# Toward the simulation of the Amazon-influenced mangrove-fringed coasts dynamics using *Ocelet*

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Abstract: Efforts to describe the functioning and the dynamics of the 1600-km-long mangrove-fringed coast of the Guianas, a giant ocean-mud-mangrove interface, depict a highly complex system where sedimentary, ecological, morphodynamic, biogeochemical and oceanographic processes are closely linked at all spatial and temporal scales. To our knowledge, no model is presently capable of simulating multi-scale influences of coastal physical processes on mangrove development. Existing models are relatively few and are disconnected. In this paper we explore an approach based on a landscape modelling language called Ocelet. After a brief description of the modelling approach and its simulation environment, we explain how we would decompose the complex mangrove dynamics modelling problem into more accessible parts. One of the parts focusing on mangrove expansion on a mud bank is detailed, and the incremental enrichment of the model with other coastal interactions between vegetation, mud and ocean is discussed.

Keywords: Domain Specific Language; dynamic landscape; incremental modelling

# Introduction

The 1600-km-long mangrove-fringed coast of the Guianas, from the Amazon River mouth to the Orinoco Delta, receives about 20% of the 1.2 $10^9$ tons $yr^{-1}$ of suspended particulate matter discharged to the Atlantic Ocean by the Amazon River (e.g. Kineke *et al.,* 1996). A portion of this huge solid discharge, being diverted by oceanic currents and littoral dynamics, follows a NW path after a complex history of deposition and resuspension processes (e.g. Allison *et al.,* 2000). Shore-attached mud banks of 10- to 40-km long and extending up to several tens of kilometres offshore, very gently sloping down to about the 20-m isobath are then created and migrate toward Venezuela along the Guianas coast (Froidefond *et al.*, 1988). Efforts to describe the functioning and the dynamics of this giant ocean-mud-mangrove interface depict a highly complex system where sedimentary, ecological, morphodynamic, biogeochemical and oceanographic processes are closely linked at all spatial and temporal scales (e.g. Baltzer *et al.*, 2004; Fromard *et al.*, 2004).

To our knowledge, no model is presently capable of simulating multi-scale influences of coastal physical processes on mangrove development. Existing models are relatively few and are disconnected. A hydrodynamic model (MOBEEHDYCS) is currently being used to study the influence of some of specific physical processes on the extension and morphology of the Amazon plume (e.g. Nikiema *et al.*, 2007) but the formation of shore-attached mud banks cannot be examined with the same pool of physical equations. Besides, relevant works have been conducted to simulate mangrove trees growth in the Para region (e.g. Berger *et al*. 2000; 2008). They remain independent of the local coastal dynamics which however controls mangrove birth, development and death.

The present case can be considered particularly challenging for modellers as it brings together interrelated processes occurring at different spatial and temporal scales. In this paper we explore an approach based on a landscape modelling language called *Ocelet*. One interesting characteristic of this approach lies in the flexibility of adding new elements into an existing model, and of replacing elements with more appropriate ones, thus allowing potentially complex situations to be modelled by assembling simpler parts (Degenne *et al.*, 2009). The *Ocelet* language is still under development and the mangrove dynamics modelling case is one of several cases used for the design and testing of the language. After a brief description of the modelling approach and its simulation environment, we explain how we would decompose the complex mangrove dynamics modelling problem into more accessible parts. One of the parts focusing on mangrove expansion on a mud bank is detailed, and the incremental enrichment of the model with other coastal interactions between vegetation, mud and ocean is then discussed.

# 1. Material and method

*The Ocelet approach*

The *Ocelet* modelling language is a Domain Specific Language (DSL) that has been designed for studying issues related to space, time and multiple scales that are raised when dynamic landscapes are modelled. The *Ocelet* approach is based on the modelling language, and also on a code generator and a service execution environment (see Fig. 1). These allow modellers to concentrate on the conceptual model, while leaving to an associated software tool the transformation of the model into an implementation that runs on a computer.

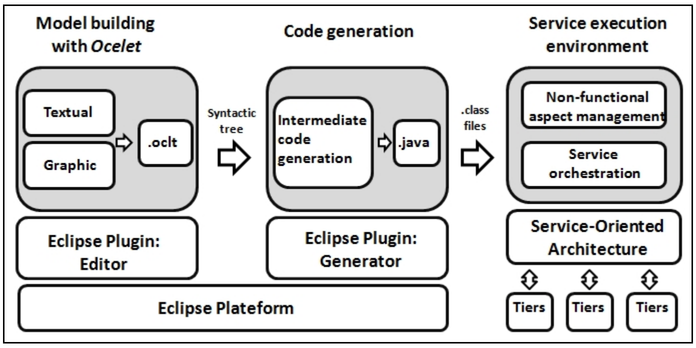


*Figure 1: The Ocelet modeling and simulation framework (from Degenne et al., 2009)*

A DSL that can support research on modelling processes in landscapes however needs to be flexible, and especially so at the very basic level where landscape features and their interactions are defined. Therefore, strong requirements were set on the DSL in terms of expressiveness and ease of use. The *Ocelet* language is designed around five main concepts, although more common concepts, not requiring specific descriptions, such as properties, attributes and arguments, are also used:

*Entity*: Entities are the basic elements that can be linked together to build a model. An entity may contain other entities, and is then called a composite entity. Entities that do not contain other entities are atomic entities.

