# A combined agent-based and biophysical modelling approach to address GHG mitigation policy issues

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***Keywords:*** *agent-based simulation, socio-ecological systems, greenhouse gases, tax, incentives*

## EXTENDED ABSTRACT

Climate change is widely recognised as the most serious environmental threat facing our planet today, and a major challenge facing society is to find ways to decouple the link between economic activity and greenhouse gas (GHG) emissions. The agriculture, forestry and the land use sector is important in that not only is it a contributor to national economies, but it can act both as a source of GHG emissions as well as a carbon store, contributing in the order of about 20% of total GHG emissions, but removing about 16%. Various options for reducing the emissions of GHGs from the land use sector have been proposed, but several of these options involve a cost to the land manager, thus creating a 'social dilemma', in which individual interests of making a livelihood conflict with societal goals of reducing GHG emissions. Farmers, for example, may have to accept lower crop yields by reducing the amount of fertiliser they apply, or reducing the number of livestock they carry, so that emissions of $N_2O$ are minimised. If the societal goals are to be achieved, ways of reconciling these social dilemmas need to be found.

Agent-based modelling (ABM) is an approach that has been receiving attention as a way of linking the biophysical and socio-economic components of a system to study such social dilemmas. Advantages of the approach include its ability to accommodate multiple scales of decision-making, to incorporate individual variation in decision-making at the micro-level, and to study the emergence of collective responses to environmental management policies. The People and Landscapes Model (PALM) is a combined agent-based/biophysical model operating at the level of a catchment, and consists of a number of household agents located on a landscape made up of heterogeneous land units, each of which contains routines to calculate its water balance and carbon and nitrogen dynamics. Decisions made by the household agents result in actions which may influence the fluxes of water, carbon and nitrogen within the landscape. In this paper, we describe some initial results from the model in which we examine ways in which GHG emissions might be reduced and the impact that this may have on farmer livelihoods.

Preliminary results from the model show that GHG emissions can be reduced by economic instruments such as (a) imposition of a GHG tax, (b) providing incentives for low emitting land uses, and (c) a combination of the two. A GHG tax has the disadvantage of extracting money from the economy of the region so that average returns decline over time even though agents select low emitting land uses. An incentive scheme to reward agents selecting land uses that emit less GHGs is beneficial to the economy of the region with overall annual returns increasing over time, although this does require the influx of money from some external source. A combination of taxation and incentive, with revenue generated from taxing agents selecting land uses with GHG emissions above a threshold and distributing this to agents with land uses emitting below the threshold, would appear to be a 'cost-neutral' solution to reducing overall GHG emissions. We discuss some of the challenges facing the implementation of such schemes, including the setting of appropriate thresholds of GHG emissions, and measuring and monitoring of individual and aggregate behaviour of land managers. The transaction costs of these, particularly of the latter, along with technical issues, are factors that have so far prevented the operationalisation of such schemes.

The hypothetical landscapes we used in this study are examples of 'socio-ecological systems' (SESs) containing social, economic and biophysical components interacting together. The distribution of land uses remaining at the end of the simulation for each scenario represent 'basins of attraction' for these SESs on a 'stability landscape' (Walker *et al.*, 2004). In our case, the external imposition of emissions taxes and/or incentives seemed to shift the whole basin of attraction and the system along with it from the base line (i.e. with no tax or incentives) to another location on the stability landscape rather than moving the system from one basin into another neighbouring one, as proposed by Walker *et al.* (2004).

