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Learning how to model ecosystem trade-offs at the farm scale

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Abstract: The ecosystem service framework provides a forum for scientists from a range of disciplines to communicate and work together alongside other key stakeholders. However to be effective, place-based comparison of the tradeoffs of ecosystem services need further development. These place-based comparisons are vital in agricultural systems due to the increasing global demand for food production, coupled with the realization that this should be achieved with minimal negative impact on the environment. The farm is the logical unit of management in agricultural systems and hence there is a need for ecosystem tradeoff assessments at the farm scale. We have carried out a literature review of the tradeoffs in the delivery of ecosystem services from intensively managed temperate grassland systems. Building on this work, we are now setting up a farm scale experiment to examine the tradeoffs, identified from the refereed literature, as requiring further investigation due to either limited or conflicting evidence. To facilitate an improved understanding of these tradeoffs we need to learn how to model them, based on previous and current modelling frameworks and coupled with improved knowledge of international best practice. Fundamentally, this requires a dialogue between modellers and field scientists.

***Keywords**:* legume; grassland; technology; water; greenhouse gases

1 INTRODUCTION

Agricultural land is one of the largest terrestrial biomes on the planet [Foley et al. 2005], and it is expected to expand over the next decade, driven by an increased demand for both food and bioenergy [Steinfeld and Wassenaar 2007]. This increase in the level of food production must be carried out in a sustainable and equitable manner [Firbank 2005, Godfray et al. 2010]. Evidence shows that we can no longer give priority to meeting contemporary human needs at the expense of future requirements [McIntyre et al. 2009, Millenium Ecosystem Assessment 2005a, b]. Therefore it is essential that we learn how to increase food production whilst minimizing impacts on other intermediate and final ecosystem services, so these conflicts and trade-offs can be managed more effectively [Foley et al. 2005, Raudsepp-Hearne et al. 2010]. Ecosystem service (ES) is increasingly being adopted as a common language for ecosystem-based management e.g. coastal ecosystem management [Granek et al. 2010]. The Millennium Ecosystem Assessment [2003] has resulted in policy makers adopting the ESs approach in the UK [Defra 2007]. Subsequently this has led to an assessment of the ESs provided by different habitats, both semi-natural and intensively managed across the UK [UK National Ecosystem Assessment]. Furthermore, a recent review of the relationships between land use and biodiversity as part of the UK Land Use Foresight Initiative concluded that the main scientific challenges were to develop more robust monitoring approaches to provide both more data and opportunities to advance our ability to model these relationships [Haines-Young 2009].

Intensively managed grassland systems (IMGS) are characterized by their high levels of inorganic and organic fertilizer inputs, perennial vegetation, presence of livestock (sheep and cattle) and in general socio-economic, physical or climatic characteristics that make the land unsuitable for annual cultivation. In addition to producing food, fiber or bioenergy, it has become apparent that IMGs lead to significant losses of nitrogen [Scholefield et al. 1993] and phosphorus [Hawkins et al. 1996] to nearby water bodies, as well as gaseous emissions of methane [Jarvis and Pain 1994], nitrous oxide [Jarvis et al. 2001] and ammonia [Denmead et al. 1974]. The emphasis on increased production has also had a negative impact on biodiversity, reducing the amount of wildlife associated with the farmed landscape [Hooper et al. 2005]. The majority of studies to date have examined impacts of agricultural production on individual ecosystem services from a single disciplinary perspective. However, there is a need for more holistic, systems-based assessments from the plant to global scales.

In this paper we review the literature in support of carrying out a farm scale experiment on the tradeoffs between ESs within temperate IMGS. We seek to learn how previous studies of ES tradeoffs have been modelled and how to adapt these approaches to meet our aims. The second aim of this paper is to present a farm scale ecosystem tradeoff experiment and discuss how we may model these in addition to the structures and processes that control the ecosystem functions we propose to model.