*Service*: A service is an operation defined by an entity or relation; it has a name, parameters and a possible result. There are two types of services: *i*) a service provided is defined within an entity, and *ii*) a service required is invoked within the entity and supplied by another.

*Relation*: A relation is a connection between two or more entities that provide and require compatible services. It defines the nature of interactions between these entities and provides services for the activation of those interactions.

*Scenario*: A scenario is a sequence of actions composed of service calls or relation expressions within a composite entity. A scenario is activated for a period of time.

Therefore the scenario expresses the spatial and temporal internal behaviour of a composite entity.

*Datafacer*: A datafacer is an atomic entity specialized in data access. The datafacer provides different mechanisms for data persistence.

We use the term "primitive" to refer to a piece of code in *Ocelet*, containing an entity, a relation, a scenario, a datafacer or a combination of them, that had previously been written for a given case, and that could be used again for another. When numerous different situations will have been modelled with this approach, we expect that a set of most useful types of primitives will emerge, from which modellers would pick and adapt to their case studies. Then, when developing a model, model parts are either built using the DSL, or taken from libraries of previously built ones, and adapted to the specific model. More information on modelling dynamic landscapes with *Ocelet* can be found in Degenne *et al.* (2009). Once a model is written in *Ocelet*, it can be analysed in order to verify that the specification written in *Ocelet* is correct (syntax and type checker). The corresponding java code is automatically generated (code generator). Simulations can then be carried out using a dynamic execution framework based on component-oriented programming approach. Other software and hardware aspects related to the execution service-oriented component framework, that supports mechanisms for dynamic extension and a distributed execution, can be found in Ait Lahcen *et al.* (2009).

### *Mangrove dynamics case-study*

Our case-study is characterized by rapid changes taking place over large areas. The most visible changes are due to pioneer mangrove plant species continuously colonizing new mud flats, and unstable lands being washed away by currents. The formation of mud flats is itself the result of complex coastal hydrodynamics, displacing large volumes of silt brought to the ocean by the River Amazon. The complete system can be simplified into three main dependent processes: 1) the formation, migration and destruction of mud banks under the combined forces of waves, tides and currents, 2) the colonization of mud banks by mangrove plants and 3) mangrove tree growth. There are many obvious reasons why the processes cannot be considered independent, but ecosystem research may also suggest other non-obvious dependencies and modelling may be an appropriate tool to test them. In this paper we briefly present the colonization of mud banks by mangrove plants. The two other processes cannot be ignored, and are modelled with simple predefined mud bank formation and mangrove tree growth patterns.

### *Modelling mangrove expansion on mud banks*

The study of mud bank colonization by mangroves in French Guiana had led to the identification of two distinct colonization processes: a) the regular step-by-step mangrove expansion and b) the 'opportunistic' occupation of mud cracks by pioneer *Avicennia* (Proisy *et al.*, 2009). Here we consider only the first process, where mature mangrove trees produce seeds that are dispersed in their immediate surroundings. The seeds may either be washed away into the sea, or develop into seedlings and become young, then mature plants.

In this study, we test how *Ocelet* can be used to model this type of situation. The focus is on model development, and not on model validation and testing. We therefore did not use any ground data, and seed production and dispersal were simulated using random draws from normal distributions. Model parameters are mainly those defining the distributions. We propose to build this model with only two types of *Entities* (Plant and Surface) and one *Relation* (SpreadSeeds). Surface entities are areas that can receive seeds. Three instances of Surface are created at initialization: Coast, Mud bank, and Ocean. Two instances of the SpreadSeeds relation are created: treeSpread is responsible for the exchanges between plants and any type of Surface, groundSpread is responsible for the neighbourhood relationships between the different Surface entities (i.e. sending seeds from the coast to the mud bank, from the coast to the ocean or from the mud bank to the ocean).

```
relation SpreadSeeds[emitter,reciever] {
service dropSeeds() {
reciever.catchSeeds(emitter.seedsToSpread());
emitter.spreadDone();
}
}

// In the Surface entity:

service catchSeeds ( group seeds )
{ for (Plant pli in seeds) {
if                          (isOnThis(pli.pos))
treeSpread.connect(pli,this);
else toSpread.add(pli);
}
}
```

*Figure 1: Definition of the* SpreadSeeds *Relation and* catchSeed *Service in Ocelet*

The Plant entity has many instances, one for every living plant in the model. It has a *service* that is responsible for the daily evolution of the Plant, switching from the 'seed' state to the next states: young plant, adult plant, and finally dead plant at appropriate times. When a plant is in 'adult' status, it can emit new seeds and spread them in the environment through the treeSpread instance of the SpreadSeeds relation.

