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Modeling trade-offs among ecosystem services in agricultural production systems☆

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ABSTRACT

Although agricultural ecosystems can provide humans with a wide set of benefits agricultural production system management is mainly driven by food production. As a consequence, a need to ensure food security globally has been accompanied by a significant decline in the state of ecosystems. In order to reduce negative trade-offs and identify potential synergies it is necessary to improve our understanding of the relationships between various ecosystem services (ES) as well as the impacts of farm management on ES provision. We present a spatially explicit application that captures and quantifies ES trade-offs in the crop systems of *Llanada Alavesa* in the Basque Country. Our analysis presents a quantitative assessment of selected ES including crop yield, water supply and quality, climate regulation and air quality. The study is conducted using *semantic meta-modeling*, a technique that enables flexible integration of models to overcome the service-by-service modeling approach applied traditionally in ES assessment.

1. Introduction

Agricultural systems constitute a source of provisioning, regulating, and cultural services ecosystem services (ES), while at the same time depend highly on them in order to function (Power, 2010). Furthermore, certain agricultural management practices greatly impact service-producing ecosystems, as in the case of intensive farming or intensified food production (Arriagada and Perrings, 2011; Godfray et al., 2010; Kleijn et al., 2006). The delivery of ES by agricultural ecosystems becomes increasingly important as demand for food brings new areas of land under agricultural management and the attempts to raise crop yield intensify, while increasing urbanization and land degradation reduce agricultural land availability. Along with the growing need to ensure food security globally, there has been a significant decline in the state of ecosystems and the services they provide (FAO, 2007; Steinfeld et al., 2006; Thiaw et al., 2011). The Millennium Ecosystem Assessment (MA, 2005) highlighted trends of significant decline in many ES of high relevance to food security, especially those provided by cultivated ecosystems.

In order to reduce negative trade-offs and identify more sustainable management scenarios, it is necessary to improve our understanding of the relationships between various ES (Bennett et al., 2009). The integration of ecological and agronomic factors is necessary to account for the complexity of cropping systems (Athanasiadis et al., 2007) and its important consequences. This complexity arises at multiple scales in both space and time, resulting from the interplay of biotic and abiotic factors under the effect of both global and regional change (Schröder, 2006). The interplay of human and natural capital represented in current agricultural systems determines multiple interdependencies between natural and anthropogenic elements; these should not be ignored if the ultimate goal is sustainable production.

A broader ecosystem-based approach to food security has been advocated to avoid major negative repercussions to human

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societies (Richardson, 2010; Steinfeld et al., 2006; Thiaw et al., 2011; Poppy et al., 2014). Such a shift cannot happen without methods that can make scientifically sound knowledge available to natural resource decision makers (Tallis and Polasky, 2009). While sophisticated simulation models of crop production have been developed, most of them do not account for the whole range of ES, and only very few incorporate spatial aspects with an emphasis comparable to what modern ES science considers crucial (Bagstad et al., 2013a; Villa et al., 2014). Earlier agricultural system models focusing on individual processes have later adopted a more holistic system dynamics approach (Belcher et al., 2004) but stopped short of becoming spatially explicit and of incorporating more fully ES-relevant processes. Examples of such models are EPIC (Williams et al., 1985); CERES (Ritchie et al., 1986); CREAMS/GLEAMS (Knisel, 1980; Leonard and Knisel, 1987); CENTURY (Metherell et al., 1993; Parton et al., 1987) and APSIM (Holzworth et al., in press).

More recent studies have attempted to address agro-ecosystem sustainability by integrating multiple models representing agricultural systems in a multi- or inter-disciplinary manner (e.g. Jones et al., 2003) and, in a few cases, have shown the ability to generate spatially explicit outputs by connecting to geographical information systems (GIS) (e.g. Lorentz et al., 2013; Koschke et al., 2013). Such results exemplify the usefulness of pursuing an integrated approach to the management of certain ES affecting agricultural systems. These approaches often link existing models dynamically or through meta-modeling (Lotze-Campen et al., 2008). However, significant challenges remain. Firstly, attempts to model non-linear systems are hampered both by lack of data and the difficulty of accounting for integrated response relationships, pointing to the need to capture uncertainties in both quantitative and qualitative information. Secondly, generating reliable solutions for multi-disciplinary problems is rarely possible with just one type of model. Deep model integration combined with model inter-comparison rules is therefore necessary.

