Use of Agent Based Modeling to simulate complex ecological systems in contexts with poor information; the case of the Winton Wetlands in Victoria, Australia

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ABSTRACT

There have been numerous frameworks and approaches developed for the study of complex ecological systems. For the most part, these approaches require extensive amounts of information. The aim of this paper is use Agent-Based Models to simulate complex ecological systems and examine overarching trends, using the Winton Wetlands in Victoria, Australia as a case study. The study showed that even though there are gaps of information about the functioning of this particular site, this type of framework could increase the understanding of complex ecological systems and assist in decision-making processes.

INTRODUCTION

In the last decades, ecological systems, as complex systems, have been gaining relevance in scientific, management and policy spheres (An 2012; Young et al. 2006). The study of their modeling has lead to the development of several tools in order to better understand the interactions within ecological systems when many elements are involved (Ford 2010; Grimm and Railsback 2005), and in many cases, in an attempt to further incorporate them into larger systems i.e. socio-ecological systems (Binder et al. 2013; Perez-Mujica et al. 2013).

The study and management of ecological systems, and wetlands in particular, requires the development of integrated management plans covering all the aspects of the wetlands and their relationships with their catchments (Finlayson et al. 2005).

Lack of information, uncertainty, non-linear relations and emergence of system's behaviors are some the common features that characterize the analysis of complex systems and require to be taken into account during the modeling process (Ladyman et al. 2013; Sterman 2001).

Top-down simulation frameworks and aggregational models, such as differential equations have been most commonly used to model complex ecological systems (Ford 2010). Top-down frameworks require thinking in terms of global structural dependencies and the behavior of the system is defined in the onset. (Bonabeau 2002; Scholl 2001). However, for some systems, we might know very little about how things affect each other at the aggregate level, or what is the global consequence of operation, but we might have some perception of how individual participants of the process behave. In instances like this one, Agent Based Modeling can be useful.

Agent-Based Modeling (ABM) has been gaining importance as a tool to understand complex systems, (Epstein 2006; Gilbert 2008; Gilbert and Bankes 2002). As a bottom-up approach the behavior of individual agents accounts for lack of knowledge of the general structure of the system, as well as for the adaptation of the agents in response to the changes in the environment (Bonabeau 2002). In this regard, ABMs can be used to look for trends and patterns at a level where there is just sufficient data to capture the dynamics of the system (Epstein 2006).

Authors of ABM, or Individual Based Modeling in Ecology, define agents as elements with autonomous decisions that help them achieve their goals (survival, reproduction, etc.) and adapting the decisions to the rapidly changing environment (Grimm and Railsback, 2005; Grimm et al. 2005).

ABMs have been used in the context of ecological systems to describe the structure and interactions in complex ecological systems, from development and growth of beech forests to selection of habitat by trout (Grimm and Railsback 2005; Grimm et al. 2005). In addition, ABMs have also been used in the context of

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environmental management to simulate and model of the effect of human decisions on the environment with the aim of evaluating policies and support decision making processes (Bennett and Tang 2006; Tang and Bennett 2010) but they are still far from being used extensively for ecological systems.

Wetlands, as complex systems, are comprised of a network of interactions among different biotic and abiotic elements, which make complete representation extremely difficult (Powell et al. 2008). The Winton Wetlands is no exception. Over the years, the site has been subjected to different hydrological and ecological regimes. It was transformed from a network of wetlands to agricultural land, followed by an irrigation lake and finally turned back into natural wetlands during a process of restoration (Winton Wetlands Committee of Management Inc 2011). These dramatic changes of land use are associated with different levels of information. There is little or close to no information about the state of the network of wetlands prior to the establishment of European settlers and during the first two years after the creation of the irrigation lake. The main body of literature available was collected during the 1990s when it was still a lake and during the decommissioning process of the lake. Although the current Committee of Management of the restoration project has directed certain monitoring programs, there is little knowledge about the behavior of the system, which would aid in the decision-making process

This paper is part of a larger project about the Winton Wetlands, focusing on the development of a systemic approach to study complex socio-ecological systems in the context of sustainability (Perez-Mujica et al. 2013; Perez-Mujica et al. 2014) and its validation with the participants is currently in process.