2 LITERATURE REVIEW

2.1 Farm scale assessment of ecosystem services provided by intensively managed temperate grassland systems

Here we review previous modelling studies of multifunctional agricultural systems and ES tradeoffs to help guide our planned modelling of ES tradeoffs at the farm scale. At the farm scale the modelling of a complete range of ESs has not been fully developed. However, there has been a widespread interest in modelling the multi-functionality of agricultural systems e.g. [Keating et al. 2003, Renting et al. 2009, Van Ittersum and Brouwer 2009]. The farm scale is a logical scale to guide management and modelling activities of agricultural production and interaction with wider ESs. However, there are relatively few farm scale monitoring and modelling studies in the literature. One example is the De Marke system that was established in the 1980s to design and test ways to increase milk production whilst meeting environmental limits on nutrients emissions in the Netherlands [van Keulen et al. 2000]. The result was to make better use of manures leading to a 74% reduction in mineral nitrogen fertilizer use and a balancing of the inputs and outputs of phosphorus. The Agricultural Production Systems Simulator (APSIM) modelling framework has been developed in Australia by CSIRO over the last 20 years. Since 1991 APSIM has been developed to include modules for a wide range of arable crops in addition to pastures and trees, biogeochemical processes controlling nitrogen and phosphorus cycling, water balance and soil erosion under an extensive range of management options. An overview of the APSIM modelling framework, its implementation and testing is given in Keating et al. [2003]. Recently, there have been calls for farm scale experiments to enable the impacts and trade-offs to be studied [Garcia et al. 2008]. Previous attempts to model farm scale impacts of IMGS include: assessing the nitrogen budgets of multiple farms using a suite of models [Cuttle and Jarvis 2005], comparing models of greenhouse gas emissions [Schils et al. 2007] and a broader assessment of IMGS sustainability [Del Prado and Scholefield 2008]. These later assessments have not been fully integrated with farm scale experiments. The $SIMS_{DAIRY}$ modelling framework [Del Prado and Scholefield 2008] integrated existing models of nitrogen [Brown et al. 2005] and phosphorus [Davison et al. 2008] cycles, equations for losses of ammonium and methane, livestock nutrient requirements, and 'score matrices' for measuring soil quality, animal welfare, biodiversity and landscape quality alongside an economic model. It models seasonal grazing and livestock housing during the closed period i.e. winter months. The breadth of the $SIMS_{DAIRY}$ model enabled a more holistic assessment of the trade-offs of livestock production with wider ESs across the UK [Del Prado et al. 2009].

With the current trend for land to be managed to enable the delivery of multiple ES, there is an increasing need to learn more about the interactions resulting from the delivery of a number of ESs [Pilgrim et al. in press]. However, as these ESs are not independent from each other, there could be many unintended consequences if we manage an area of land for one ES without accounting for these relationships [MA, 2005]. Improving our understanding of these interactions will reduce the risk of producing negative trade-offs, squandering potential win-win scenarios and possibly experiencing dramatic and unexpected changes in the provision of ESs [Bennett et al. 2009]. Increasingly we are recognizing that place based assessments are needed to examine such trade-offs [Carpenter S. R. et al. 2009, Gordon et al. 2010].

