Adaptive Agents Simulation of Freshwater Ecosystems

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Abstract: A concept for adaptive agents simulation of food web dynamics and algal species interactions is designed for freshwater lakes. Agents for food web entities will be based on evolving differential equations adopted from process based lake models such as SALMO. Alternative agents for algal species will be extracted from a lake database by means of artificial neural networks and evolutionary algorithms. The database contains multivariate time-series of 9 lakes different in eutrophication, climate and morphology. The suggested concept will not be constrained by rigidity as typical for traditional lake models but evolves ecosystem structures and behaviours by emerging, submerging, interacting and evolving ecological entities simulated by adaptive agents.

Keywords: Adaptive agents; Lakes; Evolving differential equations; Neural networks; Evolutionary algorithms

1. INTRODUCTION

Ecologists are consistently searching for new modelling paradigms in order to simulate realistically the distinct nature of ecosystems by computer models. The ecosystem concept as established by Forbes [1887] had the most forming influence on ecosystem modelling in the past century. It no longer bears close examination as ecosystems like lakes are known to evolve and being driven by exogenous forces rather than existing permanently and in isolation. However, the ecosystem approach has resulted in valuable databases as well as quantitative and qualitative descriptions of ecosystem dynamics and has made ecology a predictive science [Rigler and Peters, 1995]. Computer models resulting from the ecosystem concept were mainly based on differential equations (DE) for well-defined ecological entities and processes, adjusted by measured or estimated parameters. Radtke and Straskraba [1980] firstly tried to overcome the rigidity of such models by parameter optimization of ecological goal functions relevant to lake ecosystems as introduced by Straskraba [1979]. The authors considered their results as contribution to a structural self-optimising ecosystem model but admitted that more adequate models and more suitable optimisation procedures would be needed to make it a success. In order to overcome model rigidity, Kaluzny and Swartzman [1985] suggested a library of alternative representations of ecological processes from where a simulation model picks the most relevant for a specific ecological situation. The authors concluded that their approach was limited by validation data and 'the difficulty of tracing model response to single processes' [Kaluzny and Swartzman, 1985]. Jorgensen and Mejer [1979] introduced the thermodynamic entity exergy for holistic ecosystem modelling that has lead to the concept of structural dynamic models [Jorgensen 1986]. It implies to equip an ecosystem model with a global rather than local goal function, namely exergy, to be satisfied by optimising process parameters in the course of simulation. Even though this approach avoids the problem of biasing by 'local' optima as faced by Radtke and Straskraba [1980] it may require more adequate models and more suitable optimisation procedures as well.

Machine learning techniques such as artificial neural networks (ANN) [Rumelhart et al., 1986] and genetic algorithms (GA) [Holland 1992] allow looking at the same problem from a different angle. They are inductive techniques and are capable of extracting empirical patterns as reflected by multivariate time series data. Even though the range and extent of data available may limit ANN, GA can explore both causal and empirical information by means of hybrid frameworks to induce and evolve models [Bobbin and Recknagel 2001; Whigham and Recknagel 2001a, b]. However predictive capacity of resulting models still relies on underlying causal and empirical knowledge.

The application of adaptive agents (AA) [Holland, 1992; Holland, 1998] is an attempt to go one step further: to evolve ecosystem structures and behaviours by emerging, submerging, interacting and evolving ecological entities simulated by adaptive agents.

The present paper designs a concept of how AA can best be applied in order to simulate species/population abundance and succession of algae and zooplankton in freshwater lakes. AA represent state variables of ecological entities by DE, ANN, GA and hybrids of GA and DE. Whilst DE are adopted from verified deterministic lake models such as SALMO [Recknagel and Benndorf, 1982], ANN, GA as well as hybrids will be extracted from a lake data base [e.g. Recknagel et al., 1997; Recknagel, 1997; Bobbin and Recknagel, 2001; Whigham and Recknagel, 2001a, b]. The database currently contains multivariate time-series of 9 lakes different in eutrophication, climate and morphology. The range of conditions in the database will result in alternative agents for the same species/population resting in an agent bank. During simulations only those agents will be fired at a certain time that best suit the current conditions otherwise will remain in the agent bank, awaiting conditions to change. Fired (emerging) agents simultaneously evolve based on GA in order to reach their optima.

The proposed concept is currently implemented and tested towards adaptive lake ecosystem simulations.

