FEARLUS-W: An Agent-Based Model of River Basin Land Use and Water Management

L. R. Izquierdo, N. M. Gotts and J. Gary Polhill

Macaulay Institute, Craigiebuckler, Aberdeen. AB15 8QH

l.izquierdo@macaulay.ac.uk, n.gotts@macaulay.ac.uk, g.polhill@macaulay.ac.uk
http://www.macaulay.ac.uk/fearlus/

Abstract

This paper describes a spatially-explicit agent-based model of river basin land use and water management. The model is being implemented within a project aimed at investigating ways of synthesising stakeholder priorities, taking the EU Water Framework Directive as a case study.

There are many human activities that take place in a river basin and can alter the ecological status of the water, and there are also many activities whose outcomes depend on that ecological status. These interactions between the socio-economic and the ecological aspects of the river basin are shaped by the spatial distribution of the situation. Water users upstream generally have an advantage over those downstream: the first chance to use (and perhaps abstract or pollute) the water. The flowing nature of water creates asymmetries in the interactions between users. FEARLUS-W is a spatially-explicit agent-based model built to increase our understanding of these complex interactions and explore how common-pool resource problems in river basin management might be tamed through socio-economic interactions between stakeholders (primarily rural land managers), and through management strategies aimed at shaping these interactions.

FEARLUS-W is being constructed within an extended version of an existing spatially-explicit agent-based model of land use change, FEARLUS (Polhill, Gotts and Law, 2001), drawing on theories of common-pool resource use, and on survey work among stakeholders. The main extensions to FEARLUS deal with water, water flow and water pollution on the one hand and allow for agents with multiple and potentially conflicting top-level goals on the other.

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Introduction

What therefore Nature hath joined together, let not Science put asunder.

In recent years, the need to improve our understanding of how the socio-economic and ecological aspects of the world system interweave in coupled socio-ecosystems has become increasingly obvious. In water management in particular, the impact of human activity on water bodies is so overwhelming, and the importance of the ecological status of water bodies for society is so crucial, that an integrated approach is particularly necessary. Already in 1992, the United Nations Conference on Environment and Development held in Rio acknowledged that economics could not be separated from the management of water resources: "Integrated water resources management is based on the perception of water as an integral part of the ecosystem, a natural resource, and a social and economic good" (UN, 1992).

Environmental issues in general are characterised by complex interactions between societies and the ecosystems they occupy. As Weisbuch (2000) points out, there is a loop of interactions between the agents' cognitive properties and their immediate environment. On one hand, agents take decisions according to their beliefs, which are determined by the perceived state of their immediate environment. On the other hand, each agent's decisions influence other agents' views directly and, at a global level, they change the state of the ecosystem as a whole.

The importance of these complex interactions is boosted in the case of water resources due to the presence of harmful externalities and the crucial role of the physical space. Harmful externalities appear whenever the utility of one agent is affected negatively by the actions of another agent. The presence of strong harmful externalities is likely to lead to *economic socially inefficient*[1] levels of appropriation, since individuals do not usually value other individuals' benefits as much as their own. Moreover, when rather than an agent affecting directly other few agents' utility, the externalities take place *through* the environment, harm is often spread out and the full consequences of agents' actions on other individuals are often underestimated by the actors. In particular, damaging the environment can reduce the utility of agents who were not appropriating the resource. The situation of socially efficient resource use is usually highly unstable. The instability stems from the fact that individuals might have an incentive to move away from the socially efficient outcome and from the fact that the actions of one single individual can have devastating consequences for the group, both directly and through social influence. Hence it is convenient to represent individuals explicitly in our models.

[1] An outcome is economic socially efficient if it implies an optimum degree of utilisation of the resource from the perspective of the appropriators as a whole. The optimum degree of utilisation of the resource is that which maximises the net economic yield, the difference between total cost, on the one hand, and total income, or value, on the other. We consider economic social efficiency in terms of monetary profit (payoffs) and not in terms of utility unless stated otherwise. Note that an economic socially efficient outcome may be ecologically unsustainable.

The spatial distribution is another vital issue in river basins. Water users upstream generally have an advantage over those downstream: the first chance to use (and perhaps abstract or pollute) the water. This fact has serious consequences for both users and the ecological status of the river, as we will explain in the next section.

The need to explicitly represent and study the diversity of the agents and the complexity of their interactions, both mutually and with their environment, in a spatially-explicit model can be addressed using a complex dynamical systems approach (Weisbuch, 1990). In particular, we use Agent-Based Social Simulation (ABSS) (Conte, Hegselmann, and Terna, 1997). ABSS is a form of computer modelling of complex adaptive systems in which the agents within such a system are represented explicitly and individually within the model. The model agents typically represent human individuals, but may also represent human collectivities such as firms or states.

Clean water as a common-pool resource

We consider the good ecological status of a water body as a Common-Pool Resource (CPR): a resource which can be depleted by use (pollution or abstraction), and for which it is difficult to limit users' consumption (Ostrom, Gardner, and Walker, 1994). These two characteristics often lead to undesirable outcomes, i.e., situations where individuals are rationally appropriating the CPR to an extent that is not optimal for the group as a whole (socially inefficient outcome), and sometimes not even optimal for any individual (social dilemma (Gotts, Polhill, and Law, 2003a)). If there are institutionally feasible alternatives for these suboptimal situations, then we have a CPR dilemma (Ostrom, Gardner, and Walker, 1994).

When dealing with water, it is important to distinguish between reciprocal externalities (that lead to what we will call symmetrical CPR dilemmas from now on) and unidirectional externalities. In the ideal symmetrical CPR dilemma all the participants hold the same strategic position. This means that the set of possible actions available to any participant is the same. Such a condition is likely to take place in small-scale irrigation systems and ground water basins. The beauty of studying and overcoming symmetrical CPR dilemmas is that there is often an institutionally feasible state that makes *all* the participants *and* the ecosystem better off (Ostrom, Gardner, and Walker, 1994). This socially efficient state is what is usually called the cooperative behaviour. Such an ideal state is often unstable however, because participants might have incentives to individually increase appropriation.

