Policy Briefings

BASQUE CENTRE FOR CLIMATE CHANGE
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MODELLING ECOSYSTEM SERVICES TRADE-OFFS IN AGRICULTURAL SYSTEMS

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Key Points

- *Agriculture is a source of provisioning, regulating and cultural ecosystem services, and depends on them to function.*
- *Reducing negative trade-offs and identifying potential synergies between ecosystem services demands a better understanding of the impact of farm management on their provision.*
- *An ecosystem-based approach to food security is advocated to avoid major negative repercussions to society.*
- *Novel methods such as semantic meta-modelling are necessary to improve ecosystem services management*
- *In Álava, it is possible to significantly reduce emissions using informed farming practices.*

Introduction

Although agricultural ecosystems can provide humans with many varied benefits, agricultural system management is mainly driven by food production. Consequently, the need to ensure food security globally has been accompanied by a significant decline in the state of ecosystems on which it depends. It is essential to improve our understanding of the relations between various Ecosystem Services (ES), as well as the impacts of farm management on their provision, to reduce negative trade-offs and identify potential synergies. Capturing and quantifying ES trade-offs in agricultural systems provides the means to implement more effective agricultural subsidies and operational programmes such as the Common Agricultural Policy (CAP) or Payment for Ecosystem Services (PES) voluntary schemes. Last but not least, the strategy to cope with the effects of Climate Change (CC) in the Basque Country (PVCC 2015) recently published by the Department of the Environment, demands an integrated assessment to develop operative mitigation and adaptation policies to manage the impacts of CC on all economic sectors.

By 2012, around 40% of the Earth's land surface was being used for agriculture. Conservative estimates reveal that globally, six million hectares of land are converted from natural state to crop land every year. As land is a non-renewable resource, extensive use of land for agriculture severely affects the generation of many other ES. Modern agriculture expansion 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.

Certain detrimental impacts from agriculture 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 and the subsequent pollution of air, water and land;
2. The damage to productive land brought by soil erosion and degradation, causing food insecurity, where access to nutrients is scarce or where extensive tillage is practiced, especially when combined with removal or in situ burning of crop residues;
3. The contribution to 19%-29% of global anthropogenic greenhouse gas (GHG) emissions primarily through methane and nitrous oxide emissions and secondarily through the use of fossil fuel for fertilizer production;
4. The effect on water resources: water withdrawals from rivers and lakes doubled globally since 1960, of which almost 70% was used for irrigation.

These impacts are likely to become exacerbated in the future, with on-going population growth and a growing middle class that will determine an increasing demand for food.

This Policy Briefing describes the assessment of certain ES including crop yield, water supply and quality, climate regulation and air quality for crop systems, using the Llanada Alavesa in the Basque Country as case study. Semantic meta-modelling (Villa et al. 2014), a technique enabling the flexible integration of models to overcome the service-by-service modelling approach traditionally applied to the assessment of ES, was used. An extended version of this research is available at Balbi et al. (2015).

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2- Why model trade-offs?

As the diagram in Figure 1 shows, agricultural systems constitute a source of provisioning, regulating and cultural ES, whilst at the same time being highly dependent on them in order to function. Furthermore, certain agricultural management practices greatly impact service-producing ecosystems, as in the case of intensive farming or intensified food production. To ensure a sufficient supply of food for all, a careful balance has to be struck between an agricultural system and its underlying ecological supporting framework.

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. This has resulted in encouraging a broader ecosystem-based approach to food security, so as to avoid major negative repercussions to human societies. Such a shift cannot happen without methods that can make scientifically sound knowledge available to natural resource decision makers. Any approach adopted must provide the means to capture the uncertainties in current quantitative and qualitative information, together with sound model integration mechanisms.