Drawing on the best available information, including quantitative modeling and qualitative "expert opinion", the aim of this paper is use Agent-Based Models to simulate complex ecological systems and examine overarching trends, using the Winton Wetlands in Victoria, Australia as a case study. The ABM will simulate the ecological interactions resulting from different climatic and hydrological scenarios for two distinct areas inside the site: the wetlands and the woodland.

The aim is not to provide an accurate prediction of the future of the site but to increase our understanding of about the emergent behavior, i.e. the dynamics at the level of the whole system. The use of ABM in systems like this could help improve the level of understanding of complex ecological systems with information gaps, help in the decision making process and guide future research and monitoring plans.

METHODS

Study area

The Winton Wetlands is a transformed wetland located in North East Victoria in Australia, approximately 200km north from Melbourne. After its decommissioning as a lake, the state government has implemented a restoration project to return, as much as possible the Winton Wetlands to its original state (Goulburn Broken Catchment Management Authority 2012).

Data collection and analysis

Data was collected in the form of 13 semi-structured interviews of the Scientific and Technical Advisory Group of the Winton Wetlands, as well as wetland ecologists and conservation employees of the Catchment Management Authority that have the Winton Wetlands within their jurisdiction. Interviews where transcribed and coded for themes in Nvivo, using the Actors, Factors, Sectors Framework proposed by Kok and colleagues (2006) to characterize socio-ecological issues (Perez-Mujica et al. 2013). Where possible, official documents about the ecology of the Winton Wetlands were used to complement the information used in the model, e.g. the Restoration and Monitoring Strategic Plan (Winton Wetlands Committee of Management Inc 2011).

The elements and interactions were represented in a conceptual model and then converted to an ABM. The implementation language was Netlogo (Wilensky 1999).

The Model

Based on the interviews and the documentation, a conceptual model of the Winton Wetlands was established (Figure 1). The general elements and interactions presented in the model represent causal interactions established by the participants and recorded as relationship themes in Nvivo. The basic structure of the study area is divided into two main areas of the site: the wetland and the woodland. The wetland portion is comprised of the area of the site that can be flooded. The woodland portion is the permanently dry part of the site.

Ephemeral wetlands, such as the Winton Wetlands are complex systems whose ecological integrity is intimately linked with natural hydrological and climatic cycles, which results in the increase and decrease of the quantity of water in the wetland (Powell et al. 2008). Most of the other elements of the system depend upon it. When there is water in the system (via rainfall and water inflows from the catchment), the quantity of water in the wetland, allows fish populations to enter the system from river feeds and woodland vegetation to increase. When there is water in the wetland, species of migratory birds also visit the wetland and they leave when there is no more water.

However there are some threats to the ecological function of the site. These can be in the form of introduced pests, such as exotic fish and feral animals, as well as exotic plants.

To specify the ABM, the different variables were extracted from the conceptual model (Table 1). Because there are two distinct portions of the site, there are two