The situation in river basins and large-scale irrigation systems is somewhat different because the flowing nature of water sets a fixed order of priority to act among the appropriators. Upstream appropriators can act before downstream appropriators and, very often, downstream appropriators' actions have very little, if any, effect on upstream appropriators (there are unidirectional externalities). As an extreme benchmark, when the latter conditions occur, systems of mutual restraint cannot emerge, and what was a common-pool resource effectively turns into a sequential chain of private goods. From the point of view of good ecological status of the river, the implications are serious. Assuming that individual motivation is exclusively selfish, and that the economic return as a function of the CPR appropriation is not decreasing for any individual, group rationality can be shown to lead to at least the same level of appropriation that individual rationality leads to in this situation (Izquierdo, Gotts, and Polhill, 2003). This effectively means that, unlike what happens in a symmetrical CPR dilemma, the socially efficient outcome does not imply a reduction in the level of appropriation. In other words, in this case policy makers are forced to make a compromise between the benefit of the group of appropriators and the protection of the resource (reducing appropriation).

Fortunately, empirical evidence shows that individuals have other motivations besides economic yields and there are many instances where institutions develop to protect against overexploitation (Ostrom, Gardner, and Walker, 1994). Such institutions – rules-in-use – are formalised social networks of influence, which emerge from processes of social learning, social monitoring, and normative influence (Conte and Dignum, 2001). Given the importance of these social networks, they must be taken into account in our model.

Why agents?

Several authors have identified computer simulation (Gilbert and Troitzsch, 1999; Ostrom, 1988), particularly agent-based social simulation (Gilbert and Terna, 2000; Moss, 1999), as a useful way of building social science models. ABSS complements verbal argumentation and more abstract mathematical models: verbal representations of social phenomena lack the rigour necessary to assess consistency and generalise whereas mathematical approaches are very often unrealistic due to the simplifying assumptions that must be made in order to achieve tractability. Using agent-based social simulation we have the potential to build models that to some extent combine the intuitive appeal of verbal theories with the rigour of analytically tractable mathematical modelling. ABSS models can increase our understanding of social processes when used in combination with the other two approaches, through enriching the media by which we can express their dynamics.

One of the main advantages of ABSS, and what distinguishes it from other modelling paradigms, is the possibility of establishing an exact correspondence between entities in the real world and agents in our model, "so that the boundary of the entities corresponds to those of the agents and that the interactions between entities correspond to interactions between agents" (Edmonds, 2000). This represents a step towards both realism and rigour. In particular, ABSS is especially appropriate to address integrated water management issues for the following reasons:

- The importance of heterogeneity among agents (Axtell, 2000). The use of representative agents is particularly inappropriate to study CPR dilemmas, since the actions of one single agent can have major global effects.
- The importance of adaptation (at appropriator and resource management levels).

- The crucial role of the geography of the physical space concerned.
- The significance of social networks (often spatially structured).
- The importance of addressing the relationship between the attributes and behaviour of individuals (the 'micro' level) and the global properties of social groups (the 'macro' level) (Gilbert and Troitzsch, 1999).

For an insightful study of the consequences of adopting Multi-Agent Systems as a modelling framework, see (Edmonds, 2000). For a comprehensive review of agent-based simulation in the study of social dilemmas, see (Gotts, Polhill, and Law, 2003a).

The existing FEARLUS[2] model

The model described in this paper, FEARLUS-W, will be built as an extension of the present FEARLUS modelling system. The FEARLUS project is aimed at using spatially explicit agent-based simulation modelling to increase understanding of the processes underlying land use change, particularly at the regional scale and in the medium to long term; current models are quite abstract, reflecting an approach which involves beginning with quite simple models, and building in additional complexity only as and when required. Early experiments with FEARLUS are described in (Polhill, Gotts, and Law, 2001) and (Gotts, Polhill, and Law, 2003b); the first of these papers also includes a more detailed description of the modelling system than is given here.

The present FEARLUS model consists of a set of *Land Managers*[3] (these represent households rather than individuals), and their *Environment*. Physically, the Environment consists of a grid of square *Land Parcels*. Every *Year*, Land Managers use their *Selection Algorithm* to choose one of a limited set of *Land Uses* for each Land Parcel they own. Parameters of the model specify the size and the shape of the grid of Land Parcels, along with the range of *Biophysical Properties* they may have (these are fixed for the duration of the run) and the ways these can vary across space. Other parameters specify the amount and type of variation in the *External Conditions* (which represent climatic and economic factors, and can change from Year to Year, but apply across the whole grid). Two further parameters are a *Break Even Threshold* (BET), specifying the *Yield* required from a Land Parcel to break even, and the *Land Parcel Price* (LPP).

After an initial *Year Zero,* in which Land Parcels are created and assigned to Land Managers, and there is a random setting of External Conditions and allocation of Land Uses to Land Parcels, events follow an annual cycle structured as follows:

1. Land Managers select the Land Use of each Land Parcel they own.

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[2] FEARLUS stands for 'Framework for Evaluation and Assessment of Regional Land Use Scenarios'. The existing FEARLUS model source code and user guide are available online at http://www.macaulay.ac.uk/fearlus/download.html

[3] Terms referring to elements of FEARLUS models begin with an upper-case letter, and are italicised when first used.