2. ADAPTIVE AGENTS FRAMEWORK

Holland [1992] introduced Echo as a generic simulator designed to explore interactions among large numbers of different agents. It provides for the study of populations of evolving, reproducing agents distributed over a geography with different inputs of renewable resources at various sites. Each agent has simple capabilities – offence, defense, trading, mate selection – determined by a set of "chromosomes". Chromosomes in each agent are differentiated into two classes:

(1) Tag chromosomes determine the agent's external phenotypic characteristics and distiguish: offence tag, defence tag and mating tag. Tags are displayed on the exterior of an agent and are analogous to signature groups of an antigen or the logo of an organisation.
(2) Condition chromosomes determine what kinds of interactions take place when agents encounter one another and distinguish: combat condition, trading condition or mating condition.

The fact that an agent's structure is completely defined by its chromosomes, which are just strings over the resource alphabet {a,b,c,d}, plays a critical role in its reproduction. An agent reproduces when it "collects" enough letters to make copies of its chromosomes. An agent can collect these letters through its interactions: combat, trade, or uptake from the environment. Each agent has a reservoir in which it stores collected letters until there are enough of them for reproduction to take place. Interactions between agents, when they come into contact are determined by a simple sequence of tests based on their tags and conditions. In the simplest model they first test for combat, then they test for trading and finally they test for mating as follows:

(1) Combat: Each agent checks its combat condition against the offence tag of the other agent. E.g., if the combat condition is given by the string aad, then this condition is matched by any offense tag that begins with the letters aad. If the combat condition of either agent matches the offense tag of the other, then combat is initiated. Combat can be initiated unilaterally by either agent. If combat is initiated the offence tag of the first agent is matched against the defense tag of the second and a score is calculated.
(2) Trading: If combat does not take place, then the first agent in the pair checks its trading condition against the offence tag of the second agent, and vice versa. Unlike combat, which can be initiated unilaterally, trading is bilateral – a trade does not take place unless the trading conditions of both agents are satisfied. The trading condition in the simplest model has a single letter, as a suffix, that specifies the resource being offered for trade. If the trade is executed then each agent transfers any excess of the offered resource (amounts over and above the requirements for its own reproduction) from its reservoir to the reservoir of its trading partner. Though this is a very simple rule, with no bidding between agents, it does lead to intricate, rational trading interactions as the system evolves. Trades that provide resources needed for reproduction increase the reproduction rate, assuring that agents with such rational trading conditions become common components of the population.
(3) Mating: While an agent can reproduce asexually, simply making copy of each of its chromosomes when it has accumulated enough resources (letters), there is also a provision for recombination of chromosomes. When agents come into contact and do not engage in combat, the mating condition of each agent is checked against the mating tag of the other. As with trade, mating is only executed as a bilateral action. Both agents must have their mating conditions satisfied for recombination to take place. If this happens, then the agents exchange some of their chromosome material, as with crossover under the genetic algorithm.

AA characterised by these simply defined capabilities provide for a rich set of variations illustrating the key kernel properties of complex adaptive systems. They were originally developed and applied for the study of complex adaptive economic systems [Holland and Miller, 1991] such as stock markets [Wan and Hunter, 1997] and businesses [Lin and Pai, 2000]. However modified versions of Echo have meanwhile been used to simulate spatial dynamics of species or populations represented by individuals strictly based on causal knowledge [Booth 1997; Schmitz and Booth 1997; Kreft et al., 1998]. These examples are based on the assumption that local emergence or submergence of individuals is driven by interrelationships between well-defined individuals and their environment. Such an individual-based approach seems to be relevant to terrestrial ecosystems like forests [Schmitz and Booth, 1997] where spatial spreading of individual tree species as an outcome of competitive success is of major interest. AA simulation of aquatic ecosystems requires a different approach as normally neither individual nor spatial aspects are relevant, nor adequate data are available.

3. CONCEPT FOR ADAPTIVE AGENTS SIMULATION OF FRESHWATER LAKES

A lake ecosystem has a definite boundary with primary producers dominated by microscopic algal cells (1 to 200 µm) with generation times of hours to days, and secondary producers dominated by mesoscopic zooplankton (20 to 2000 µm) with generation times of days and weeks [Rigler and Peters 1995]. Dissolved inorganic nutrients are homogeneously distributed within the euphotic surface layer where algal cells strongly interact and grow as a result of competiton for nutrients and light. The wind continuously stirs the surface layer contributing to an almost homogeneous horizontal distribution of algal cells. Zooplankton may also be affected by wind but are mobile to a certain extent. They tend to form horizontal patches in response to food availability and predation pressure by fish.