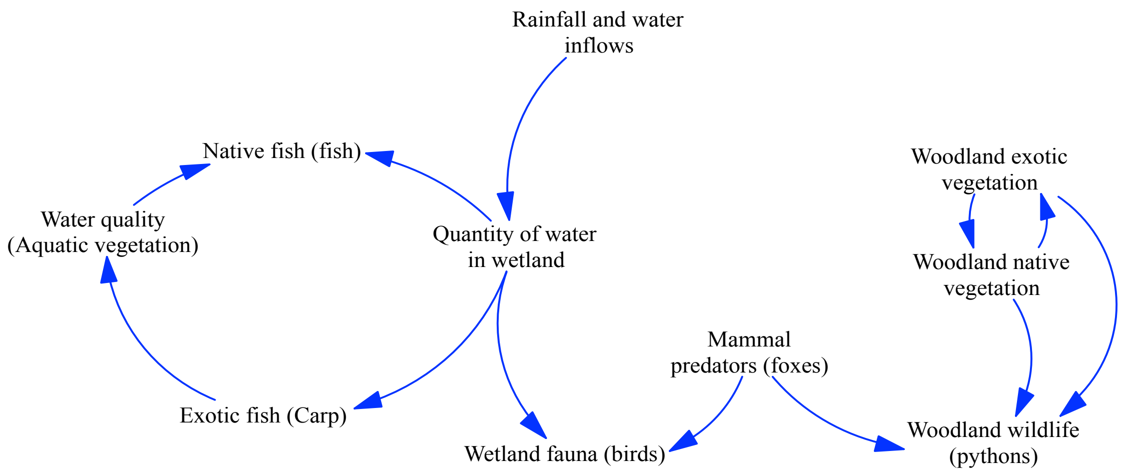

Figure 1: conceptual map of the Winton Wetlands ecological system

groups of behavioral rules; one for the wetland and one for the woodland (Figure 2, Figure 3).

As mentioned previously, rainfall and the subsequent amount of water in the site determine many of the interactions within the system. In the case of the wetlands, the amount of rainfall from year to year is random, but there are two distinct stages; a drought stage (in most years the wetland retains some water but can at times dry out completely) and decadal flooding that refills the entire wetland. Based on this, there are four main behaviors for the wetland (Figure 2):

1. If there is no rainfall and it corresponds to a period of drought where the wetlands are completely dry, all the carp and native fish die, and the wetland becomes a seed bank for new aquatic plants.
2. If there is a big flood, the wetland is refilled and native and exotic fish enter the system via streams from the surrounding catchment.
3. If there is rainfall but it doesn't correspond to a big flood, there is a mosaic of areas with and without water. In the areas with water, carp, which churn mud and disturb aquatic vegetation, decrease the quality of water, which in turn affects the population of native fish.

On the other hand, in the woodland part of the reserve (Figure 3) there is a competitive interaction between native woodland vegetation and exotic vegetation. Through wind, both types of vegetation disperse their seeds to colonize new spaces but the exotic species are far more successful and vigorous than native species. Nevertheless, through competitive exclusion, once one type of vegetation types establishes, the other cannot establish itself anymore.

Table 1. Variables of the Winton Wetlands ABM

Variable/ type	Description
Wetland	**Wetland portion of the site**
Carp/agent	Exotic fish that enter the wetland every big flood
Fish/agent	Native fish that enter the wetland every big flood
Birds/agent	Terrestrial fauna associated with the wetlands
Water quality/patch	Level of health of the aquatic vegetation of the wetland. It is a proxy of the ecological function that the wetland provides to aquatic biota.
Shore/patch	Dry portion of the wetland
Woodland	**Woodland portion of the site**
Water quantity/patch	Amount of water in the wetland
Pythons/agent	Native woodland wildlife
Native plants/patch	Proportion of native woodland flora
Exotic plants/patch	Proportion of exotic woodland flora

Finally, there is a predatory interaction in both portions of the reserve, wetland and woodland, involving animal pests (in this case, foxes and feral cats). They predate on terrestrial fauna associated with the wetlands, such as migratory birds, as well as on woodland wildlife, such as carpet pythons. In the case of the predation on birds, this stops once the birds leave the wetland when it is completely dry.