2. The Year's External Conditions are calculated, in a way determined by model parameters.
3. Yield is calculated for each Land Parcel by matching the requirements of its current Land Use against its Biophysical Characteristics and the current External Conditions. The amount in the *Account* of each Land Manager is updated for each Land Parcel owned by subtracting the BET from its Yield, and adding the result to the Account.
4. Land Managers with Accounts below zero sell their worst-performing Land Parcels one by one (at the LPP) until reaching or exceeding zero. A Land Manager obliged to sell all their Land Parcels leaves the simulation. The buyer for a Land Parcel is chosen stochastically from a list consisting of those who owned at least one of the Parcel's eight orthogonal or diagonal *Grid Neighbours* during the preceding Year, and have enough in their Account (each Grid Neighbour owned gives its owner one chance to win), plus one potential new Land Manager (given a single chance to win).

The main extensions of the present FEARLUS modelling system will allow for agents with multiple and potentially conflicting top-level goals on the one hand, and deal with water, water flow and water pollution on the other. The extension process, however, is planned to take place in stages, with each stage increasing the level of detail and realism capable of being modelled.

Context: the Water Framework Directive project

The design and construction of FEARLUS-W is being undertaken as part of a larger project, aimed at developing ways to synthesise stakeholder priorities in relation to environmental issues. This project is using the implementation of the EU Water Framework Directive (EU, 2000) as a case study, and is referred to here as the WFD project.

The Water Framework Directive requires the development of decision frameworks, including social, economic and scientific aspects, to assist in the management of water basins. The WFD project involves hydrological modelling, and socio-economic approaches including interviews of stakeholders which will explore their environmentally-relevant values, in addition to agent-based social simulation. FEARLUS will be used primarily in an attempt to pin down the circumstances in which various intervention strategies (such as fines, incentives, or the formation of participatory planning forums) are likely to be effective in preventing over-exploitation. It is planned that the three strands of the project will be coordinated by concentrating attention on a specific catchment (the Tarland), and by using a scenario development approach, specifically a modified version of the "story-and-simulation" approach described in (European Environment Agency, 2001a). A number of "possible futures" for the Tarland catchment will be mapped out, with particular attention being paid to phosphate pollution, and the interviews and hydrological and agent-based modelling strands of the project will be used to check and improve the plausibility of these scenarios.

Modelling CPR dilemmas: the symmetrical case

Time and space are two crucial factors to consider when studying and modelling any CPR situation. Concerning time, it is important to remark that most CPR situations in the real world show significant dynamic features, not only because actors' behaviour is adaptive, but also because the CPR withdrawal rate is or can be higher than the CPR natural replacement rate. When the latter condition occurs, the yield obtained from the resource depends on the strategies adopted by the appropriators in the past. In general, the repercussions of appropriators' actions can appear with a certain time lag and can extend largely over time, making the perceived relationship between actions and their effects very diffuse. In our agent-based model we will consider a range of different situations between the case where the CPR state is time-independent and the case where the state of the environment depends on a long history of actions undertaken by the appropriators.

As far as space is concerned, we will initially focus on the symmetrical case, where identical appropriators share a CPR whose resource units are homogeneously distributed across space. After having studied the symmetrical CPR dilemma (with only reciprocal externalities) we intend to explore the effects of different spatial distributions (unidirectional externalities might appear). This will require changes to the way FEARLUS represents the physical environment, which are discussed in a later section.

One of the simplest models of CPR dilemmas is the time-independent symmetrical CPR model. This idealised model can be a good starting point because it captures the conflict between individual rationality and group rationality and its effects on the CPR while remaining fairly simple. The model is as follows: assume a fixed number n of appropriators with access to the CPR. Let x_i denote individual i's appropriation of the CPR. The group return from appropriation of the CPR is given by the production function $F(\sum x_i)$, where F is a concave function, with $F(0) = 0$ and $F'(0) > 0$. Initially, appropriating pays off ($F'(0) > 0$), but at some level of appropriation the outcome is counterproductive (F is concave). The payoff to an individual from appropriating the CPR depends on aggregate group appropriation and on the individual's appropriation as a percentage of the aggregate (this creates reciprocal externalities). Let $\overline{\boldsymbol{x}} = (x_1,\ldots,x_n)$ be a vector of individuals' appropriations and $p_i(\overline{\boldsymbol{x}})$ the payoff to appropriator i.

$$p_i(\overline{\boldsymbol{x}}) = \begin{cases} \dfrac{x_i}{\sum x_k} F\left(\sum x_k\right) & \overline{\boldsymbol{x}} \neq \overline{0} \\ 0 & \overline{\boldsymbol{x}} = \overline{0} \end{cases}$$

The dilemma comes from the fact that individuals have incentives to increase appropriation even when this would cause a decrease in the group payoff. In game theory terms, players' rationality leads to a deficient equilibrium (Dawes, 1980). This is better understood by calculating the variation on the individuals' payoff resulting from individual i appropriating a bit more of the CPR.

Variation on individual *i*'s payoff $$\frac{\partial p_i(\overline{\boldsymbol{x}})}{\partial x_i} = \frac{x_i}{\sum x_k} F'\left(\sum x_k\right) + F\left(\sum x_k\right) \frac{\sum x_k - x_i}{\left(\sum x_k\right)^2} \qquad (1)$$

Variation on individual *j*'s payoff (i≠j) $$\frac{\partial p_j(\overline{\boldsymbol{x}})}{\partial x_i} = \frac{x_j}{\sum x_k} F'\left(\sum x_k\right) - F\left(\sum x_k\right) \frac{x_j}{\left(\sum x_k\right)^2} \qquad (2)$$

The first term on the right-hand side of equations (1) and (2) represents the effect on the individual's payoff due to the CPR yield variation. This effect, which is negative when total appropriation exceeds the group optimum level of appropriation, is shared by all the appropriators. The second term represents the effect on individuals' payoff due to the variation of their share. This term is positive for individual i (whose share increases) and negative for the rest of appropriators (whose share decreases)[4]. In particular, at the group optimum, in equation (1), the first term is zero and the second term is positive, so the sum is positive. In other words, at the group optimum individuals have incentives to appropriate more and therefore to cause a decrease in the total payoff. Of course, this incentive remains even if we impose common knowledge of rationality ($\sum x_k = n \cdot x_i$), making the symmetrical Nash equilibrium[5] level of appropriation higher than the group optimum level of appropriation. Conclusion: the outcome dictated by individual rationality is worse for *all* individuals than the socially efficient outcome and it implies a higher level of CPR appropriation.