## 1. INTRODUCTION

Climate change is widely recognised as the most serious environmental threat facing our planet today, and a major challenge facing society is to find ways to decouple the link between economic activity and GHG emissions. The agriculture, forestry and the land use sector is important in that not only is it a contributor to national economies, but it can act both as a source of greenhouse gas (GHG) emissions as well as a carbon store, contributing in the order of about 20% of total GHG emissions, but removing about 16%. Various options for reducing the emissions of greenhouse gases from the land use sector have been proposed, including energy crops, increased C sequestration through different ground covers and land management, reducing $CH_4$ emissions from livestock, more efficient use of organic and inorganic fertilisers, and increased afforestation (Smith *et al.*, 2006b). Several of these options, however, involve a cost to the land manager (Smith *et al.*, 2006a), thus creating a 'social dilemma', in which individual interests of making a livelihood conflict with societal goals of reducing GHG emissions. Farmers, for example, may have to accept lower crop yields by reducing the amount of fertiliser they apply, or reducing the number of livestock they carry, so that emissions of $N_2O$ are minimised. If the societal goals are to be achieved, ways of reconciling these social dilemmas need to be found (Smith *et al.*, 2006a), to evaluate strategies that land managers might adopt to help reduce GHG emissions without compromising their own livelihoods

Understanding social dilemmas has been the focus of much research using agent-based models (e.g. Axelrod, 1997). Agent-based modelling (ABM) is also a promising approach to integrate social, economic and biophysical processes of landscapes (Matthews & Selman, 2006), and, indeed, several such models have been used to address issues of relevance to land use (Matthews *et al.*, 2007). However, so far, most agent-based land use models (ABLUMs) treat the biophysical environment as a relatively static entity, and do not simulate processes within it, such as soil water and nutrient dynamics. Towards this end, we have been exploring ways to link ABLUMs with existing biophysical process models to help evaluate the impact of different policies on land manager decision-making, and hence on ecosystem function, particularly in relation to C and N dynamics in soils (Matthews, 2002; Matthews & Pilbeam, 2005; Matthews et al., 2005b; Matthews, 2006). In this paper, we describe progress in developing these approaches, and their use in evaluating the impact and robustness of policies aimed at decoupling GHG emissions from economic performance.

## 2. THE PEOPLE AND LANDSCAPE MODEL (PALM)

PALM (People and Landscape Model, Matthews, 2006) simulates resource flows in a rural subsistence community and its environment, and consists of a number of households, the landscape, and livestock, all of which are simulated simultaneously on a daily time-step. The landscape is made up of a number of homogeneous land units, or 'fields', each of which consists of a number of soil layers, with each layer containing routines to calculate its water balance and carbon and nitrogen dynamics. Organic matter decomposition is simulated by a version of the CENTURY model (Parton *et al.*, 1988), while water and nitrogen dynamics are simulated by versions of the routines in the DSSAT crop models (Tsuji *et al.*, 1998). The soil processes are simulated continuously, and vegetation types (crops, weeds, trees) can come and go in a field depending on its management. Crop growth and development is simulated by a generic model based on the DSSAT crop models, and which can be parameterised for different crops. Decisions made by the households result in activities being performed, which in turn influence the flows of resources within and between farms. The numbers of households, fields and livestock to be simulated are specified by the user.

## 3. MATERIALS & METHODS

The model was set up to simulate a landscape containing 200 household agents, each with a parcel of land of 1 ha size. Two hundred land uses were also defined, each with an associated net economic return (excluding any modifications by external economic instruments such as taxation or incentives) and net GHG emission (Figure 1). For the purposes of the exploratory simulations, it was assumed that there was a general positive linear relationship between net economic return and net GHG emissions (i.e. land uses with higher returns also tended to emit more GHGs), albeit with considerable variation around this trend. Net GHG emissions were also allowed to be negative to represent those in which C sequestration was occurring (e.g. forestry), but we assumed for the time being that no land uses would produce a negative return, although, of course, in reality this may not be true. We did not define the 200 land uses specifically, but assumed that these could include different land covers (e.g. agricultural, forestry, etc.) as well as different uses within a specific land cover (e.g. wheat, pasture, etc.), and different management practices within a specific land use (e.g. differing levels of fertiliser). Each of the 200 land uses was allocated to a specific parcel at the beginning of the simulation, but the land use of a parcel could change during the course of the simulation depending on strategies followed by the household agents. Thus, Figure 1 represents a 'stability landscape' (Walker *et al.*, 2004), or solution space, with the goal of this study being to identify ways of moving land uses chosen by the households from one region of this landscape to a more desirable region in relation to GHG emissions. As such, the units of the axes in Figure 1 should be seen as indicative rather than precise values.