If we focus modelling on the euphotic zone as the scene of primary and secondary production in lakes, we can imply that lake communities are almost homogenous distributed and almost instantaneously respond to exogenous disturbances.

As the prediction and explanation of instantaneous population abundance and succession appears to be the biggest challenge to freshwater ecologists, the focus of AA simulation for lakes shifts from individuals to populations (respective functional groups of populations) and from spatial to temporal distributions. Therefore AA simulation of lake ecosystems currently appears to be relevant at two levels: aquatic food web interactions and aquatic species interactions.

3.1. Food Web Interactions

Adaptive agents simulation of freshwater ecosystem dynamics will be designed and implemented according to Figure 1. Seven agents will be considered initially to represent the following major entities of pelagic food-webs in freshwater lakes: blue-green algae, green algae and diatoms, herbivorous and carnivorous zooplankton, planktivorous and piscivorous fish (see Figure 1a).

These seven agents interact by predation and competition, and are determined by environmental driving forces such as solar radiation, water temperature, nutrient loadings. Each single agent is determined by evolving DE in order to maximise (adapt) their performance (abundance) in relation to current environmental conditions (nutrient loadings, light, temperature and abundance of competitors, predators or preys). Evolving DE utilise evolutionary algorithms in order to steadily optimise parameter values and functions of balance equations as used by Recknagel and Benndorf [1982]. As a result, each agent adapts simultaneously to current environmental conditions by producing "offspring" agents based on its evaluation and selection of mates, recombination strategy and mutation strategy (see Figure 1b). Successful case studies on evolving DE have been conducted by Whigham and Recknagel [2001a, b] and Recknagel et al. [2000].

3.2. Algal Species Interactions

Adaptive agents simulation of algal species dynamics will be designed and implemented according to Figure 2. Four agents will be considered initially to represent the following blue-green algae species typically competing in eutrophic freshwaters in summer: *Microcystis, Oscillatoria, Anabaena* and *Phormidium* (see Figure 2a). These four agents interact by competition and are determined by environmental driving forces such as solar radiation, water temperature, nutrient loadings. Each single agent is determined by evolving neural networks or evolving rule sets in order to maximise (adapt) their performance (abundance) in relation to current environmental conditions (nutrient loadings, light, temperature and abundance of competitors). Evolving artificial neural networks [Yao. and Liu, 1997] utilise evolutionary algorithms in order to steadily evolve best adapted neural network models. Successful case studies on evolving rule sets have been conducted by Bobbin and Recknagel [2001] and Recknagel et al. [2000]. They utilised evolutionary algorithms in order to steadily evolve rule-based models. As a result, each agent adapts simultaneously to current environmental conditions by producing the best adapted model or agent "offspring" based on its evaluation and