We will start simulating a common pool (e.g. an irrigation system) that all the agents can appropriate in the same way. Each Land Use will have a certain demand for water. The production function of the common pool will be a concave quadratic function and the yield obtained from the pool will be shared among the agents proportionally to their appropriation. As we have just shown, that is sufficient to create a CPR dilemma.

We also intend to model a situation in which there are two possible choices for the agents: a pollutant Land Use and a non-pollutant Land Use, with an external agent (representing a governmental authority) offering a reward to be shared by all the agents as long as the total pollution does not exceed a certain level. In the absence of the reward, the pollutant Land Use is more advantageous in economic terms. However, once the reward is offered, all individuals in the society are better off if all choose the non-pollutant Land Use than if all pollute.

When studying these two situations we will depart from game theory approaches by assuming that agents are not fully rational and their motivation is not exclusively selfish. The decision making of the agents is discussed in the next section.

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[4] We are assuming that there is at least another individual appropriating apart from individual *i*.

[5] If there is a $\overline{\boldsymbol{x}}$ with the property that no individual can benefit by changing their individual appropriation while the other individuals keep their individual appropriations unchanged, then that $\overline{\boldsymbol{x}}$ constitutes a Nash equilibrium. At the Nash equilibrium individuals have no incentives to appropriate more because, if they did so, the positive effect on their individual payoff for increasing their share would be outweighed by the negative effect on their individual payoff due to the variation on the CPR yield.

As the WFD project progresses, we will increase the realism of our simulations, enlightened by the work undertaken by our hydrological and socio-economic colleagues and by the results obtained from our simpler models. This will undoubtedly mean addressing spatial heterogeneity (which is discussed in a later section) and time-dependent externalities.

Agents with multiple dimensions of utility

Several empirical studies have shown that theoretical predictions derived from the assumption of full rationality in CPR dilemmas fail to explain observed outcomes in many situations (Ostrom, Gardner, and Walker, 1994). There are people who behave in a cooperative way even though they are aware of the fact that it is not immediately advantageous in economic terms. One way of explaining this kind of behaviour is to assume that people have *multiple* utilities or values that determine their behaviour, and some of these utilities are associated with aspects of people's behaviour other than the economic payoffs they receive (e.g. morality). Some people cooperate in CPR dilemmas because they face a utility structure that does not correspond to the payoff structure of the dilemma in economic terms (Dawes, 1980). In other words, the apparent dilemma is surmounted because there is not such a dilemma in utility terms. Jager (2000) reviews several factors that seem to influence behaviour in a CPR dilemma besides the economic payoffs. In our design of socio-economic agents we will initially consider two factors: economic payoff and social approval; we may later incorporate intrinsic concern for the environment and for other people.

Representing social approval

In order to give social approval a role in the dynamics of Land Use change within FEARLUS, a new phase will be added to the annual cycle, following the current phase 4 (land sales) . In this phase, each Land Manager will apply a *Social Approval Function* to each of their "neighbours" (initially, these neighbours will be those Land Managers owning contiguous Land Parcels; later, we are likely to want to distinguish social from spatial neighbourhood, although not to divorce them altogether). Factors that might influence this process are:

1. What my neighbour has done (e.g., the Land Use or Uses they selected).
2. What my neighbour has (e.g., number of Land Parcels, wealth, social approval of third parties…).
3. What my neighbour thinks of me (e.g. I approve of them if they approve of me).

The output from the Social Approval Function will be in numerical form – although in the simplest case, it could be confined to three values: 1 (*Approval*), -1 (*Disapproval*) or 0 (*Indifference*). Initially at least, a given Land Manager's Social Approval Function will remain fixed over time; but different Land Managers may have different Social Approval Functions.

The decision making algorithm

Land Managers in FEARLUS-W must choose a Land Use from a set of alternatives for each Land Parcel they own. Assume that at least some agents care about both their economic returns (Yield), and Social Approval from other agents – the *Social Acceptability* of their actions; these agents would like to choose an alternative that maximises both, but in general there may not be an alternative that outperforms the rest in both dimensions, so agents will have to select an alternative which is non-optimal on at least one dimension. The decision process we currently envisage for each Land Parcel will consist of the following steps:

1. Deciding whether there is anything unsatisfactory about the current Land Use.
2. Estimating attribute values (Yield and Social Acceptability) for each alternative.
3. Eliminating any Land Uses which are "dominated" by another: Land Use B is dominated by Land Use A if it is estimated to be worse on at least one of the two dimensions, and no better on the other.
4. If more than one remains, selecting one alternative using a *Weighting Function*. This may vary between agents, and over time, as explained below.

1. Deciding whether there is anything unsatisfactory about the current Land Use. The answer will be "Yes" (and the remaining steps below will be carried out) if and only if either or both of the following conditions are fulfilled:

    a) The Yield from that Parcel was below a specified "Aspiration Threshold" (Gotts *et al* 2003b).
    b) The current level of social approval the Land Manager is receiving is below a specified "Approval Threshold" (if this is the case, the answer will be "Yes" for *all* Land Parcels owned by that Land Manager).