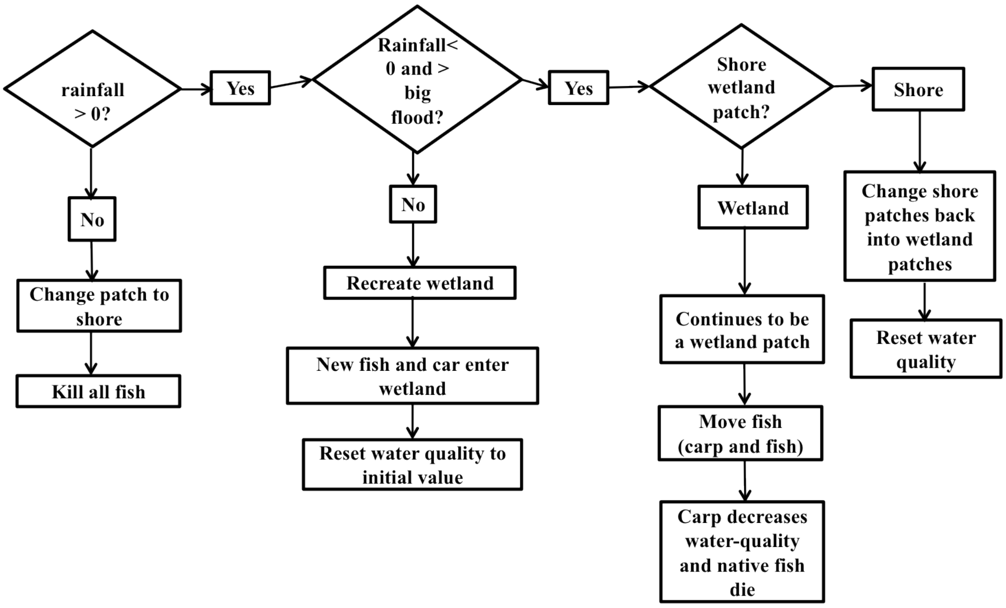

Figure 2: Behavioral rules for the dynamics of the wetland

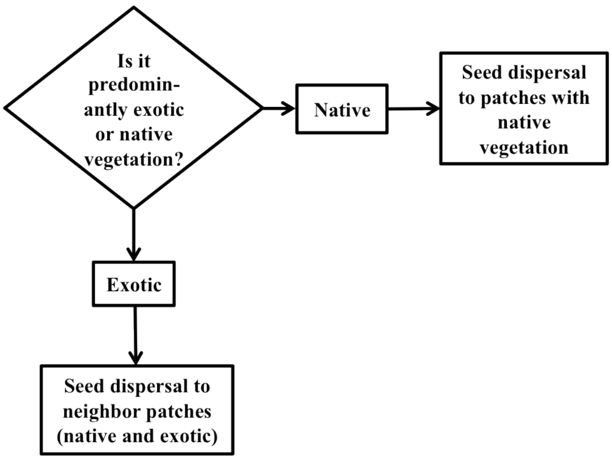

Figure 3: Behavioral rules for the dynamics of the woodland vegetation

RESULTS

For the wetlands, two different scenarios were simulated based on the important elements and interactions gathered from the interviews. Most participants mentioned that the water quality and quantity in the wetland were the two most important elements in the wetland system.
Firstly, the quantity of water in the system responds to the amount of annual rainfall and the presence of big flooding events.

In general, it was stated that the rainfall events are unpredictable but that approximately every ten years the wetlands would receive an important influx of water from the nearby rivers and that during the period in between these "big floods" the wetlands would have different levels of water and would eventually be completely dry at some point. Secondly, it was established that the presence of carp, in terms of the disturbance of sediment and subsequent increase in turbidity, were some of the main causes for the decrease of water quality. When the quality of water decreases other native species can no longer survive and the population of native species (fish in this model) decreases.
The difference between scenario (a) and (b) is that the first one has a bigger population of carp in the wetland. Both scenarios have the same amount of fish (native species) and initial quality of water.
When there is an increase in the entrance of carp to the system through the big floods, i.e. there is not an efficient management plan to control the entrance of carp, the population of native fish and water quality decreases (Figure 4a).
When the entry of carp is controlled, by means of fish way traps for example, (cages at the inlet channels of the wetlands), the water quality is more stable and the population of fish does not decrease (Figure 4b).
In both scenarios, the wetlands have periods of complete dryness, in which both the carp and native fish die.