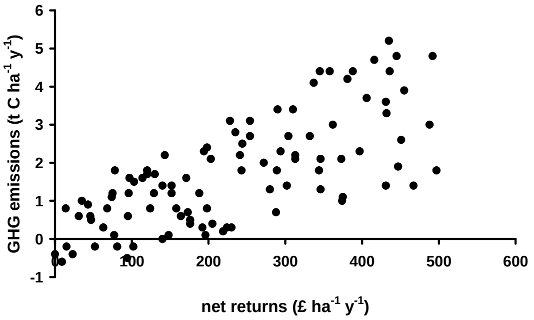

**Figure 1: Relationship between economic returns and GHG emissions of the 200 abstract land uses used in the simulations.**

Households and their parcels were allocated randomly on the landscape. Simple social networks were established between the agents, in which each agent could interact with a specified number of its nearest neighbours. For the purposes of the simulations reported here, each agent was allowed three neighbours. Agents could also be allocated at random one of three 'world-views' – (a) one in which 'profit maximisation' was their goal, (b) one in which 'social responsibility' was the only factor influencing decisions, and (c) a 'social pressure' one in which profit maximisation was the 'default' goal, but this could be overridden depending on what neighbours were doing. Each agent also had an 'aspiration level', representing the level of return from their parcel below which it would consider switching to another land use (Gotts *et al.*, 2003).

At each time-step, agents examined the return they obtained from the current land-use of their patch, and if it was below their designated aspiration level, they chose another land-use according to a set of rules depending on their world-views. Agents with the 'profit maximisation' world-view would select the land-use in their social network giving the highest economic return regardless of its GHG emission level, while those with the 'social responsibility' world-view would select the land-use in their social network with the lowest GHG emission level regardless of its economic performance. Agents with the 'social pressure' world view would tend to select the land-use in their social network giving the highest economic return unless the majority of neighbours (i.e. two or more) had a lower emitting land-use, in which case they would select the one of these two land-uses that gave the higher economic return. Thus, all land-use change was through imitation of neighbours according to different rules (Polhill *et al.*, 2001). If no neighbours in an agent's social network had a more desirable land-use than its current one, it would retain the latter. However, to represent farmer experimentation and avoid 'lock-in' to local optima, a household was selected at random at each iteration and allocated a random land use from the total possible.

The model was set up to investigate four scenarios. In the first of these, the baseline scenario, no taxes or incentives were applied throughout the simulation. In the second, it was assumed that there was a steadily increasing GHG tax imposed by the government from 2020 onwards, rising at £1.50 tC$^{-1}$ per year to £140 tC$^{-1}$ by the year 2100. In the third scenario, it was assumed that the government paid a steadily increasing incentive for every carbon-equivalent tonne of GHG emitted below a threshold of 4 t C ha$^{-1}$. In the fourth scenario, a redistributive tax was applied, in which a threshold of GHG emissions was set based upon the average emissions across all parcels of land the previous year. In the current year, any land-uses that emitted GHGs above the threshold were taxed according to the magnitude of the difference, and the total tax collected in this way then redistributed *pro rata* to agents with land-use emissions below that level. For each agent, taxes or incentives were subtracted or added appropriately from the base returns shown in Figure 1 for its selected land-use to give an actual economic return upon which it based its choice of land use in the following year. This ensured that it was not just payments *per se* that determine decisions, but that the opportunity cost of alternative land uses was also taken into account.

Simulations started from the year 2000, and were run for 100 years until 2100. The year 2020 was chosen as the starting date for the interventions to allow the model 20 years of 'settling down'.

## 4. RESULTS

Results of the simulations are shown in Figure 2, Figure 3 and Figure 4. For reasons of space, only results for scenarios 2, 3 and 4 are shown. In the scenario with the steadily increasing GHG tax (Figure 2), there was a general decline in overall GHG emissions from 3 t C ha$^{-1}$ down to a level of 1.5 t C ha$^{-1}$ after about 30 years as agents selected lower emitting land-uses. Beyond that, despite the GHG tax still increasing, there was no further reduction in emissions, as this value represented the lowest emissions possible for the highest return (Figure 1). Overall annual income of the agents, however, declined throughout the period, as might be expected with money being increasingly extracted from the system through taxation.