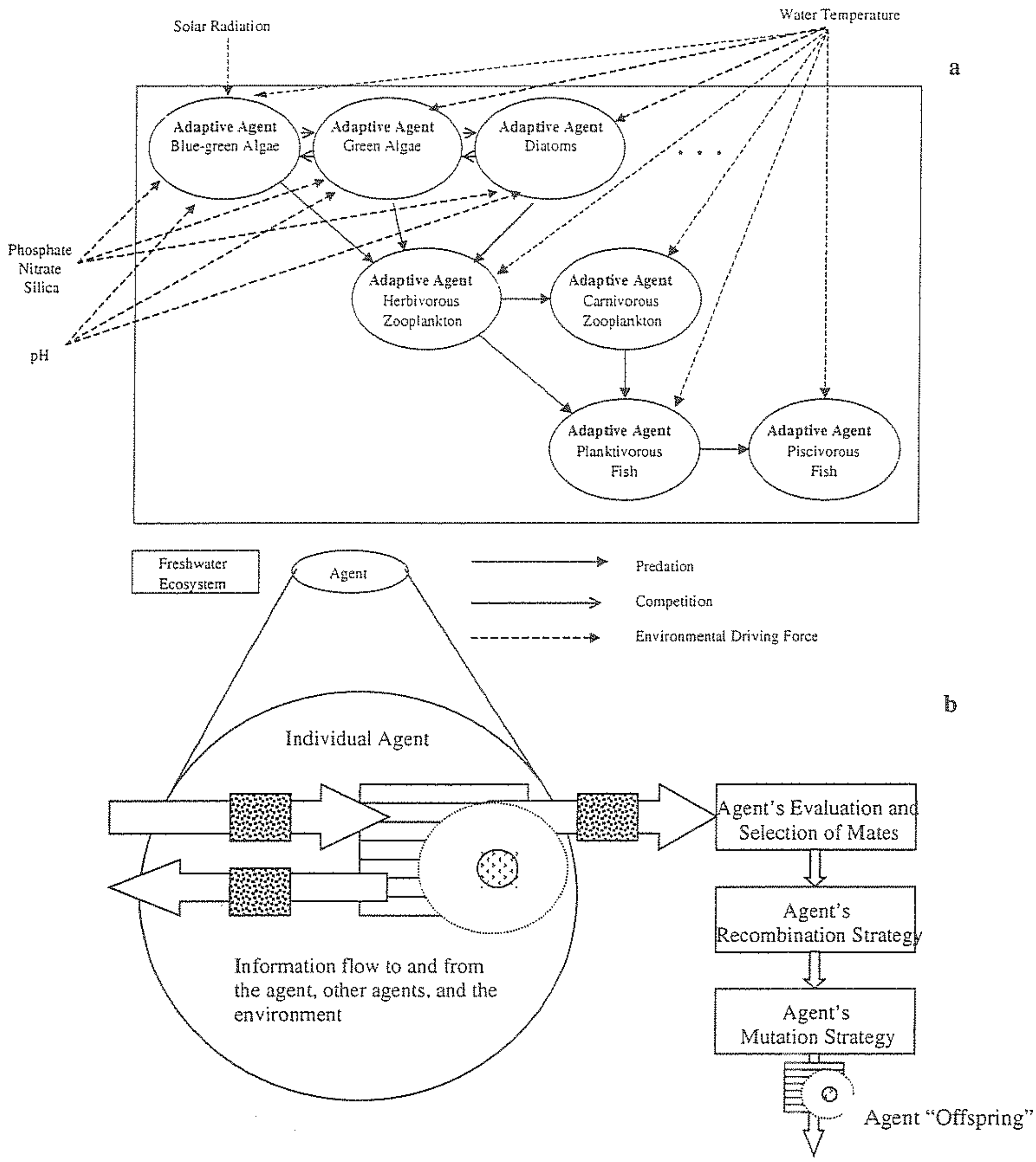

Figure 1. Adaptive agents simulation of aquatic food web dynamics.

mates, recombination strategy and mutation strategy (see Figure 2b).

Natural ecosystems are characterised by redundancy in their composition and structure. They gain a certain degree of resilience to changing environmental conditions depending on the extent of redundancy. In order to develop adaptive agent models that gain such resilience to environmental changes, they need to have redundancy in their composition as well. Therefore a bank of ecological agents (models) for additional algae species will be developed occurring seasonally and locally in specific lakes under certain environmental conditions.

Neural network and evolutionary algorithm techniques will be used to develop these algae specific agents from a database that currently contains