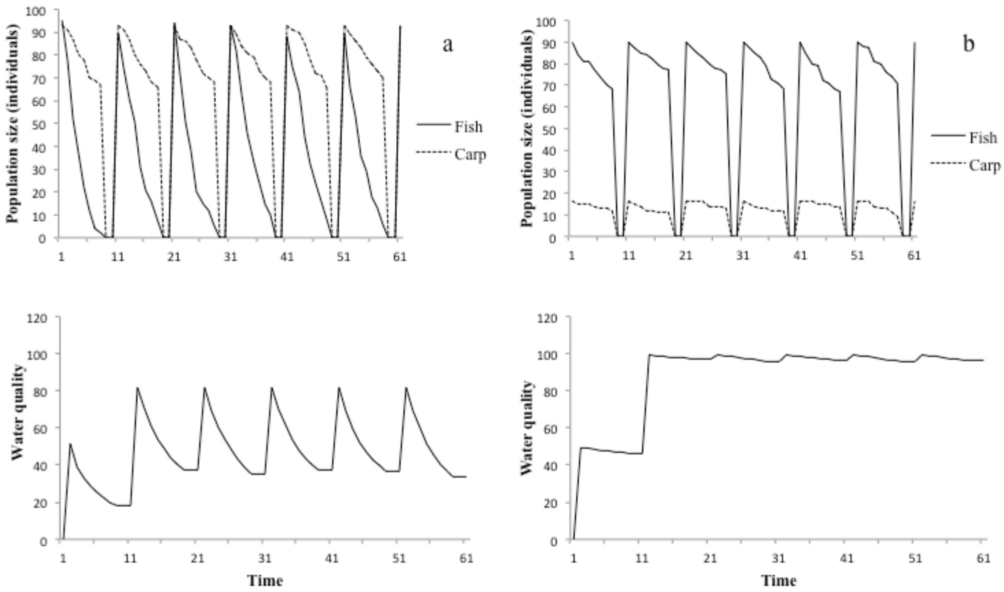

Figure 4: Two scenarios for carp and fish populations and water quality; one with a high initial population of carp (a) and one with low initial population of carp (b)

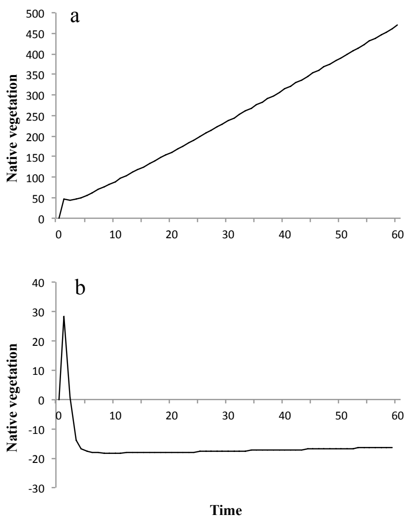

Figure 5: Two scenarios for native vegetation; one with high initial native vegetation (a) and one with low initial native vegetation (b)

When this happens, the wetlands goes through a process of "refreshing" according to a participant expert in wetland restoration in which the wetlands recycle nutrients, among other processes that allow native vegetation and fauna to reestablish once the wetland is refilled.

In this regard participants agreed that even though people normally want to see the wetlands always pretty and full of water, it is in fact important for the wetlands to dry out.

For the woodlands, there are three important elements and several interactions. Firstly, all participants agreed that the biggest problem of the woodland and grassland is the dominance of a few introduced species, which prevent colonization by native species. Without the implementation of management plans that control the spreading of exotic plants in the system, the survival and proliferation of native plants is compromised (Figure 5b).

However, if management plans are successful in controlling these weeds, the ratio of native vegetation to exotic plants increases because native plants are able to colonize (Figure 5a).

Finally, two scenarios were developed to simulate the response of the populations of native woodland fauna (pythons) and associated terrestrial fauna (birds) as a result of the predation of foxes.

