A NON-MODULAR CELLULAR DEVS MODEL OF THE DEGRADATION OF A CULTIVATED SOIL SURFACE BY RAINFALL

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ABSTRACT

We aim to model and simulate the evolution of the surface structure of a cultivated soil surface during rainfall. The surface degradation is mainly the consequence of the creation and the transport of soil fragments, which are caused by the circulation of water, rainfall and runoff in particular. Our first intent was to use Cellular Automata (CA), but these processes cannot easily be modelled in a pure CA model because they are both discrete and continuous, local and global. We explain in this paper how non modular cellular DEVS can efficiently model this natural system and we present in detail the coupled model of the simulator and the atomic model of the terrain, and we give a sketch of the way we model the processes involved.

INTRODUCTION

The objective of our project, called SoDA (Soil Degradation Assessment), is to develop and validate a dynamic simulation of the evolution of the surface structure of a cultivated soil surface during a rainfall at the meter scale, keeping in mind a constant care for visualization. Major aspects of this evolution are the formation of soil crusts and the development of cracks (Valette et al., 2006a): which strongly influence water infiltration or seedling emergence for example. Therefore, such a model, able to predict soil structure under different initial soil conditions and climatic scenarios, would be for example a useful tool to select adequate tillage and sowing practices.

In the literature, most models predicting soil erosion generally do not aim to simulate the evolution of the soil surface and its structure, but rather only to predict soil loss, see for example (Lane and Nearing, 1989; Morgan et al., 1998; Favis-Mortlock et al., 2000). They often operate at rather large scale, and share the same basic principles and range of processes described, as well as the formalism used to describe these processes. For example, they almost have in common the principle of flow of water or material according to the greatest gradient, or the transport capacity concept. Although on that point our simulator does not significantly differ from most models, it presents several originalities arising mainly from the (small) scale considered and the fact we focus on the evolution of soil surface relief and structure rather than on soil loss. Our model considers explicitly a 3D space, it allows the fragmentation of the soil into particles of different sizes which can be mobilized, projected by splash, transported or deposited by runoff, which permits a tracking of the granulometry of sediments. This is an important issue as it allows to describe a spatial (vertical and horizontal) and temporal evolution in the physical state of the soil, and interactions between this evolution and the processes at work. Finally, most processes descriptions have been revisited to include new important aspects and/or the more recent knowledge, and the description remains open so that our simulator could be a useful tool to test hypothesis and modelling new ideas.

A preliminary version of our work was presented in (Valette et al., 2006b). This model was based on Extended Cellular Automata (Avolio et al., 2003) but we were confronted with two main difficulties: i) rainfall is better represented as a discrete events process than as a discrete time process; ii) we needed the possibility of modelling a process in a global way, in order to keep the simulator as open as possible to new ideas. Thus, we changed our modelling approach by using Discrete EVents system Specification (DEVS), and in particular the concept of non modular cellular DEVS proposed in (Shiginah, 2006). The aim of the present paper is to present in detail this new model of soil degradation by rainfall.

BACKGROUND

Informal description

We study the evolution of a portion of land of metric size which is submitted to a rainfall, real or simulated. This evolution is governed by the three types of water transfer: rain, infiltration, runoff. We don't take into account the effect of evaporation because it is negligible during rainfall. The three processes transport water but rainfall and runoff have also an effect on the soil: rainfall can break the soil into fragments and project them, runoff can mobilize, transport or deposit fragments (Fig. 1).

These three processes are very comparable in their effects on the soil, but they are very different by their nature: when they occur, infiltration and runoff are continuous phenomena, whereas rain is a succession of arrivals of raindrops, each one being localized precisely in time and in space. That is why we chose to model the first ones as discrete time processes, and the third one as a discrete events process (Fig. 2). Another difference between these

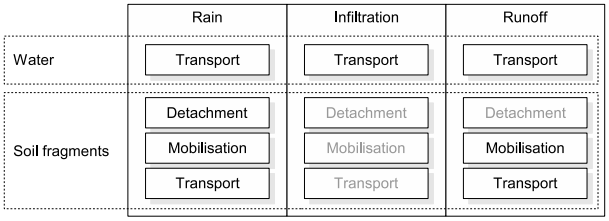

Figure 1: Description of the processes governing the evolution of the soil.