2. Estimating attribute values (Yield and Social Acceptability) for each alternative.

    a) Estimating the Yield that a Land Use will provide. The Yield from a given Land Use in a particular Land Parcel is uncertain because it depends on External Conditions and other agents' actions. In order to implement agents' estimation of Yields, we are considering case-based reasoning (CBR). CBR consists of "solving a problem by remembering a previous similar situation and by reusing information and knowledge of that situation" (Aamodt and Plaza, 1994). A case is a contextualised piece of knowledge representing an experience (Watson, 1997). The experience could be the Land Manager's own, or a neighbour's. In the latter case we would be implementing a type of social learning (Conte and Paolucci, 2001). A case for an agent comprises:

        i. The state of the world when the case occurred, characterised by the factors that the agent considers relevant to estimate the Yield (i.e. external conditions, biophysical properties and local CPR appropriation).
        ii. The Land Use that they applied, and
        iii. The Yield that they obtained.

When agents hold in memory several cases with the same state of the world and the same Land Use applied but with different Yield obtained (conflicting knowledge), we might calculate the mean of the Yields. This is intended to represent Land Managers trying to inductively discover the deterministic component of the function determining yield by averaging out any random component in this function.

We are exploring different ways for agents to deal with situations in which they do not recall a case that exactly matches the state of the world and/or a certain Land Use. When the agent holds in memory at least a case for each Land Use although it does not exactly match the state of the world, then they could take both the degree of match and the recency of the case into account. When the agent does not recall any case for a particular Land Use, then we have to make sure that they still can select that Land Use (we must allow for innovation). One way of implementing this would be by setting *Experimentation Thresholds* for the attributes of the Land Uses. If none of the Land Uses for which the agent has information presents attribute values high enough to prevent experimentation, then the choice could be made stochastically from a list of the Land Uses for which the agent has no information.

b) Assigning an estimated measure of Acceptability to each Land Use on the Land Parcel under consideration (note that, for example a High Pollution Land Use might be considered far more unacceptable on some Parcels than others, depending on how easily the potential pollutant could cause problems to other agents or the environment): we are again considering a CBR approach. However, there are additional questions to be resolved here, since Social Acceptability has no obvious measure corresponding to the economic Yield from the Land Parcel, and may also be influenced by factors other than the Land Use on the Land Parcel under consideration. Initially at least, we intend that each Land Manager should take equal account of the opinions of all its neighbours, and possibly of those of a special "Public Opinion" agent, representing the views of the community at large – so an estimate of Social Acceptability might be arrived at by averaging the Approval ratings from neighbours at the end of the Year in which the retrieved case occurred. We may later refine this approach: distinguishing between neighbours whose opinions are valued more, less, or not at all, and between the views of different wider communities and/or organisations to which different Land Managers may belong, and looking at *changes* in Social Approval as well as static values.

3. Eliminating any Land Uses which are "dominated" by another. The dominance approach uses pairwise comparison. When Land Use A is better than Land Use B on one criterion and equal or better on the other, option A dominates, and B is eliminated from consideration. After using the dominance approach we obtain the "Pareto Front" of undominated Land Uses (Fig. 1). The problem then is how to select among these remaining alternatives.

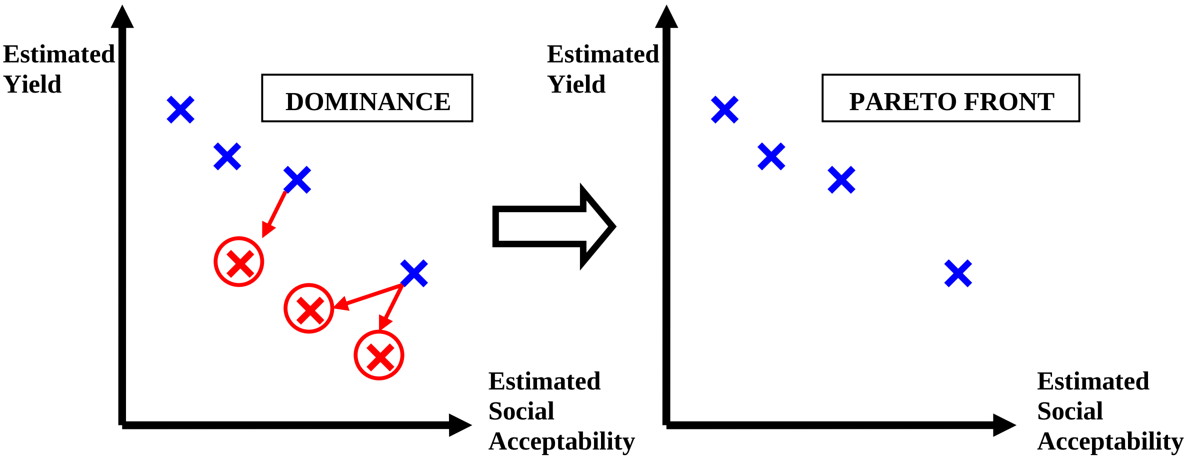

Fig. 1. After using the dominance approach we obtain the Pareto Front.

4. Selecting one alternative using a *Weighting Function*. To select a Land Use from the set of alternatives remaining after step 3, the values for each attribute must be combined into an overall index of worth or utility. Given that the estimate of Social Acceptability can be given a numerical value, as suggested above, an overall index can be calculated in a linear fashion by assigning weights to each attribute[6]. We are studying different possibilities for allowing agents to update their weights, in order to reflect the fact that human agents do not appear to have "fixed exchange rates" between goods or utilities of such different types as money and social approval (Fig. 2).

[6] We are aware that if we apply a Weighting Function from the beginning only alternatives in the Pareto Front could be chosen. Hence there would not be need to apply the dominance approach before if we knew in advance that we are going to use a Weighting Function. However, we want to keep our options open for other methods at step 4.

