here, we report the results for a 3yr lucerne-1yr wheat-1yr barley (3LWB) rotation. This rotation is representative of crop-pasture rotations commonly used in the case study region.

There has been extensive work on indicators of ES changes in agro-ecosystems [e.g. Bockstaller et al. 1997, Dale and Polasky 2007, Rigby et al. 2001]. We include:

1. **Agricultural production** (*mean yields kg/ha.yr*) captures the *provisional services* from agriculture. The model predicts wheat and barley yield and pasture production. To enable a comparison between these yields, production was converted into *agricultural production value (\$/ha.yr)* using gross margins for case study region. The gross margin analysis followed the approach by Verburg et al. [2007] where lucerne gross margin was calculated from the effective contribution of pasture biomass to sheep rearing. We used 2005 prices for the Eastern Wheatbelt of WA [DAFWA 2005]
2. **Drainage** (*mean total mm/yr*) below the bottom of the root zone, captures *water regulation* and *soil moisture retention*
3. **Soil organic carbon stock** (*mean kg/ha.yr* for the 1.5m deep soil profile) is a measure of SOC sequestration that contributes to *climate regulating services*, and to improved *soil structure and fertility*
4. **Nitrogen mineralisation** (*mean total kg N/ha.yr*) is used to represent nutrient cycling. Nitrogen mineralisation a measure of the rate of conversion of Nitrogen from organic to inorganic sources, and thus a proxy for *nutrient supply* and reductions in *nutrient losses* to ecosystems
5. **Groundcover** (*mean annual mean daily value expressed as a fraction*) is an important provisioning service for *biodiversity habitat*, and a supporting service for e.g. *soil, water, and nutrient retention*

4 RESULTS

4.1 Increasing the proportion of pasture in the rotation mix

In this first scenario, we increased the lucerne phase in the crop-pasture rotations. APSIM predicts averages for each of the ES indicators for each year of the 120 year simulation period. In Figure 4, we report the median predicted levels of agricultural production values and other ES-over the 120yr simulation period-for a step-wise increase in the lucerne phase. The 40th and 60th percentiles of simulated values ($\pm 10\%$) for the environmental services (soil organic carbon, nitrogen mineralisation, drainage, and groundcover) provide a measure of predictive uncertainty in the indicators. Note that, although agricultural production is plotted

on the x-axes and environmental services on the y-axes, these figures show the interrelationships between marketed values and ES, not necessarily the causalities between their provision.

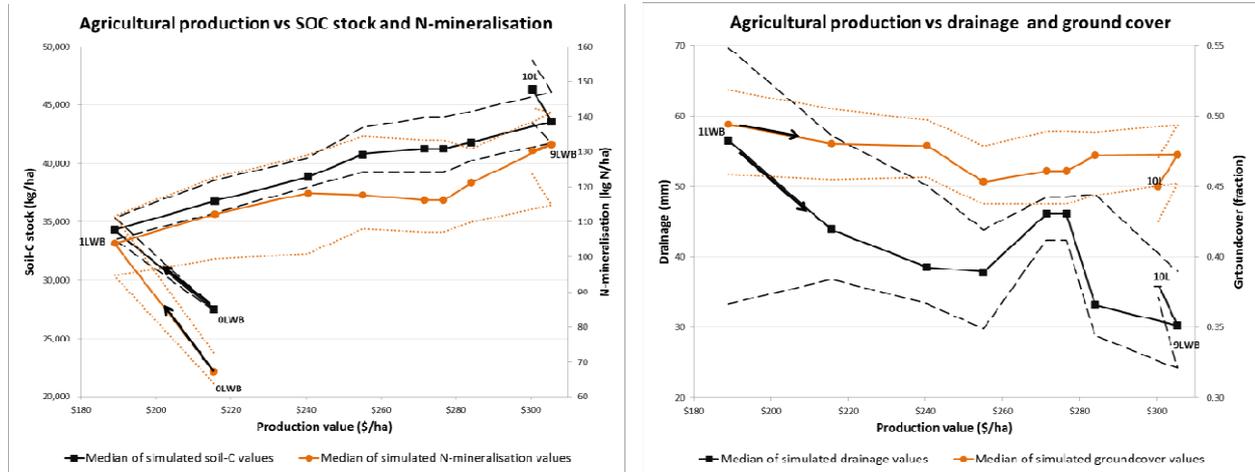


Figure 4. APSIM simulated production possibilities frontiers (PPFs) for agricultural production and ecosystem services by changing lucerne phase in the rotations (arrows = increasing years of lucerne, dotted lines = 40th / 60th pctl. of simulated ES values) Increasing the proportion of pasture in the rotation mix will increase production value because of the higher revenues from livestock rearing in the case study region. The PPFs between production value and SOC stock, and between production value and N-mineralisation show an initial loss in production value when a farmer moves from continuous cropping (0LWB) to one year of pasture in the rotation mix (1LWB), with the assumption that prices remain unchanged. This is due to the establishment costs of pasture, which are all incurred in one year in the 1LWB case. Increasing the years of pasture beyond 1L will continue to contribute to more ES provision on the paddock: Nitrogen fixation from the legume will increase N and C input, and hence N-mineralisation and soil-C stock. The results indicate ‘win-win’ possibilities between marketed agricultural products and soil carbon sequestration / nitrogen supply.

The results are less clear-cut for groundcover and drainage. The deep-rooted perennial lucerne decreases drainage (a positive impact) because of greater rainfall transpiration, and less water loss below the root zone. The increase in drainage around 5LWB/6LWB is a result of the starting year in the climate file used in the APSIM analysis. A phase simulation analysis (i.e. varying the starting years for each scenario) is expected to smooth this result.