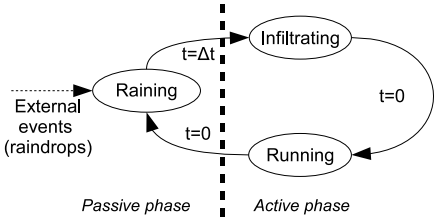

Figure 2: The event scheduling graph of the processes.

processes is their localization: infiltration and runoff can be modeled by using local information, i.e., the state of the immediate neighbours of a cell, whereas the transport of fragments by splash (i.e., the impact of a raindrop) may concern distant cells. Finally, the time step required to simulate these different processes may differ by one or two orders of magnitude.

Cellular Spaces and DEVS

In order to model a system in a spatialized way, cellular spaces are of great interest. When the behaviour of the system depends on local interactions, like diffusion, Cellular Automata (CA) can be used, and many examples can be found in the literature, in various domains. Nevertheless, natural phenomena are often complex behavioral dynamic systems and cannot easily be modelled with a standard CA model. For this reason, many works were dedicated to improve simulation based on CA. In order to simulate different phenomena like lava and debris flows, landslides or contaminated soils bioremediation, Di Gregorio et al. (Di Gregorio and Serra, 1999; Di Gregorio et al., 1999) proposed the principle of Macroscopic CA, with four main novelties: (i) for each cell, a nearly unlimited number of states is permitted, each state being composed of substates, with possibly continuous values; (ii) the transition function is split in several parts, each one corresponds to an elementary process of the macroscopic phenomenon; (iii) each elementary process may have its own neighboorhoud and internal transformations are allowed; (iv) substates of type "outflow" are used in order to account for quantities moving from a cell toward another one in the neighbouring. This model assumes that the whole phenomenon can be described by sequentially calculating internal transformations and local interactions. Avolio et al. (Avolio et al., 2003) developed this empirical approach and used Extended CA in order to model surface flows, taking into account "external influences" which cannot be described in terms of local rules.

We used Extended CA to describe a preliminary version of our simulator (Valette et al., 2006b). However two difficulties raised: i) Extended CA does not offer a way to rigorously specify these external influences which are simply considered as special or additional functions; ii) these influences must be treated as discret time processes, thus, they consider the state of the cells at the end of the previous iteration in order to compute the new state of the cells. In the case of the rain, it is obvious that the arrival of a raindrop is better represented as a discret event: a raindrop modifies the state of some cells, and this state must be taken into consideration for the next event. Asynchronous CA (Schönfisch and de Roos, 1999) can model such behaviour, but runoff and infiltration should then be considered as discrete events also although they are better modeled as discret time (i.e., synchronous) CA.

For these reasons, we chose to use the Discrete EVent system Specification (DEVS) formalism. This formalism was introduced by Zeigler (Zeigler, 1976), in order to allow specifying simulation programs independently of a particular language. In (Zeigler, 1984) it was extended to enable constructing discrete event simulation models in a hierarchical and modular manner. At the lowest level, an "atomic" DEVS describes the autonomous behaviour of a discrete-event system with three transition functions: an internal transition function δ_{int} which determines the transitions between sequential states, an external transition function δ_{ext} which describes how the system reacts to external input (events), and an output function λ which is in charge of the generation of output (events). An advantage of DEVS is this separation between internal and external transition functions, which permits to specify in an independant way the behaviour of the system in case of the presence, or absence, of an external influence — that is exactly what we needed. At the higher level, a coupled DEVS describes a system as a network of "coupled" components. These components are either atomic DEVS or, thanks to the property of closure under coupling, coupled DEVS. To reproduce the interactions between components, a component communicates via ports to send outputs to other components and to receive inputs from components. The parallel version of DEVS, Parallel DEVS (P-DEVS), was introduced in (Chow and Zeigler, 1994). This model preserves hierarchical and modular construction properties of DEVS and permits to introduce Cellular DEVS (Zeigler et al., 2000) and Cell-DEVS (Wainer and Giambiasi, 2001b) which integrated the theories and algorithms of CA in DEVS.