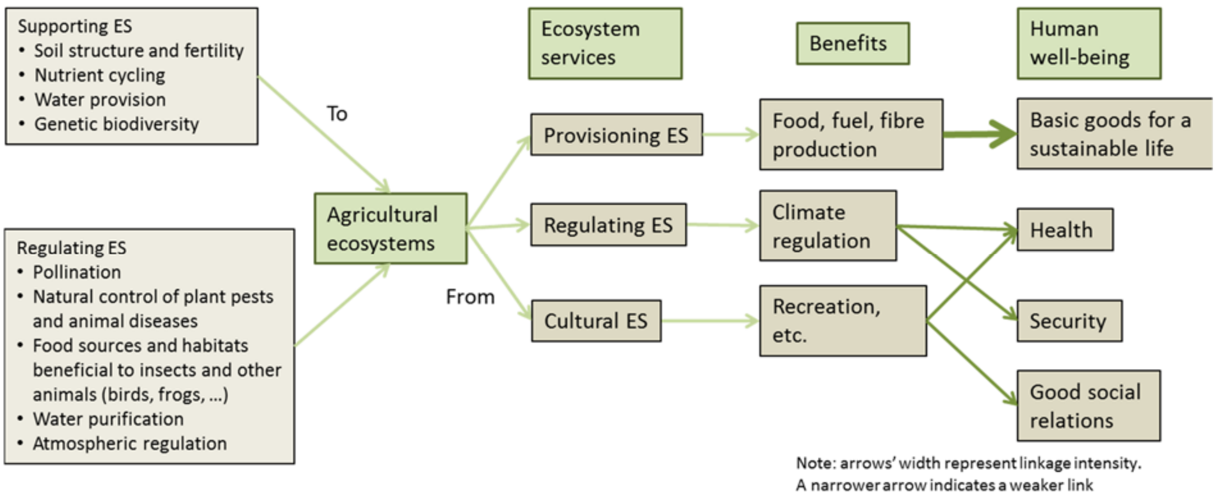

Figure 1 Food and Ecological Security: Identifying synergy and trade-offs ("To" arrow represents a supporting ES for Agriculture, "From" arrow represents supporting ES "provided by" Agriculture), (adapted from UNEP Policy Series 2011)

Traditional frameworks to account for the value of ES have been challenged for their inadequate understanding of the specifics of what these services constitute and for market failures in capturing their value. Flows of ecosystem services connect stocks of natural capital produced by ecosystems to societal groups that need them. In order for such flows to exist, the capability of the ecosystem to produce benefits needs to be complemented with that of delivering them.

To address ecosystem service flows in a consistent manner, the ES should be expressed in terms of their effects on human well-being derived through the flow of benefits from an ecosystem endpoint to a human endpoint at given extents of space and time. Semantic meta-modelling is an approach designed to overcome the modelling constrains outlined. The solution developed enables the study of ES trade-offs connected with agricultural production and food provision. The results highlight the importance of ES, the need for a deeper understanding of their relationships with agricultural systems and demonstrate its applicability to policy formulation.

Needs expressed by regional authorities, together with consolidated direct knowledge of the region explain the choice of location for the case study. The key land use types are natural forest (38%) and agriculture (35%), with some semi-natural grassland distributed between them. The agricultural surface is predominantly (92%) composed of rain-fed cereal crops (wheat, barley, oat), and some irrigated potato and sugar beet crops. The use of manure and fertilizer is restricted in about 30% of cases to comply with nitrate vulnerability legislation. The climate is temperate-humid Mediterranean.

3- Quantifying trade-offs in Agriculture

Figure 2 shows the conceptual model developed to capture important ES trade-offs in an agricultural landscape. It provides the means to analyse the effects of farming practices and local environmental conditions on several ES of importance to the case study:

1 .Crop production (winter wheat yield – Kg/(ha*y))

2. Water quality (nitrate leaching (mg/l) and phosphorus losses (Kg/(ha*y)) from the agricultural soil)

3. Climate regulation (soil carbon storage and nitrous oxide emissions - KgCO2e/(ha*y))

4. Air quality (ammonia pollution - Kg/(ha*y))

Farming practices covered include irrigation, tillage, and application of both organic and mineral fertilizers. Environmental conditions replicated include soil characteristics, precipitation and above ground temperature. Each ES is developed as a stand-alone module, all modules share input variables and are linked by the infrastructure, making the overall model responsive to scenarios in an integrated way. Choices of farming practices and environmental conditions can affect the ES production in non-trivial ways. For example, increasing the use of fertilizer affects crop yield positively but also affects climate regulation services negatively through the indirect emissions derived from the manufacture of fertilizer, which results in an increase of the sector's carbon dioxide (CO2) footprint.