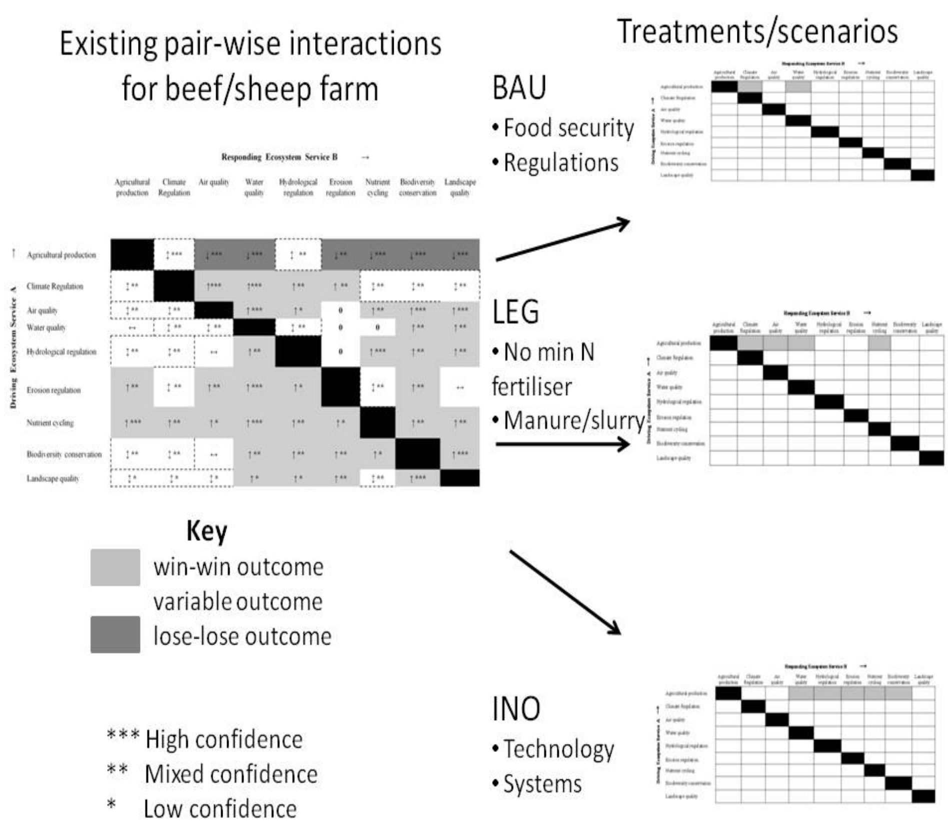
Previous studies in modelling ecosystem service trade-offs were focussed on spatial scales larger than individual farms. Two examples are the development of the Patuxent landscape model [Costanza et al. 2002] and more recently modelling of a peri-urban environment [Raudsepp-Hearne et al. 2010]. In both of these studies GIS were used to enable spatially explicit assessment of the ESs. Costanza et al. [2002] used a grid based land use parameterisation of a systems dynamic (using Stella graphical modelling software) model of biophysical processes linked to an economic land conversion model. One main improvement the authors raised was the need to develop a spatially explicit modelling approach that was less reliant on coupling to a GIS. Costanza et al. [2002] suggested that through the use of a spatially explicit modelling framework e.g. Modular Modelling Language [Maxwell and Costanza 1995] then the importance of processes that operate at differing scales could be examined more readily. The Simile visual modelling language has also been widely applied in agricultural systems [Muetzelfeldt and Massheder 2003]. Whilst these systems dynamics-based approaches are very useful for non-modellers to pull together their understanding of a particular system, like all approaches they have their drawbacks. It has been observed that any user of these approaches needs to be aware of the mathematics that sits behind the interface as differing results can be obtained with different packages [Seppelt and Richter 2005]. These graphical modelling languages do have limitations, for example it can be difficult to use the Simile modelling language to model fluxes between model components. One way around this may be to couple more detailed process based models (when we have the knowledge and data to parameterise these) with a graphical modelling language.

Though there are benefits in valuing ESs in monetary terms to support decision making, there are additional problems in their valuation e.g. there may not always be a market or the methods of valuation have been applied inappropriately) [Turner et al. 2010]. Traditional models of agricultural systems have focussed on ecosystem functions. An example is the Functional Assessment of Wetlands developed by Maltby et al. [2009]. This approach can be applied by both experts and non-experts and enables the assessment of the functions (which equate to services) a wetland is performing. It is a field and desk based exercise using a hydrogeomorphic unit approach, breaking the landscape down into features based upon their hydrology, geomorphology and soil type. It takes into account the spatial patterns and occurrence of landscape features, and allows the assessment of hydrological, biogeochemical and ecological functions. This type of approach to assessment of ESs could easily be adapted for other ecosystems, and provides a relatively rapid, widely applicable assessment tool, enabling better strategic land use and site-specific management decisions to be made, particularly at the farm scale. It has also been developed further to enable social and economic valuation of the functions and services assessed.

3 CASE STUDY: A FARM SCALE ECOSYSTEM SERVICE TRADE-OFF EXPERIMENT

In a recent review investigating the interactions among agricultural production and other ESs delivered from European temperate grassland systems Pilgrim et al. [in press] studied pair-wise interactions between the delivery of nine different ESs, namely: agricultural production, climate regulation, air quality regulation, water quality regulation, hydrological regulation, soil erosion regulation, nutrient cycling, biodiversity conservation and landscape quality (Figure 1). For each pair, the authors sought information on how each ES responds to changes in the other. Negative relationships resulted only from the effects of increasing the intensity of agricultural production on other ESs. Furthermore available evidence infers that erosion regulation and good nutrient cycling were the only two driving ESs shown to enhance agricultural production implying that their protection will enhance our ability to meet future food needs [Pilgrim et al. in press]. In contrast, the set of interactions between ESs reported to be variable included relationships amongst atmospheric, hydrological and landscape functions. Much of this variability is probably due to inconsistent effects across spatial and temporal scales and because the evidence base is weaker here than for some of the other interactions.