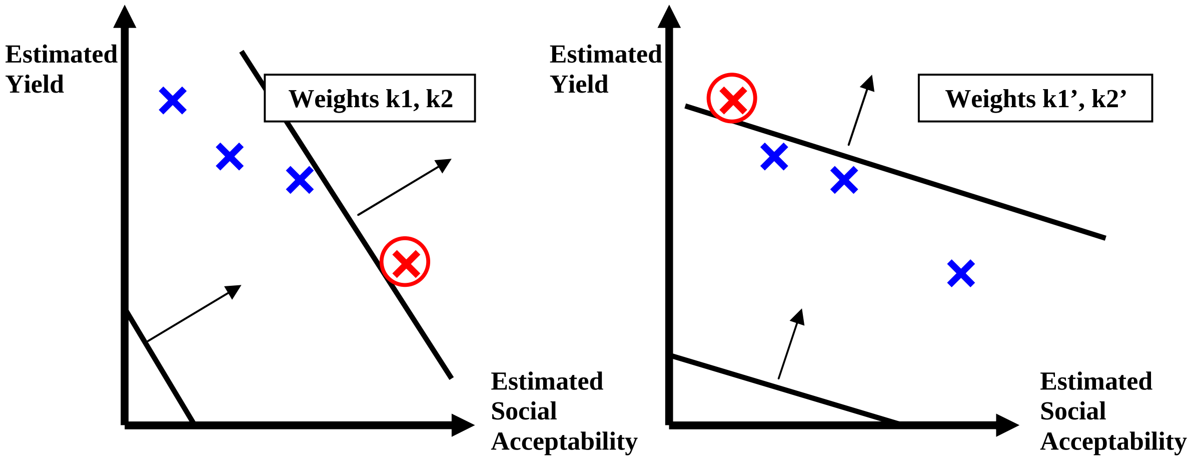

Fig. 2. Selection of a Pareto optimum using different weights.

Our currently favoured option is to update a weight after specific events such as the sale of a Land Parcel, a neighbour's bankruptcy, or a marked decline in Social Approval from one's neighbours. Such unfortunate events would increase the salience of the relevant dimension of utility, and hence increase the weighting of the corresponding attribute.

Water, water flow and water pollution: the asymmetrical case

The work outlined so far can all be undertaken without altering the way in which FEARLUS represents the physical world. Once we wish to represent spatially distributed processes occurring in river basins, however, even if this representation remains at quite an abstract level, we need to go beyond the current approach.

Our chief interest, so far as the Water Framework Directive project is concerned, is in diffuse pollution from agricultural sources, and particularly (but not exclusively) in phosphorus pollution, which our hydrological colleagues are studying. The commonest river pollution problem in industrial countries is that of eutrophication, due to excessive levels of plant nutrients. Eutrophication is defined by the European Commission (EC, 1991) as: "the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned." Phosphorus is the key eutrophication nutrient in fresh water (European Environment Agency, 2001b). Eutrophication can damage the aesthetic qualities of water bodies, and adversely affect commercially valuable species, as well as reducing biodiversity across many types of organisms (Harper, 1992). In recent years there has been marked progress in reducing discharges from point sources in Europe. However, effective control of discharges from diffuse sources (of which agriculture is the most important) is still at a very early stage (European Environment Agency, 2001b).

Clearly, it is land parcels on river banks which will contribute most to such diffuse pollution in a river basin, and a given parcel can only contribute to the pollution levels in parts of the river *downstream* from the parcel, but can then affect the river right down to its mouth. This creates an asymmetry between upstream and downstream land managers: the former can affect more of the river than the latter, and if the latter are directly affected by the pollution (for example, by being unable to use the water for their crops, or unable to use the river for their own leisure purposes or to gain income from other leisure users), they are in general at a disadvantage, since their own behaviour with respect to pollution cannot affect those upstream. River basins also have a hierarchical structure: small streams join up to produce successively larger streams and rivers, and pollution levels in the reach after a confluence of two streams or rivers will tend to lie between those of the merging watercourses; and land managers A and B (owning land on two streams that merge) can both have an effect on land manager C (owning land below those streams' confluence), without either affecting the other. The directional and hierarchical aspects of river basin structure thus have important effects on the structure of socio-economic interaction between land managers neighbouring the basin.

Since our primary interest is in the circumstances in which various intervention strategies might alleviate environmental problems related to water use, we wish at this stage in our research to concentrate our modelling effort on interactions between land managers, not on hydrological details. If our research is successful, FEARLUS models will point the way toward management strategies with a good chance of being successful in various sets of circumstances; detailed hydrological models would then be required for fine-scale investigation of particular catchments. Hence, our representations of water flow and water pollution, particularly in our first models, will be quite simple and abstract.

In current FEARLUS models, the environment consists of a grid of square Land Parcels, each of which is assigned a Land Manager, a set of Biophysical Properties, and a Land Use. In the first version of FEARLUS-W at least, this will continue to be the case, but in addition, a Land Parcel will be assigned a *Watercourse Morphology*. Each of the set of alternative Watercourse Morphologies will specify whether any streams or rivers flow through the Land Parcel, and if so, where they enter and exit, and the direction of flow. The alternative Morphologies can be thought of as resembling a set of designs for tiles, and the edges of adjacent tiles must match. Several different tile designs, and one of the ways in which a set of tiles might fit together, are illustrated in figure 3. Given the Water-Body Morphologies of all the Land Parcels in a model, it can be calculated whether either of two Land Parcels is upstream from the other. This approach can be used to produce simplified models of real river basins, as well as "typical" catchments constructed using statistics about the branching structure of real rivers.