In conventional cellular DEVS approaches, the cell space is implemented as a coupled DEVS model that contains a number of cells that are arranged in an array, each cell being considered as an atomic DEVS model which communicates with its neighbours through the system of ports. In case of a great number of cells (e.g., in our case, a typical cell space contains 200x200x10 cells), the inter-cell communication generated during simula-

tion represents a huge volume of messages and can be very time consuming. To overcome this drawback, in (Wainer and Giambiasi, 2001a) the coordinator hierarchy of the simulator is flattened. In (Muzy and Nutaro, 2005) unnecessary coordinator objects are eliminated and scheduling algorithms deal with active cells only, like in (Hu and Zeigler, 2004). These approaches consider the implementation level and keep treating each cell as an atomic model. The work presented in (Shiginah, 2006) takes advantage of these enhancements and applies similar methods to the model development level, giving as a result a non-modular cellular space representation, equivalent to a P-DEVS atomic model, which simplifies the modeling process.

Following Shiginah's approach, we consider our soil degradation model as a coupled P-DEVS model, in which the terrain is a cellular space, considered as an atomic P-DEVS model. This allows simpler specification and faster simulation. Another advantage is that DEVS naturally permits to consider raindrops as external discrete events, whereas infiltration and runoff can be yet considered as internal synchronous transitions. Moreover, the split of the transition function in elementary processes, which is an extension proposed in Macroscopic CA, is explicitely allowed in DEVS by using different phases of the model, each one corresponding to one process and to one function. Each function may have its own rules, including the neighbourhood. Finally, as we consider the cellular space in a non modular way, we allow a global knowledge of the cell space to compute the next state of a cell.

DETAIL OF OUR MODEL

Before detailing the coupled and the atomic models of our simulator, we present in the next section the structure of the terrain.

The structural model of terrain

The terrain is discretized into a regular 3D grid. The user can choose the dimension of the cells, which are geometrically identical rectangular parallelepipeds. Typically, we use cubic cells of 2mm side, for two reasons. First, 2mm is the resolution of the digital elevation maps we obtain by laser rugosimetry, and it is natural to keep this original information unchanged for the width and the length of the cells. Second, the biggest soil fragments we consider have a mean diameter comprised between 1mm and 2mm, thus a depth of 2mm is necessary and sufficient to insure that the cells can contain these fragments.

As shown in Fig. 3, our structural model of terrain consists of one 3D cellular grid and five outlets. These outlets are adimensional cells which keep information of the quantities of water and fragments coming from the boundary cells of the terrain. There is one outlet for each cardinal direction and another for the bottom. There is no need for a top outlet because neither the water nor the fragments go to the atmosphere.

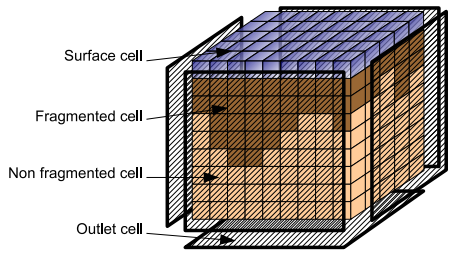

Figure 3: The structural model of terrain.

The cellular grid contains 3 types of cells:

- non-fragmented cells are cells which do not contain any soil fragments; they contain infiltrated water, matter which constitutes the original soil, considered as continuous, and the cumulated kinetic energy propagated vertically from the surface to the subsoil by the impact of raindrops;
- fragmented cells are non-fragmented cells which have been impacted by a raindrop or have received fragments from another cell, by splash or runoff; they have the same information than the non-fragmented cells, plus the volume of particles corresponding to each of 7 classes of particles, ranging from 0-20μm to 1-2mm;
- surface cells compose the top layer and contain the same information than the fragmented cells, plus 2D information: height of the water surface, height of the terrain at the center of the cell, and the volume of particles present in the flow above the cell for each of the size classes.

The coupled P-DEVS model

We use the concept of experimental frame in order to separate the experiments and the model itself. The experimental frame strategy (Zeigler, 2000) treats the model as a black box that is tested and it reflects the objectives of the experimenter who performs experiments on a real system or, through simulation, on a model (Vangheluwe, 2000). The same experimental frame can be used to test different models, or a model can be tested with different experimental frames. We use both of these possibilities, because we want our simulator to be able of producing realistic results but, in the same time, to be a way of testing new ideas about the processes involved. The experimental frame is decomposed in Acceptor, Transducer and Generator (Fig. 4).

The Acceptor produces an unique output which indicates if the simulation continues or not. To make its decision, it can compare the outputs generated by the model with expected values controls, if any.