Figure 1 Existing and future ecosystem trade-offs for the three farm scale treatments.

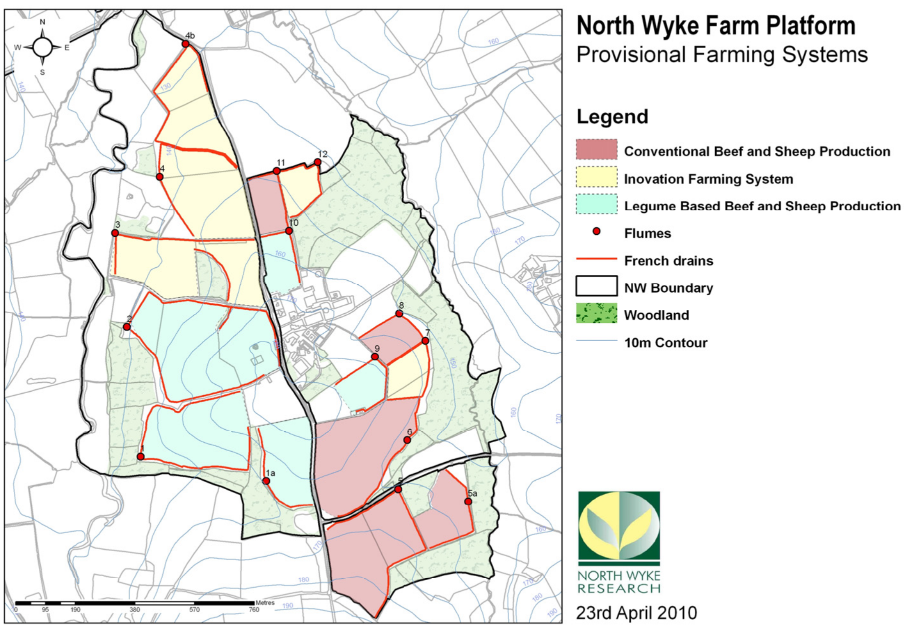


The study by Pilgrim et al. [in press] has highlighted the need for a farm scale experiment so we can truly asses the trade-offs between key final ESs and to design a farming system that delivers productivity whilst minimising wider environmental impact, i.e. sustainable intensification [The Royal Society 2009]. To address these needs we are in the process of establishing a farm scale experiment that will enable the assessment of trade-offs between key final ESs. This concept, known as the farm platform, is still under development, so here we report on progress to date. The idea of a farm platform is to compare different ways of managing agricultural production and a wide range of agri-ecosystem properties at appropriate farm scales (i.e. at the scales of land management and farmer decision making). A farm platform should enable detailed studies of sustainable land management systems and of the processes that underpin them, within a well-resourced, collaborative and integrated research environment. There has been an extensive consultation (with 41 questions) with the wider scientific community and a broad range of key stakeholders based on the following topics: questions about the concept e.g. How should the development of the platform be co-ordinated with the development of other national and international programmes? Detailed questions about the experimental protocols e.g. What are the most appropriate treatments? and questions related to how can people get access to the platform, and what facilities are required e.g. What are the critical facilities for users, both on-site and off-site, bearing in mind costs as well as benefits?

3.1 North Wyke research station

The site of the proposed farm scale ESs trade-off experiment is an intensively managed grassland farm in the South West of England ($50^0$46'N, $3^0$54'W). The underlying geology is Carboniferous Crackington Formation which comprises clay shales with thin subsidiary sandstone bands. The shales break down to form clay with an illitic mineralogy. The two dominant soil series at North Wyke are Halstow (typical non-calcareous pelosols [Avery 1980], aeric haplaquept (USDA)) and Hallsworth (peolo-stagnogley [Avery 1980], typic haplaquept (USDA)) [Harrod and Hogan 2008]. The mean annual rainfall recorded is 1056 mm with 664 mm occurring between October and March with a mean excess winter rainfall of 562 mm. The grazing season is restricted to approximately 180 days due to soil wetness even though there are on average 280 days with temperatures above 6ºC to sustain plant growth. The average annual temperature is 9.6 ºC. Currently the farmland is used for rearing cattle for beef and sheep. The total area of land proposed for the farm platform comprises 68.4 ha, and it is suggested that this is sub-divide into three areas each approximately 22 ha in size (Figure 2). These farm units will be hydrologically isolated based on dominant surface topographic drainage to enable the measurements of water quantity and quality. It is expected that there will be three treatments that will be set up as individual livestock farms with linked housing phases to test the hypothesis that 'grassland systems can be designed and managed to deliver maximum sustainable production (product/unit area/unit animal) with reduced impacts on the environment'.