Animal pests (foxes and feral cats) are ubiquitous to this region of Australia. A large proportion of reserves in Victoria have problems with foxes. A participant mentioned that the programs of pest control are very important to keep in check the population of animal pests. Although the population of birds and pythons is decreasing due to the predation of foxes, in a scenario where there was a high initial number of foxes (Figure 6b) the rate of decrease was larger than where there was a low initial number of foxes (Figure 6a).

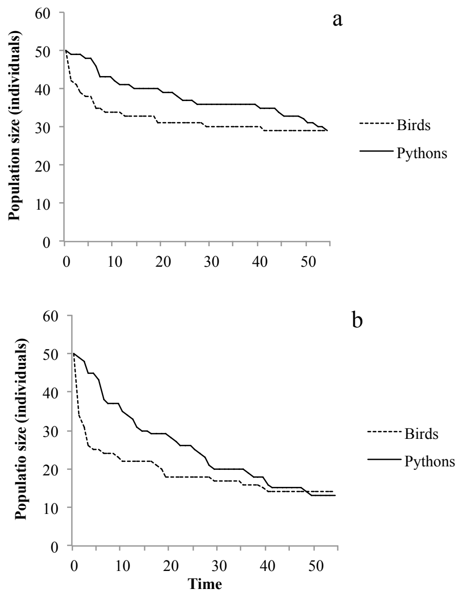

Figure 6: Two scenarios native terrestrial populations; one with high initial number of foxes (a) and one with low initial number of foxes (b)

DISCUSSION

The simulation in the wetlands showed that the population of native fish greatly depended on the population of carp because of the relationship of carp and the decrease of water quality.

However, it is noteworthy that all species of fish, native and exotic also depend on the amount of water in the wetland. So, even if carp managed to get into the system during one of the big flooding periods, once the wetland is completely dried out, all the fish will die and the wetland would refresh. In this regard, the simulation helps to communicate to a wider audience, that is 'non-scientist' about the importance of ephemeral wetlands being wet and dry in different periods.

In addition to "clearing" the wetland of exotic fish and recycling nutrients, during the dry period the wetland is also habitat for some species that require the soil to be drier. A next step of this model would be to incorporate the dynamics of biodiversity found during the drying period of the wetlands with species like wading shore birds, such as gulls.

It can also be seen that even though the wetlands would refresh every big flood, once fewer carp enter the system, the quality of water stays at a similar level until it is entirely dried. This would imply that the body of water would have a high quality of water in the periods between big floods and would be available to sustain an array of native flora and fauna.

Another important element of the system that depends on the quantity of water is the presence and absence of wetland associated fauna (birds in this model). However, the decrease in population size due to the decrease in the amount of water does not necessarily represent the death of the birds. Birds are mobile animals and they will migrate wherever they find water to feed on the fish. Once the wetland is full again, the birds will migrate back to the wetlands.

Predation by feral animals (foxes in this model) does reflect directly the death of associated fauna. A further step in the model would be to separate the migration away from the wetlands from birds as a result of the decrease on quantity of water and the death of birds as a result of predation from foxes

For the woodlands, the model represents the biggest issues mentioned by the participants was the ratio off native vegetation to exotic vegetation. In the case of the woodlands, participants stated that the management of exotic plants is much more complex than the wetland because "the wetland dries and floods and takes care of itself". In the woodland, things are different, vigorous exotic vegetation will dominate the landscape.

The simulation for the woodlands and the wetlands helps to shed light on the importance of implementing accurate and efficient management plans to control animal pests and weeds. If the carp are never managed by controlling their entry to the wetland, native aquatic species populations will struggle to survive in the system. Something similar occurs for the woodland, control of exotic vegetation and animal pests. Re-vegetation of native species needs to be programmed and implemented in order to restore the ecological function of the woodland. This will possibly never be achieved to the original pre-European settlement state, but closer to a functioning woodland state.

As mentioned before, this model is part of a bigger project. It is still in the process of development and collection of empirical data for more precise parameterization. Future work will investigate the interaction of social and economic subsystems.

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