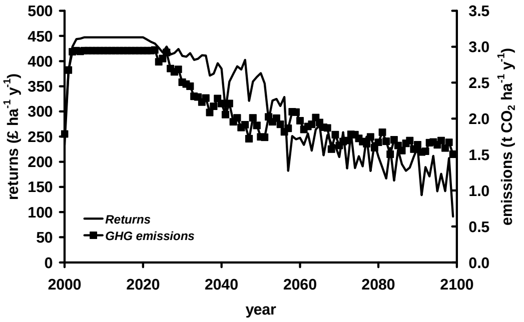

**Figure 2: Effect of a steady increasing tax from 2020 on GHG emissions and returns aggregated at the landscape level.**

Under the steadily increasing incentive scenario (Figure 3), as the agents selected lower emitting land-uses, overall GHG emissions declined steadily over the period 2020-2100 to the same level of $1.5\ \mathrm{t\ C\ ha^{-1}}$ as the previous scenario, although the decline was more gradual. However, the overall annual income of the agents increased steadily due to the influx of external money into the system through the incentive scheme. Thus, while the agents benefited from this, this scenario would cost the incentive-providing agency (e.g. government, society) money to achieve the emissions reductions.

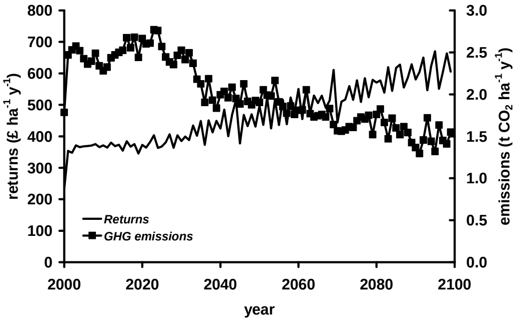

**Figure 3: Effect of a steady increasing incentive from 2020 on GHG emissions and returns aggregated at the landscape level.**

Under the fourth scenario of a redistributive tax (Figure 4), overall GHG emissions declined over the period to similar levels as with the previous two scenarios, but there was no overall upward or downward trend in overall annual income, as the tax paid by agents selecting land uses above the previous year's average GHG emissions was paid to agents selecting land uses below this average. The system was cost-neutral in that no money entered of left the system, yet overall GHGs still declined, as it was in the interests of every agent to select land uses that were lower emitting to avoid paying tax.

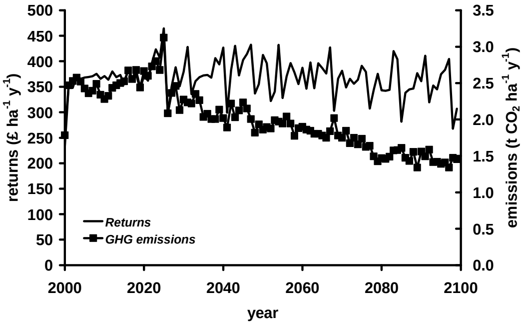

**Figure 4: Effect of a steady increasing redistributive tax from 2020 on GHG emissions and returns aggregated at the landscape level.**

## 5. DISCUSSION

Our results depend to some extent on the validity of the relationship between GHG emissions and economic returns from various land uses as shown in Figure 1. Populating this graph with real data from actual land uses is something that we are currently doing, but nevertheless, the hypothetical relationship that we have used represents a possible solution space, and serves to illustrate that external policies can be applied to move a set of land uses from one region of the solution space to another.

Results indicated that GHG emissions could be reduced by economic instruments such as imposition of a GHG tax, providing incentives for low emitting land uses, and a combination of the two. A GHG tax has the disadvantage of extracting money from the economy of the region so that average returns decline over time even though agents select low emitting land uses. An incentive scheme to reward agents selecting land uses that emit less GHGs is beneficial to the economy of the region with overall annual returns increasing over time (Figure 3), although this does necessitate the influx of money from some external source. A combination of taxation and incentive, with revenue generated from taxing agents selecting land uses with GHG emissions above a threshold and distributing this to agents with land uses emitting below the threshold, would appear to be a 'cost-neutral' solution to reducing overall GHG emissions (Figure 4).