The Transducer receives as input the state of the model and applies transformations for meaningful interpretation by the user or the Acceptor. One of the tasks of the Transducer is to produce images or animations from the state

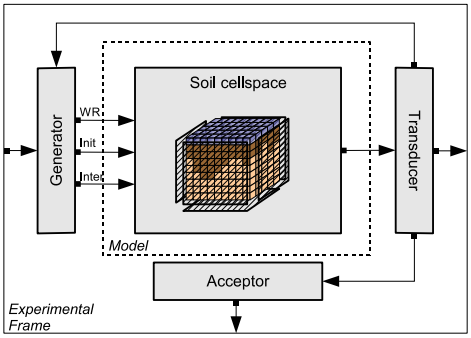

Figure 4: The coupled P-DEVS model of the soil degradation by rainfall.

of the cellular space. It is an important issue because direct visual observation is an important method of validation. We thus want to provide realistic or informative visual representation of the numerical results obtained during a simulation, in order to allow visual comparisons between the model and the real system for example. For that we use mesh rendering and volumic visualization.

The Generator describes the inputs or stimuli applied to the system or model during an experiment. In our case, we separate these inputs in 3 categories, which correspond to three ports (Fig. 4): initialization, interaction and water/rain generation. The initialization permits to define the conditions of the virtual experiment, including time step, values of parameters used in the equations of the transition functions, characteristics of the soil (topography, initial water content, size of the particles,...) It allows the user to change the model itself, by choosing the behaviour of the transition functions. For example, the user can inhibit infiltration to get an impermeable soil, or choose between different formalisms to calculate the splash distance. The interaction allows the user to send inputs to the model during the simulation, e.g., adding fragments on a cell of the terrain, changing the flow of a water source, which extends the possibilities of the numerical experiments. Finally, water/rain generation is responsible for adding water to the terrain or to let raindrops fall on it. The output is in this case composed by two indications: the coordinates (x,y) of the cell which will receive the water, and the quantity of water, i.e., the diameter d of a spherical raindrop or the height of water h to add on a cell. The Generator is able to reproduce a constant flow coming from one boundary, or a single drop falling in the center of the terrain. Of course, it can reproduce a simulated rain with respect to a given raindrop size distribution, limited or not to a portion of the terrain. Finally, it can simulate a real rain, using a hyetogram, and assuming a gamma distribution of raindrop sizes, which has been shown to be a good model of the raindrop arrival process (Uijlenhoet and Stricker, 1999). The main advantage of the discrete representation of raindrops is to permit an explicit discrimination between the effects of rain intensity and raindrop size.

Thus, the coupled P-DEVS model SD of the soil degradation by rainfall is defined by the following structure, illustrated in Fig. 4:

$$SD = \langle X, Y, D, \{M_d\}, \{I_d\}, \{Z_{id}\} \rangle$$

- X is a set of the input values, which are indications sent by the external world, e.g., the user interface, to the Generator.
- Y is a set of the output values, coming from the Transducer (e.g., images, plots) or the Acceptor (yes/no).
- $D = \{g,t,a,s\}$ is a set of components references.
- for each d in D, M_d is a component, i.e., a P-DEVS model: M_g is the Generator, M_t is the Transducer, M_a is the Acceptor and M_s is the Soil.
- for each d in $D \cup \{SD\}$, I_d contains the influencees of d (d cannot be in I_d): the influences of the model are represented by the arrows in Fig. 4.
- for each i in I_d, Z_{id} is a function, the i-to-d output-to-input translation.

Atomic model of the terrain

In (Shiginah, 2006), there is a proof that a non-modular cellular space keeps the general P-DEVS structure and hence equivalency, the former model having more details and parameters which can be implied in the internal behavior of any P-DEVS atomic model. Thus, we use the specification of a P-DEVS model to describe the atomic non-modular cellular model T of the terrain:

$$T = \langle X, S, Y, \delta_{int}, \delta_{ext}, \delta_{con}, \lambda, ta \rangle$$