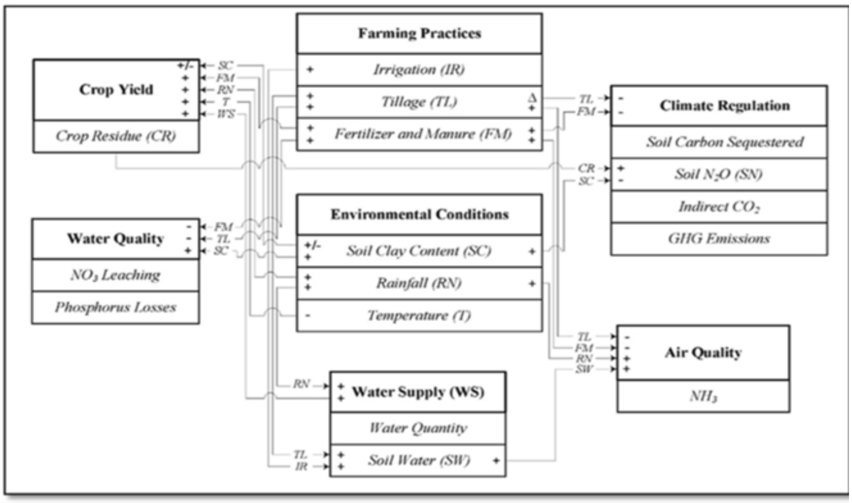

Figure 2 Conceptual model adopted for this study. Rectangles in bold line represent main model components and regular rectangles sub-modules; each label includes an acronym that is used to identify the interactions. The sign "+" means "More of"; the sign "-" corresponds to "Less of"; and the delta symbol "Δ" should be read as "Change in (tillage practice)".

In addition to being sensitive to similar inputs, different ES have interdependencies that demand more trade-offs. For example, increased crop yield will negatively affect climate regulation services through an increase of soil nitrous oxide (N2O) emissions due to larger amounts of plant residue. Other interactions modelled are:

• The effect of water supply on crop yield, through rain and irrigation;

• The effect of soil water on ammonia (NH3) emissions.

The combined effects of ES are expressed as semantic dependencies in the modules. These were mapped to input/output relationships in the final integrated model assembled by the infrastructure, connecting models to data and models to models.

4- Model results

The effectiveness of the model to support decision making was tested using input data from two historical periods (1997 and 2007) in which widely different wheat crop yields were recorded. A summary of certain model outputs is listed in Table 1. An initial analysis showed manure usage, precipitation and soil type are the inputs which explain most of the outputs variation (3rd col, Table 1). A second stage of analysis demonstrated how the three most influential inputs affect the outputs variation over the entire variation attributed to the inputs. The rate of influence (4th col, Table 1) is the percentage of overall variation that can be attributed to each input. For crop yield, the ranking shows manure usage is the most influential input, with a 62% normalized rate of influence.