Essentially the latter is a 'cap-and-trade' scheme in which an upper limit of overall emissions is set by the government, with entities emitting above their share of that level are required to purchase ‘credits’ from those that are polluting below their share of the level. In theory this is a ‘win-win’ situation in which both buyers and sellers of credits benefit. In practice, however, a major challenge is that of determining an appropriate cap. The initial problems of the European Union Emissions Trading Scheme (EU-ETS) established in 2005 were due mainly to the setting of too high a cap, so that, apart from an initial flurry of activity, there was no need for companies to buy carbon credits, and the price of carbon plummeted with no real effect on overall emissions. Our results would suggest that setting the cap at the total emissions actually emitted in the previous year is sufficient in itself to drive the overall emissions down over a period of time, implying that each year the majority of agents try to select land uses with emissions below the mean of the previous year. This is despite it being conceivable that a stable equilibrium could be reached in which there is no decline in emissions, with the higher return of higher emitting land uses compensating for the increased tax required to be paid. It is likely that this would depend on the market price of the credits, which we intend to examine further.

A second major challenge to be overcome in ensuring the feasibility and sustainability of GHG credit schemes is that of reliable measuring and monitoring of emissions. At a coarse level, remote sensing could be used to monitor changes in land cover, and possibly certain practices such as the change in tillage or crop type, and these related to changes in GHG emissions, but in the latter case, observations would probably need to be more frequent than satellite information generated at present (Subak, 2000). Direct verification of GHG emissions from different land uses is more difficult. For example, crude emission factors from livestock do not take into account interventions such as a change in diet, which can reduce $CH_4$ emissions significantly (e.g. Waghorn *et al.*, 2002). Similarly, in relation to carbon sequestration, considerable quantities of carbon stored can result in only small changes in soil organic carbon (SOC) contents which are difficult to measure. Various studies have determined that the level of detection of SOC changes ranges from 3% of the mean (Brejda *et al.*, 2000) to 34% of the mean (Homann *et al.*, 2001). Based on a SOC value of 147 Mg $CO_2$-equivalent (MTCO2e) ha$^{-1}$, the minimum detectable difference is roughly 15 MTCO2e ha$^{-1}$, or the result of nearly eight years of improved management (Conant *et al.*, 2001).

Yet, if land managers are to be rewarded for adopting lower emitting practices, then such verification systems need to be developed. Recording and reporting by individual farmers of all agricultural practices they use is one possibility, but the cost of this, and verification of data, is likely to be excessive (Subak, 2000). An interesting possibility is that of direct remote sensing of GHG fluxes. A number of approaches have already been developed based on measurement of infra-red and microwave radiances and extraction of GHG concentrations by comparing differences between observations and simulated radiances (e.g. Chédin *et al.*, 2003). Atmospheric concentrations of CO, $CH_4$ and $CO_2$ can be determined from near-infrared measurements by SCIAMACHY (http://envisat.esa.int/instruments/sciamachy/) on the ENVISAT satellite, for example (Buchwitz *et al.*, 2005). In addition, the Japanese Greenhouse Gases Observing Satellite (GOSAT) with similar capability is planned to be launched in 2008 (http://www.jaxa.jp/projects/sat/gosat/index_e.html). Many technical challenges remain, however, before these could be reliably used for measuring GHG fluxes at the farm level for monitoring purposes. The effect of lateral transfer of GHG concentrations from neighbouring cells by wind is one example. The spatial resolution of such approaches is another – the SCIAMACHY data, for example, has a resolution of 30×60 km; a cell of that size may contain a hundred or more land managers each employing a range of heterogeneous farming practices contributing to the single GHG measurement for the cell. In such cases, it might be possible to allocate incentives according to the GHG flux at the level of the cell, and allow social pressure between land mangers in the cell to self-regulate the practices being used (e.g. Izquierdo *et al.*, 2003).