Figure 2 Map of the proposed farm scale ecosystem service trade-off experiment.



The proposed experimental design will provide evidence of the ES trade-offs of: i) conventional sheep and beef rearing (business as usual) which will follow current (e.g. nitrate vulnerable zone) and future (e.g. reduced greenhouse gas emissions) regulatory constraints whilst pursuing maximum productivity, ii) making better use of manures and legumes to fix nitrogen to eliminate mineral additions of nitrogen that are expensive to the farmer and to the wider environment due to the increased risk of leaching losses of nitrate and N_2O emissions. The breeding of new forage legumes have been shown to have the potential to deliver multiple ESs in the way of reduced pollution of air and water by nitrogen, increase productivity, increase biodiversity and help adapt to a changing climate through increased tolerance of periods of water deficit [Marshall et al. 2007] and iii) a treatment that will make use of more innovative technological options e.g. new forage cultivars to reduce runoff [Macleod et al. 2007] and the risk of soil erosion [Grime et al. 2008]. This could involve close alignment with work currently underway in New Zealand, to assess the benefits to grazing cattle by improving the sustainability of intensively managed swards; namely by sowing of *Trifolium pratense, Plantago lanceolata* into a grass sward containing a range of different grass species (e.g. *Lolium perenne, Festuca pratensis*) with different rooting depths. This could enhance a number of ESs namely i) biodiversity by creating habitats and a food source for a range of insect and bird species ii) improve soil nutrient cycling by planting species associated with soil fungal growth and iii) agricultural production since the antihelmintic properties arising from a range of forage can benefit livestock health and performance (Katherine Tozer, Project Manager Agresearch, Pers. comm.). The overall aim is to create an experimental platform for integrative and multidisciplinary scientific studies to gain a much greater understanding of the complex interactions involved in the delivery of sustainable agricultural production.

4 DISCUSSION

All ESs, but especially those occurring at large spatial or temporal scales, are more likely to be traded-off, as there are no international mechanisms or incentives to protect them [Millenium Ecosystem Assessment 2005a]. However, though most ES are delivered at the local scale, their supply is influenced by regional or global scale processes [Carpenter S.R. et al. 2006]. Subsequently it is vital that management regimes which protect ESs incorporate an understanding of the scales of both space and time at which each trade-off occurs and ways to ensure that there is a balance between short and long term needs from ES [Bennett et al., 2009]. This highlights the need for, as well as the importance of, long-term monitoring to understand the influence of time, management and scale on the relationships between ESs [Carpenter S. R. et al. 2009, Gordon et al. 2010]. In modelling studies of agricultural systems the focus to date has been on assessing their multi-functional nature e.g. [Del Prado and Scholefield 2008, Keating et al. 2003]. There is a need for these approaches to be developed to be able to assess a wider set of ecosystem functions and their services to enable more holistic assessments of sustainable agricultural systems. In addition to these aforementioned empirical/process based models, the use of graphical modelling languages has enabled modellers to communicate their assessments of ES tradeoffs with field experimentalists and other stakeholders and we plan to make use of these systems dynamics tools.

5 CONCLUSION

Clearly, a better understanding of the management of ESs in agricultural landscapes is critical [Bennett et al., 2009]. This will require more experimental data to help us gain a better understanding of the outcomes of the interactions between ESs and to help mitigate their detrimental effects and to meet the challenges of increasing food production. We believe that the development of a new generation of models based on our understanding of the ESs of agricultural systems is required that will enable these detailed and complex interactions to be addressed in a structured way [Pilgrim et al. in press]. To enable this we are currently developing a farm scale experiment that will examine ES trade-offs. This requires assessing what modeling approaches we could adopt for a more systems based assessment in combination with the data requirements that are required to parameterise and run these model structures. These integrated modeling and field experimental activities will help us better understand the actual tradeoffs between current and future management systems for intensively managed grasslands.

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