Module output	Most influential input factors	Coefficient of variation	Normalized rate of influence
Carbon Stock Change *(Climate Regulation: C sequestration BN)*	Tillage Management Change	0.38	60%
	Manure Usage	**0.2**	**32%**
	Manure Type	0.02	4%
Nitrate Leaching Concentration *(Water Quality: Leaching BN)*	**Soil Type**	**0.23**	**59%**
	Manure Usage	**0.07**	**17%**
	Fertilizer Usage	0.05	12%
	Tillage	0.04	11%
Phosphorus Loss *(Water Quality: Plosses BN)*	**Manure Usage**	**0.13**	**47%**
	Soil Type	**0.13**	**47%**
	Fertilizer Usage	0.02	6.30%
N2O Emissions *(Crop Yield BN)*	**Soil Type**	**0.63**	**74%**
	Manure Usage	**0.21**	**22%**
	Water Availability	0.02	2.10%
Yield *(Crop Yield BN)*	**Manure Usage**	**0.14**	**62%**
	Precipitation	0.03	16%
	Soil Type	**0.014**	6%

Table 1: Sensitivity analysis output for probabilistic model components- Column 1 includes each Bayesian network (BN) used (network name). In column 4, 100% is the sum of the coeficient of variations of each input factor.

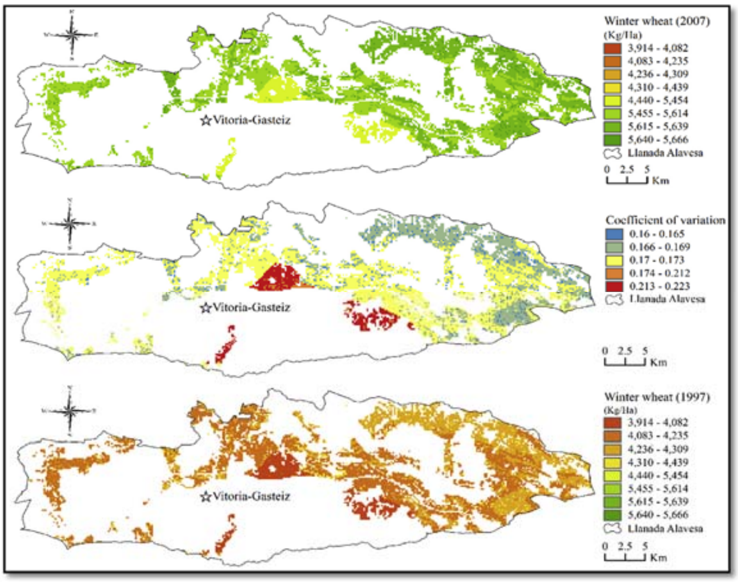

Figure 3 (a) Yield estimates for winter wheat with tillage and maximized manure usage with favourable environmental conditions (year 2007). (b) Uncertainty (coefficient of variation) associated with the estimates of a. (c) Yield estimates for winter wheat without tillage and minimized manure usage with suboptimal envi-

Figure 3 presents the wheat yield outputs for two scenarios. The first comprises maximum manure usage and good environmental conditions (Fig. 3a, sufficient rain, adequate temperature in critical period for 2007). The second demonstrates the effect of minimum manure usage and suboptimal environmental conditions (Fig. 3c, insufficient rain, high temperature in critical period for 1997). The simulations show an overall increase in wheat yield of 20% for 2007. The map in Fig. 3b includes the level of uncertainty associated to the outputs. For these same scenarios the model estimated an overall emissions reduction of approximately 400-500 Kg CO2e/(ha*year).

Additional outputs demonstrate:

1. The feasibility of a significant emissions reduction by changing practices of manure application.

2. The cost of reducing ammonia emissions, nitrate leaching concentration and phosphorus losses, through a timely and measured manure application to the field, in terms of significant potential yield reduction.

3. The possibility of increasing the rate of carbon sequestration in the soil by moving from a conventional tillage practice to limited tillage. The results suggest that this change does not translate into significant reductions on yield, at least in the case of winter wheat.

4. An additional benefit of non-tillage farming, linked to significant reductions of nitrate leaching concentration.

The results constitute a proof of concept, which demonstrate the added value of adopting a modular and complexity-aware perspective, to describe agricultural systems.

The challenges posed by global change call for a more comprehensive view of the issues related to agricultural production, shifting focus from mere yield maximisation to a paradigm more broadly oriented to sustainability. In this light, urgent needs related to food security at the global level should be tempered with the awareness of the dependence on and the impacts of agricultural practices on all other ES.

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