- X is the set of the input values coming from the Generator, i.e., for the port "WR" the values $\langle (x,y), d, h \rangle$, determining the location (x,y) on the surface of the terrain and the diameter d of the impacting raindrop, or the height h of the incoming water.
- Y is the set of the output values, i.e., the state of the terrain, transmitted to the Transducer.
- S is the set of general states of the atomic model, i.e., $\{\{\text{"}active\text{"},\text{"}passive\text{"}\} \times S^*\}$, S^* being the set of values s of the variables contained in the cells. The model is "$passive$" when it is waiting for external events, and becomes "$active$" when it has to manage infiltration and runoff (Fig. 2).
- $\delta_{int} : S \to S$ is the internal transition function, i.e., the succession of the infiltration $\mathcal{I}$ and the runoff $\mathcal{R}$ functions:
  $\delta_{int}(\text{"}passive\text{"}, s) = (\text{"}active\text{"}, \mathcal{I}(s))$
  $\delta_{int}(\text{"}active\text{"}, s) = (\text{"}passive\text{"}, \mathcal{R}(s))$

- $\delta_{ext} : Q \times X^b \rightarrow S$ is the external transition function, where X^b is a set of bags over elements in X, i.e., incoming water or raindrop and their location, and $Q = \{(s,e) \mid s \in S,\ 0 < e < ta(s)\}$, e being the elapsed time since last state transition. This function is fired in response of the arrival of a raindrop, thus it is the splash function $\mathcal{S}_p$:
$\delta_{ext}(\text{“}passive\text{”}, s, e, x^b) = \big(\text{“}passive\text{”}, \mathcal{S}_p(s, x^b)\big)$.

- $\delta_{con} : S \times X^b \rightarrow S$ is the confluent transition function and is fired when a raindrop arrives at Δt (the time step) and has a standard behaviour:
$\delta_{con} = \delta_{int} \circ \delta_{ext}$,
meaning in our case that we execute the splash function $\mathcal{S}_p$ before infiltration $\mathcal{I}$:
$\delta_{con}(\text{“}passive\text{”}, s, e, x^b) = \big(\text{“}active\text{”}, \mathcal{I} \circ \mathcal{S}_p(s, x^b)\big)$.

- $\lambda : S \rightarrow Y^b$ is the output function, called before the internal transition function, and it simply transmits the state of the terrain to the Transducer when the phase is “*passive*”:
$\lambda(\text{“}passive\text{”}, s) = s$
$\lambda(\text{“}active\text{”}, s) = \emptyset$

- $ta : S \rightarrow \mathbb{R}^+$ is the time advance function:
$ta(\text{“}passive\text{”}, s) = \Delta t$
$ta(\text{“}active\text{”}, s) = 0$

The next section briefly presents the principles of the transition functions which reproduce the elementary processes.

PRINCIPLES OF TRANSITION FUNCTIONS

Splash

The splash function $\mathcal{S}_p$ has 5 consequences on the terrain: i) it adds water on some cells; ii) it eventually detaches fragments from these cells (fragmentation of the soil); iii) it mobilizes already present fragments; iv) it projects fragments; v) it transfers raindrop kinetic energy to the impacted surface cells and also to the corresponding subsoil cells. Water is redistributed according to the projected area of the raindrop over the target cells and its neighbours, taking into account the non spheroidal shape of raindrops for diameters above 2mm (Beard and Chuang, 1987). Each drop detaches a quantity of soil which is proportionnal to its kinetic energy above a threshold (Sharma et al., 1991) and which decreases exponentially with the ratio of flow depth to raindrop size (Kinnell, 2005). We use results from aggregate stability tests to determine how to distribute the detached mass amongst the different particle size classes (Legout et al., 2004). All the newly created fragmented particles are mobilized and thus projected. The splash distance depends on the size of the fragments (Legout et al., 2005) and on the local slope (Furbish et al., 2007). The projection direction from the center of impact is randomly chosen from a probability density function which depends on local slope (Furbish et al., 2007). Finally, the transfer of kinetic energy to the downward cells is based on a decreasing function of the depth to raindrop radius ratio. The density of each cell then evolves as a function of both the cumulated kinetic energy and the granulometry.