Increasing the lucerne phase (and hence less cereal crops) appears to come at a small cost of ground cover. This is due to the greater presence of readily decomposable legume plant residues at the expense of—less readily decomposable—cereal plant residues.

4.2 Crop residue retention

In the second scenario, we assessed the effect of increasing crop residue (stubble) retention. Figure 5 shows that an increase in stubble retention rates will unambiguously increase agricultural production values and ES provision for SOC-stock, groundcover and N-mineralisation. This is because (in this semi-arid climate) increased retention of plant residues not only conserves soil moisture for plant growth, but also adds C and N to the soil organic matter, leading to higher soil carbon stocks and mineralisation of N from organic matter. Such win-win benefits are reflected by farmers in the region increasingly adopting this practice.

At the median, there are no clear predicted impacts of increased stubble retention on drainage for the analysed lucerne-wheat-barley rotation. The 40th and 60th percentiles of the simulated ES values show that increased stubble retention may

initially increase drainage (i.e. win-lose situation), but that drainage will decrease again at higher levels (above 50%) of stubble retention.

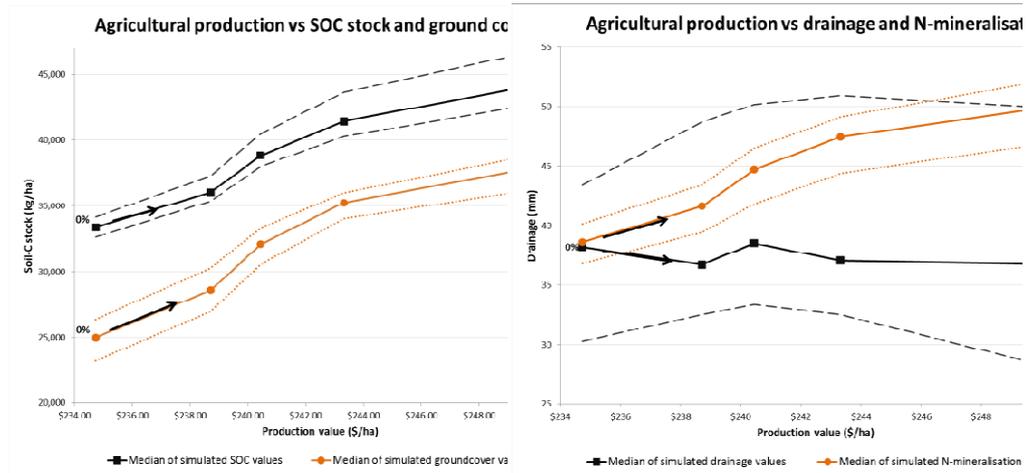


Figure 5. APSIM simulated production possibilities frontiers (PPFs) for agricultural production and ecosystem services by changing residue retention rates (arrows = increasing years of lucerne, dotted lines = 40th / 60th pctl. of simulated ES values)

5 DISCUSSION AND CONCLUSION

The purpose of this study is to predict the changes in ES provisions that can be achieved through on-farm environmental management actions. We use the APSIM model to account for the multiple and non-unilateral links that exist in agro-ecosystems. Our analysis demonstrates an approach to estimate the interactions between the multiple functions fulfilled by agricultural land uses, and quantifies these interactions as ES production possibilities frontiers.

Not unexpectedly, the results show considerable potential for synergies between increasing agricultural production values and provision of ESs, both from increasing the proportion of pastures in the crop-pasture mix and from increasing stubble retention rates on paddocks. This means that agricultural commodities and ES are complementary products. In theory, farmers thus have a private incentive to produce the non-marketed ES. Why then, is such production not ubiquitously observed? There may be various reasons for under-provision of ES on agricultural lands that will require further research:

- There may be high transaction costs hindering adoption of alternative farm practices, which are not captured in the current analysis
- There may be social barriers to adoption of alternative practices (e.g. a farmer may be personally averse to changing traditional practices)
- Even though crop residue retention is shown to improve soil conditions in this case study region, complete retention is not typically practised. Many farmers graze crop residues with livestock, which adds secondary economic benefits to removing stubble. These economic values of residues are not accounted for in the analysis presented here.
- The value of agricultural production is readily observable from market transactions, and therefore generally included in agricultural land use decisions. Environmental indicators, on the other hand, are biophysical measures with no tangible monetary value. There is an identified need to estimate the economic (market and non-market) values of ES, to enable their inclusion in future cost-benefit analyses [Swinton et al. 2007]
- Even if values are known, there is still relatively limited experience with incentives and delivery mechanisms to provide (non-marketed) ES in agriculture

[Swinton et al. 2006]. The design of suitable incentive mechanisms to cover diverse ES, multiple agricultural commodities, and different biophysical and institutional settings, remains an important research challenge

While our analysis clearly shows the relationships between ES and agricultural production on a paddock scale, further modelling will need to consider landscape scale trade-offs among ES, in order to minimise potential negative trade-offs and maximize synergies across a region. For example, reduced soil erosion and increased nutrient retention on a paddock, may have further positive effects on stream sedimentation and eutrophication elsewhere.

Finally, we note that the ES indicators in our assessment should not be viewed independently from each other. Our modelling approach includes feedback loops and interactions between ES. De Groot et al. [2002] have, however, warned for the possibility of 'double counting' ES values when services are interconnected or overlap. For example, some services, such as soil carbon sequestration, may be classified as both 'supporting' and 'regulating', depending on the scale at which the service and its impacts are considered. It is important that such interdependencies between ES should be understood to avoid double counting of the benefits provided to human beings.

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