The hypothetical landscape we have used in this study is an example of a ‘socio-ecological system’ (SES) containing social, economic and biophysical components interacting together. Walker *et al.* (2004) have conceptualised SESs as being located on stability landscapes which contain ‘basins of attraction’ representing a range of possible states with similar characteristics. A SES is hypothesised to cycle within a particular basin of attraction, although external perturbations at critical times may, depending on circumstances, transform it into a neighbouring basin representing a significantly different type of system, particularly if it is close to a critical threshold (Walker & Meyers, 2004). The concept of system resilience is used to describe the amount of effort required to move from one basin of attraction into another.

In Figure 5, we have attempted to illustrate the basins of attraction for each of the three scenarios by drawing ellipses enveloping the land uses present at the end of each simulation. The width of the axes of each ellipse represents the standard deviation of the respective land use characteristic (i.e. returns or emissions). In this case, the external imposition of emissions taxes and/or incentives has shifted the whole basin of attraction and the system along with it from the base line (Ellipse 1) to another location on the stability landscape rather than moving the system from one basin into another neighbouring one. An interesting question relating to the resilience of the system that needs to be explored is whether removal of the tax or incentive results in the system returning to the previous location, and how rapidly it does this.

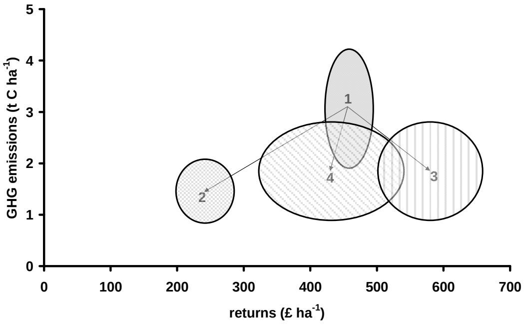

**Figure 5: Envelopes of land uses present at the end of the simulation of each of the four scenarios.**

Was an agent-based approach useful in this case? Without a direct comparison with other approaches, it is difficult to say. However, Hare & Deadman (2004) list the advantages of ABM as its ability to couple social and environmental models, to incorporate the influence of micro-level decision-making in environmental management, and to study the emergence of collective responses to environmental management policies. Parker *et al*. (2002) additionally include the ability to model decision-making at different levels (e.g. individuals, organisations), and adaptive behaviour at the individual or system level. In our study, there certainly was circularity in the link between human decision-making and GHG emissions – emissions by agents in comparison to their neighbours influenced their next land use choice, which in turn impacted on their own emissions the following year. Similarly, there was also micro-variability between households – both in terms of their own social networks, and in terms of their initial land uses, and potentially, their world views. The agents also responded collectively by adapting to the imposition of external economic instruments by imitating profitable land uses of neighbours, resulting in an overall lowering of GHG emissions. ABM potentially offers a way of exploring the feasibility of applying incentives over a large area such as that monitored by satellite discussed above, and how individual heterogeneous land mangers might respond to this. This is something that we intend to study in the next phase of the project.

## 6. CONCLUSIONS

Preliminary results from our combined agent/biophysical model show that GHG emissions can be reduced by economic instruments such as imposition of a GHG tax, providing incentives for low emitting land uses, and a combination of the two. A GHG tax has the disadvantage of extracting money from the economy of the region so that average returns decline over time even though agents select low emitting land uses. An incentive scheme to reward agents selecting land uses that emit less GHGs is beneficial to the economy of the region with overall annual returns increasing over time (Figure 3), although this does necessitate the influx of money from some external source. A combination of taxation and incentive, with revenue generated from taxing agents selecting land uses with GHG emissions above a threshold and distributing this to agents with land uses emitting below the threshold, would appear to be a ‘cost-neutral’ solution to reducing overall GHG emissions (Figure 4). However, the transaction costs of measuring and monitoring emissions by individuals may be a barrier to the implementation of such schemes.

## 7. ACKNOWLEDGMENTS

We acknowledge financial support for this work from the Scottish Executive Environment and Rural Affairs Department (SEERAD) under Work-Package 3.8 of Programme 3 of the SEERAD Research Strategy for Environment, Biology and Agriculture 2005-2010.

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