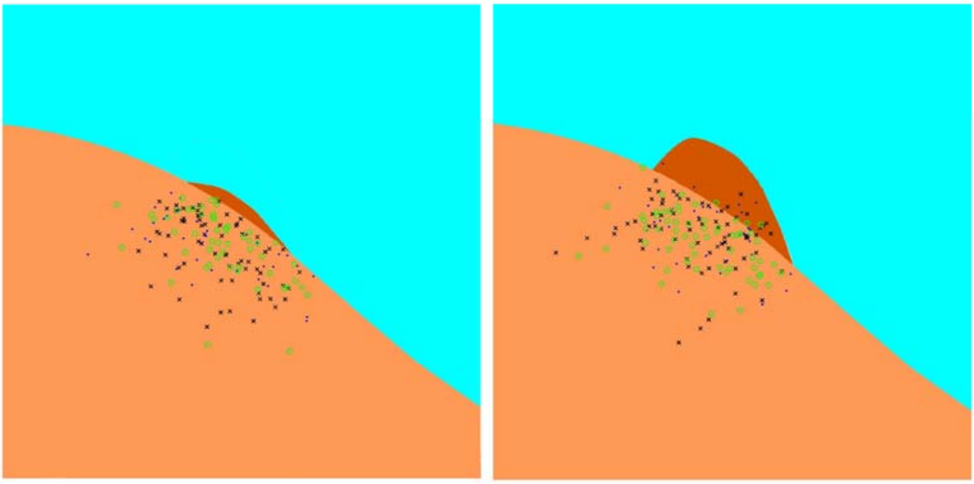

*Figure 2: Situation before (left) and after (right) simulation on a schematic land-sea interface with a developing mud bank. (Adults, young plants and seeds are shown as green circles, blue dots and black crosses respectively)*

The model's daily evolution *scenario* (dailyEv[1day]) is designed to call first a service on the relation treeSpread that will drop the newly created seeds from every Plant to the Surface where the parent plant is located. That surface will accept the seeds that are located within its area and keep the others for submitting them to their closest neighbours. A series of calls on the groundSpread relation will then exchange remaining seeds from surfaces to their neighbours until all the seeds have found their destinations. In this version of the model, the seeds falling into the ocean are considered lost. In *Ocelet*, relations hold an interaction graph and a service can be applied to all the arcs of that graph at the same time. This makes the interaction especially short to write.

# Results and discussions

The prototype model was run for a simulation period equivalent to a few years (the exact period is not meaningful as we have not searched for appropriate model parameters to reproduce real situations). The situations before and after the simulation period are given in Fig. 2. It shows that colonization of the mud bank has started. But the main result here is that modelling a simple situation remains fairly easy with *Ocelet*. The concepts available are close to those used by the modeller for understanding the system to be modelled. The modelling exercise can therefore be very pragmatic. One can start modelling part of the system with simplified entities, relations and scenarios, representing the main elements and processes in the system, and make sure that they operate well together. Then, each of these elements can be independently improved to take into account more precise (expert) knowledge of the system. Moreover, another part of the model can be developed independently in a similar way, and the two parts can subsequently be assembled within a common framework.

In the present case, the first prototype presented can be improved in several ways. First, more appropriate dispersion rules and survival rates can easily be implemented in replacement of the random draws on normal distributions. Second, once the regular mangrove expansion mechanism is functional, one can try to include the 'opportunistic' colonization process. The latter could be done simply, using empirical knowledge, and then gradually improved using more mechanistic relationships. In the present prototype, the mud bank was considered passive (a seed, wherever it lands, has the same probability to survive). This is a first approximation that could also be addressed by taking into account the changing topography of the mud bank, in relation to tide level oscillations. Third, and in a similar way, mangrove tree growth can first be modelled using empirical allometric relations, and then improved to include water, carbon or energy budgets, provided enough scientific knowledge is available. Finally, a major future step would be to couple the mangrove dynamics model with a model of mud bank formation and migration.

The present model contains an original and concise way of modelling the diffusion of something (seeds in our case) from one area to its closest neighbours. That mechanism is only based on the SpreadSeeds Relation and the associated catchSeeds() service on the surface entities. That combination is a good candidate for building a generic *Ocelet* primitive that could later be reused in models that need to simulate similar diffusion mechanisms.

# Conclusion and perspectives

The present study reports on the way *Ocelet*, a modeling language designed for dynamic landscapes, can be used to model mud bank colonization by mangroves. The overall system is particularly complex and challenging to model, and present modeling approaches have not been very successful. The present approach is also far from reaching this objective, but the possibility it offers to incrementally improving a model within a common framework, presents interesting new prospects in this direction.

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