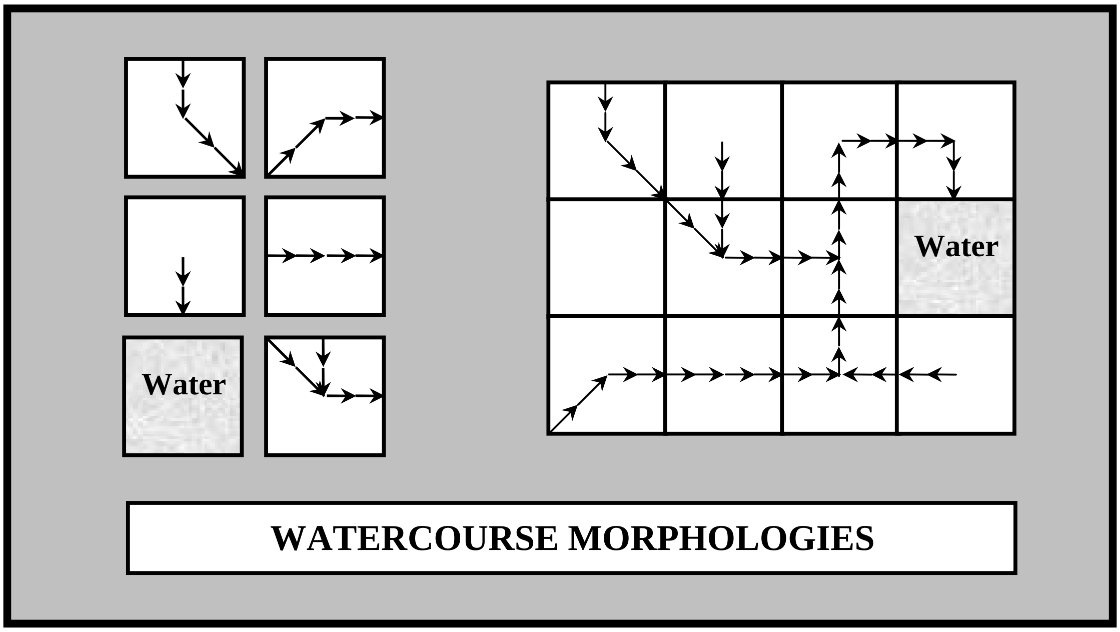

Fig. 3. Different Watercourse Morphologies and a possible way in which they fit together.

Initially, we will assume that the contribution of fields which do not border watercourses to pollution of those bodies (via runoff, throughflow, and wind-blown particles) is negligible in comparison with the contribution from fields which do; and we will distinguish Pollutant and Non-Pollutant Land Uses (the former generally assumed to be more profitable), but make no finer distinctions. We will take a very simple approach to assessing whether pollution reaches an unacceptable level during the course of a particular Year: the *probability* that it does so will be taken to depend on the Land Uses employed in that Year on the Land Parcels through which streams or rivers run. (This stochastic approach is used because, in the real world, the occurrence of unacceptable levels of pollution due to rural land use depends on weather conditions as well as on the amount of potential pollutants applied to the land.) In each Year a *Critical Proportion* (a number strictly between 0 and 1) will be selected stochastically, and unacceptable levels of pollution will be deemed to occur in the water courses running through a Land Parcel if and only if the proportion of Land Parcels upstream from it (including itself) exceeds this Critical Proportion. Figure 4 shows part of an example basin, with Pollutant (P) and non-Pollutant Land Uses (NP) shown, along with the proportion of upstream Land Parcels having Pollutant Land Use for each water-course carrying Land Parcel.

Given this representation of the physical environment, several kinds of interaction between Land Managers can be modelled, some of which include asymmetrical externalities, and some of which include an external management agent. All of these would involve "monitoring pollution" at one or more points in the river basin, and rewarding or penalising those upriver from each point according to the results.

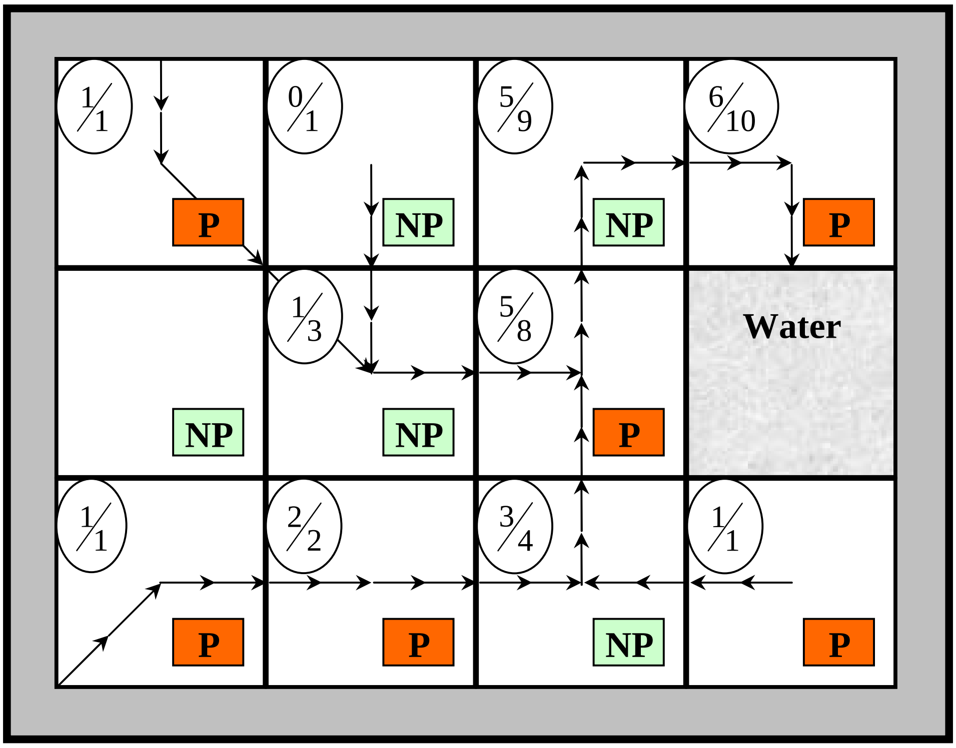

Fig. 4. Example basin. The choice between Pollutant (P) or non-Pollutant (NP) Land Use is shown in the little rectangle within each Land Parcel. The circled fraction in each water-course carrying Land Parcel indicates the proportion of upstream Land Parcels having Pollutant Land Use (including itself).