Infiltration

The infiltration function $\mathcal{I}$ removes water from the surface and adds water in the void space of the cells. Three different models of infiltration were implemented. We used first a CA-based version of the Richard's equation (both in full 3D and 1D vertical for each column of cells) based on a report algorithm between adjacent cells. The main drawback of this method (in addition to the fact it is very time consuming) was that it necessitated to extend the cellular domain well deeper than the wetting front to operate. It was not always easy to determine the correct extension before the simulation, and simulation time grows rapidly as we multiply the number of cells. We also tested the Green-Ampt approximation (Green and Ampt, 1911), with an “1D vertical for each column of cells” implementation. The results obtained with both models were compared with success, in a simple situation, to results from a numerical resolution of the Richards' equation. However the classical Green and Ampt model was not adapted to the description of flow through a crust whose properties, in addition, change through time. We thus implemented a third infiltration model, much more specific to flow through a crust, which allows a simple, quick and accurate description of infiltration (excepted at the very beginning of the simulation). We assumed for that a steady state flux through the crust and the corresponding subsoil during an iteration, which allows to estimate from the hydrodynamic properties of the subsoil and the thickness and hydraulic conductivity of the crust the pressure at the soil crust interface, and thus the flux through the crust. The saturated hydraulic conductivity of the crust is estimated by the harmonic mean of the saturated hydraulic conductivity of the crusted cells, the conductivity of the cells depending on their density (which evolves with the evolution of the granulometry and the cumulated kinetic energy). This method necessitates a definition of the crusted cells: we consider a cell as crusted when its saturated hydraulic conductivity is below a fraction of the saturated hydraulic conductivity of the initial soil. It is interesting to notice that this infiltration model is not based on local interaction, thus that it cannot be modeled with CA, which is not an issue with the current P-DEVS model.

Runoff

The runoff function $\mathcal{R}$ transports water and soil fragments after their mobilization. The transport of the soil fragments is determined by the transport of water. Thus, this function has to determine first how much water is transferred and where it is transferred, and then decides from this information how many particles, from which classes, are transported and where they are transported. In that purpose, we take into account the flow depth and the altitude of the soil surface, the sum of these two

quantities being used to define the total hydraulic head, neglecting the kinetic component which is always very small in our study context. We transfer water from one source cell to a unique target cell only, in the direction of the highest head gradient. We treat all the cells, from the lowest head cell to the highest head cell, as potential receivers of water emitted by their neighbours. When a cell emits water, it is marked and is no more eligible to transmit water for this iteration of the process. The flow from a source cell to a target cell is calculated using the Darcy-Weisbach equation (Chow et al., 1988). One main issue in this report algorithm is that the quantity of water transferred to a cell must not be higher than the difference in hydraulic head between the source cells and the target cell, because the target cell would then become a source cell at the next iteration, and so on, causing instability. For this reason we calculate a maximum quantity of water that a cell can receive from each neighbour by means of an equilibrating algorithm which is detailed in (Valette et al., 2008). In order to validate this model, we have compared the results of a simulation on a simple impermeable slope to results obtained using a numerical solution of the classical Saint Venant's equations (Zhang and Cundy, 1989) on the same terrain, and both results are in close agreement.

Water can transport sediment in several ways. The total sediment load of flowing water can be subdivided into bedload and suspension load, which is important because these modes of transport are not equally sensitive to the local topgraphy. In a cell which emits water, we first calculate the local shear stress, which depends on hydraulic conditions. Then, to decide how particles from a class will be transported, we use the Rouse number, defined as the ratio of particle settling velocity to the shear velocity (i.e., rate of fall versus strength of turbulence acting to suspend particles). The critical shear stress (which corresponds to the beginning of the motion of the particles) of particles from that class is calculated from the Shields' curve and adjusted to take into account the effect of slope (gravity, effect of the particle diameter to flow depth ratio) (Lamb et al., 2007). Sediment transport is then estimated from the excess shear stress using an empirical formula (Julien, 1998). It is worth noticing that we take also into account the effect of lateral erosion on a dry cell in the neighbouring of a cell emitting water.

CONCLUSION

We develop a simulator of the evolution of soil surface structure of cultivated soils under rainfall, at the meter scale. This is an important issue as it has both theoretical and practical interest. In this paper, we have detailed the model of our simulator, based on the P-DEVS formalism which permits to give a concise, not restrictive yet rigorous specification of its structure and its behaviour. Infiltration and runoff are modeled as discrete time processes, whereas raindrops arrivals are considered as external discret events. The models of the different processes involved were validated by comparison with numerical solutions of continuous systems or with results of real experiments available in the literature. We plan to complete the results with our own experiment of rain simulation on a portion of soil, in order to calibrate the parameters of the simulator and to validate its global behaviour. Finally, we want to develop an algorithm to predict the nature of the crust close to the visual characterization made by an observer in a field.

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