This article describes the application of the *semantic meta-modeling* approach (Villa et al., 2014) to the study of ES trade-offs connected with agricultural production and food provision. The importance of ES and the need for a deeper understanding of their relationships with agricultural systems are explained further in this section. In Section 2 we introduce the methodological premises of our approach, we describe the regional context of analysis and the sub-models composing the integrated model. After illustrating results of sensitivity analysis for the Bayesian model employed, Section 3 presents the results of modeling scenarios of relevance for the region, both in an aggregated and a spatially explicit fashion. The concluding Section 4 discusses the results in the light of the methodology employed, highlighting key messages and listing some of the issues not addressed in this paper for further investigation.

1.1. *Ecosystem services: foundations*

As early as the middle of the 19th century, several prominent naturalists, ecologists and economists began to recognize the "life-support" functions of ecosystems (Coase, 1960; Helliwell, 1969; Krutilla, 1967). By the 1970s the term "environmental services" was being used to describe benefits people receive from well-functioning ecosystems, such as food, pest control, flood control, climate regulation, and recreation (Meyerson et al., 2005). Despite a rapid increase in studies of ecosystem goods and services, a systematic typology and comprehensive framework for integrated assessment and valuation of ecosystem functions has been slow to emerge (De Groot, 2002). A structured approach to ES was successfully used in the Millennium Ecosystem Assessment (MA, 2005) which integrates the discourse on biodiversity conservation and sustainable development (Tallis et al., 2008). The definition of Ecosystem Services used in the MA, now widely adopted, is the starting point for the refined perspective brought forth by the global initiative "The Economics of Ecosystems and Biodiversity" (TEEB), which defines ES as the "flows of value to human societies as a result of the state and quantity of natural capital" (TEEB, 2010). The key MA (2005) findings noted that over 60% of ES were already globally degraded and 15 of the 24 ES investigated were in a state of decline, with negative implications for human welfare.

The MA (2005) recognized four categories of ES:

1. Supporting (e.g. nutrient cycling, soil formation and primary production);
2. Provisioning (e.g. food, fresh water, wood and fibre and fuel);
3. Regulating (e.g. climate regulation, flood and disease regulation and water purification); and
4. Cultural (aesthetic, spiritual, educational and recreational).

Supporting services comprise the ecological functions necessary for the production of all other ecosystem services. Provisioning services that are generated by ecosystems are usually harvested for use by people. Regulating services are the "eco-physiological functions and ecosystem processes" necessary to maintain the functioning of ecosystems, and they directly or indirectly regulate the production of provisioning services. Cultural services represent non-material benefits and non-consumptive use values derived from ecosystems (Elmqvist et al., 2011). More recently (e.g. Haines-Young and Potschin, 2010), the "supporting services" category has been recognized as flawed due to the potential for "double counting" of service values (Boyd and Banzhaf, 2007; Wallace, 2007; Fisher et al., 2008) and it is being abandoned in favor of a more beneficiary-related perspective (Villa et al., 2014).

The concept of ES clearly implies an anthropocentric perspective although ecosystem functions encompass different combinations of processes, traits and structures and represent the potential that ecosystems have to deliver services, irrespective of their utility to humans (Braat and De Groot, 2012). At the same time, the metrics used to assess the potential of ecosystems to provide services and to determine the levels of services that are provided as benefits to humans can also be used to assess the health of ecosystems per se (Palmer and Febria, 2012; Haines-Young and Potschin, 2010).

1.2. *Ecosystem services and agricultural systems*

MA (2005) notes that by 1990, 35% of the Earth's land surface was being used for agriculture. Conservative estimates reveal that globally, approximately six million hectares of land are converted from natural state to crop land every year (Deininger and Byerlee, 2011). Nevertheless, because land is a non-renewable resource, extensive use of land for agriculture severely affects the generation of many other ES. Indeed, the expansion of modern agriculture, including livestock rearing, is a major driver of global environmental change, through impacts on land use, land cover, water balance, water quality, pollination, nutrient cycling, soil retention, carbon sequestration, climate regulation and biodiversity (FAO, 2007; Gordon et al., 2010; Nellemann, 2009).

Some of the detrimental impacts discussed in the literature are:

1. The effect on the availability and mobility of nutrients over large regions of the Earth due to the massive use of nitrogen and phosphorus fertilizers (Vitousek et al., 1997) and the subsequent pollution of air, water and land, causing human health problems (Galloway et al., 2004; Sutton et al., 2013);