In the simplest case, there would be a single monitoring point, at the lowest point in the basin represented in the model, and all Land Managers would receive a bonus (or escape a penalty) if the pollution level there was acceptable. The bonus or penalty might be equally divided, or divided according to the number of Land Parcels potentially contributing to pollution; a bonus might be thought of either as being distributed by a river management body, or as representing the return from a resource (e.g. a shellfish bed) at the monitoring point. In this case, the externalities from Pollutant Land Uses remain symmetrical.

A simple asymmetrical case can be constructed by assuming that a Land Parcel with water courses through it can generate additional income from fishing rights, if and only if pollution levels in it are below the unacceptable threshold. Optimum strategies for Land Managers would depend on the relative size of the premiums gained by employing the Pollutant Land Use and from fishing rights, the probability distribution used in deciding the Critical Proportion, and the structure of the river basin. On top of these factors, the introduction of agents concerned about Social Approval as well as Yield will clearly make a difference – and in this case, it might make sense for Land Managers to be concerned about what their upstream neighbours, but not those downstream, choose to do. (In the case of a salmon fishery, this would not apply, as salmon will not swim up a badly polluted river from the sea.)

Our hydrological colleagues will be constructing a model (Koo, 2003) of the Tarland catchment which assumes the existence of a channel (either a permanent watercourse, or temporary channels flowing only at certain times) through each grid cell (the size of a cell remains to be determined, and will depend partly on computational considerations), in a direction determined by the relative altitudes of adjacent cells. Within each cell, the model will represent the movement of water between the vegetation canopy, groundwater, soil storage and channel storage, and the concentration of phosphorus pollutants in water and sediment. Their time-step will be much shorter than that currently used in FEARLUS – probably one day. How closely the two models will be related is still being considered, but Koo's model should allow the location of permanent watercourses – with which we will initially be concerned – to be determined for the Tarland, and may also help us to choose plausible distributions of values for the Critical Proportions of High Pollutant Land Uses referred to above.

Once we have implemented and experimented with the relatively simple models of asymmetrical cases sketched above, we plan to make enhancements in three directions:

1. Toward greater realism in modelling phosphorus application to the land, and phosphorus transport into and along watercourses. This will draw on Koo's model, and is likely to require us to make use of shorter (quarterly or monthly) time-steps: phosphorus pollution clearly has the greatest eutrophication effect during times when temperature and day-length permit rapid plant growth. It will also require us to take into account the effects of phosphorus application on Land Parcels that do not border watercourses, and of the residue of phosphorus applied over periods of several years. For these purposes, a modified cellular automaton approach (Couclelis, 1997; White, Engelen and Uljee, 1997) may be used, in which the state of a cell (while remaining less detailed than intended in Koo's model) includes indications of the hydrological state of the cell, and phosphorus concentration in the permanent watercourse (if any), soil, and groundwater; and state changes depend both on External Conditions (representations of rainfall and temperature) and on the states of neighbouring cells.

2. Toward more complex socio-economic scenarios. For example, different parts of the river system might have different potential values for leisure activities: the land around some tributaries might be of higher aesthetic value than that elsewhere, hence more likely to attract tourists who could provide additional income for land managers (farms may make extra income by letting cottages or rooms, or members of the farm household may work in hotels, shops, or firms providing leisure services). Again, Land Managers' social networks might reflect factors other than physical proximity, such as wealth, or the types of Land Use employed: a certain number of social ties between Land Managers having relatively distant land holdings could make a considerable difference to the dynamics of social approval, and of the exchange of information in the case-based reasoning phase of decision-making. Watts (1999) and Barabási (2002) have investigated the profound effects which the topology of social networks can have.

3. Our current models of land use selection and land sales are unrealistic in some important ways, for example:

    a) Land Uses are selected one Land Parcel at a time.
    b) Costs of changing from one land use to another are not represented, nor are land managers' preferences and skills: it is much easier to persuade a land manager to change from one land use to another if the two are similar.
    c) All Land Parcels have the same Land Parcel Price (LPP).
    d) A Land Manager will always buy a Parcel neighbouring one of their own if possible, and will never buy any other Parcel.

    While these topics are not central to our concerns in the WFD project, they may interact in important ways with the issues surrounding CPR situations and water pollution. Our approach will be to consider these topics one at a time, investigating each to see whether changing the model in the direction of greater realism (and, inevitably, greater complexity) is likely to make an important difference to our conclusions.

Conclusions

FEARLUS-W will both utilise and extend the flexible framework for spatially explicit agent-based social simulation described in Polhill et al (2001) and Gotts et al (2003b). This extension will take place in stages, with each stage increasing the level of detail and realism of our simulations. Such enhancement will be achieved drawing on work undertaken by our hydrological and socio-economic colleagues and on insights obtained from previous work within the FEARLUS project. Specifically, we will implement agents who use more plausible and sophisticated decision making algorithms and we will improve the environment representation in the model. The new agents will have multiple dimensions of utility and their behaviour will be guided by previous observed experiences. The new representation of the environment will include a Watercourse Morphology that will allow us to address the asymmetries of some spatially distributed processes occurring in river basins. Physical space is crucial in any socio-ecosystem and particularly in river basins. The spatial distribution of the resource and its users determines the dynamics of polluting processes and shapes the interactions between users at different levels: not only users' utilities but also the structure of social networks of influence are affected by space. As we have shown, in the case of river basins, the flowing nature of water brings significant asymmetries in. FEARLUS-W will provide a flexible modelling system to address these issues paying special attention to the interactions between the socio-economic and the ecological aspects of the river basin. Following such an integrated approach we believe that we will be able to increase our understanding of how common-pool resource problems in river basin management might be tamed through socio-economic interactions between stakeholders (primarily rural land managers), and through management strategies aimed at shaping these interactions.

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