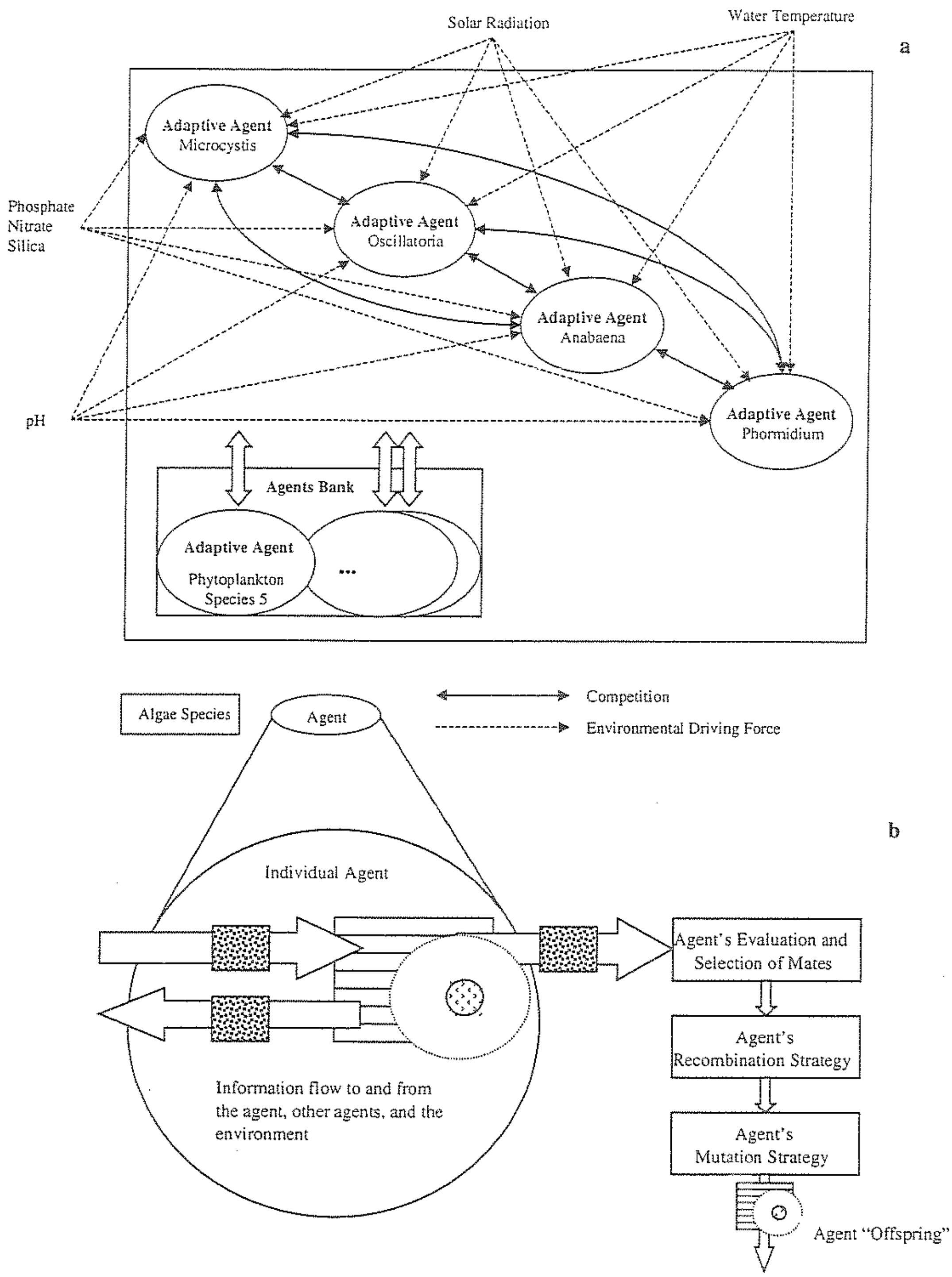

Figure 2. Adaptive agents simulation of algal species

multivariate time-series of 9 lakes different in eutrophication, climate and morphology. The range of conditions in the database will result in alternative agents for the same species/population resting in an agent bank.

During simulations only those agents will be fired at a certain time that best suit the current conditions but otherwise will remain in the agent bank, awaiting conditions to change. Fired (emerging) agents simultaneously evolve based on GA in order to reach their optima. This agents bank will be the key to enable the adaptive agents model to change the composition of agents during the simulation by temporarily activating or resting agents (eg algae species) depending on favoring or inhibiting environmental conditions.

4. CONCLUSIONS

(1) Adaptive agents provide a realistic framework for ecosystem simulation evolving ecosystem structures and behaviours by emerging, submerging, interacting and evolving ecological entities.

(2) Applications of adaptive agents to lake ecosystems appear to be relevant for dynamic simulations of aquatic food web and aquatic species interactions.

(3) Adaptive agents simulation of aquatic food web interactions can be based on evolving differential equations considering competition and predation.

(4) Adaptive agents simulation of aquatic species interactions can be based on artificial neural networks and evolutionary algorithms extracted from a diverse lake database. Simulations gain resilience to environmental change from an agent bank providing alternative agents for same species.

(5) The presented concepts are currently being developed by means of a multivariate time-series database of nine freshwater lakes different in climate, eutrophication and morphology.

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