Catchment Scale Simulation of Soil Evolution- the *mARM4D* Model: A spatially and temporally explicit 4D Soil-Landscape model

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1. Introduction

Soil properties play a major role in most hydrological and geomorphologic processes. The spatial and temporal dynamics of soil properties are typically extremely complex and therefore difficult to quantify. Here we present a novel 4D landscape-pedogenesis (soil evolution) model which allows detailed quantitative description of the spatio-temporal soil properties dynamics throughout the landscape.

2. Modelling Concept

mARM4D is a four-dimensional (3 spatial and 1 temporal dimensions) landscape-pedogenesis model. It simulates detailed changes in soil grading as a function of surface (lateral) and profile (horizontal) processes. The soil profile is explicitly described for every node (pixel) on the landscape by a finite number of layers (defined by the user).

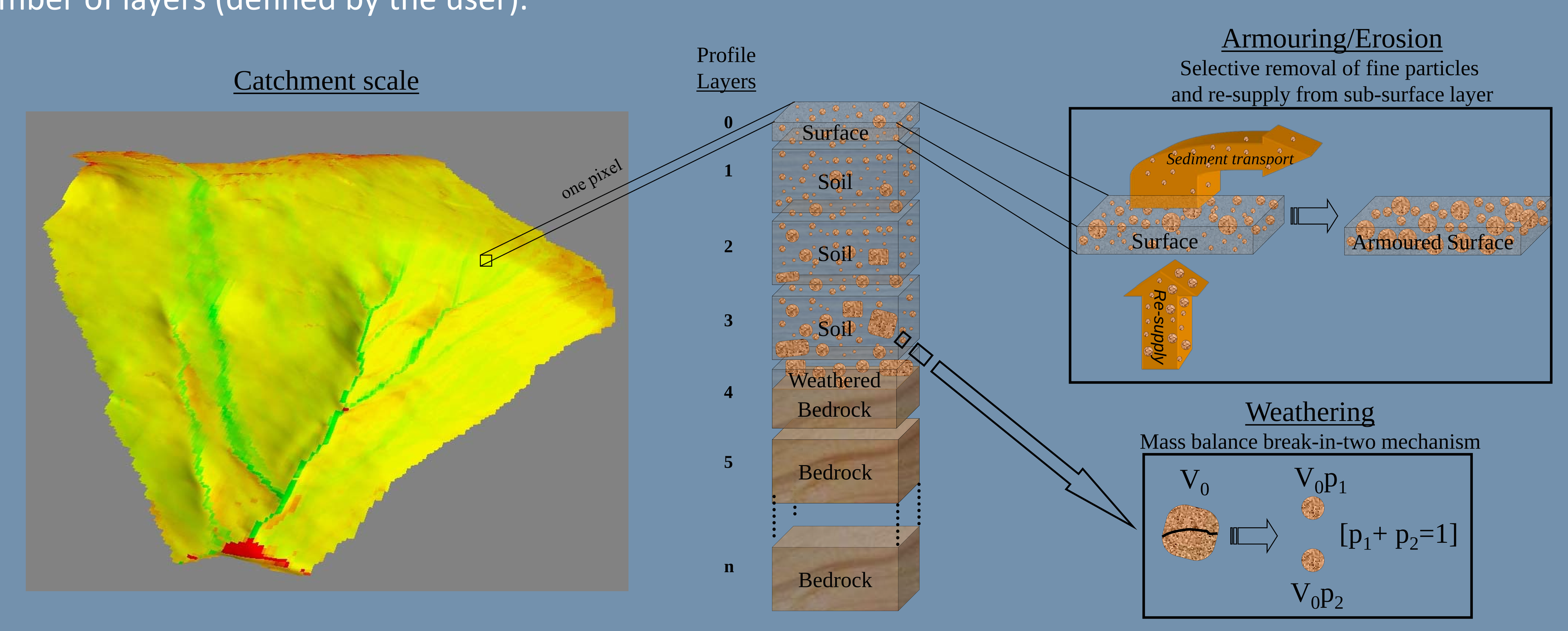

Figure 1: *Catchment-scale domain (left) and schematics of mARM4D model. Surface soil grading is simulated as a function of selective entrainment or deposition of particles. Both surface and sub-surface are represented in layers which are subject to weathering as a function of soil depth. By default the soil profile layers are set as bedrock at the start of the simulation (layers 5-n in Figure 1), an ad initio soil evolution (a detailed description is available at Cohen et al., 2010).*

Here soil evolution is conceptualized by simulating only the physical aspect of the soil-landscape dynamics: physical weathering and erosion/deposition at the surface (Figure 1).

To overcome the immense computational requirements for detail calculation of landscape-pedogenesis dynamics, mARM4D is based on a novel coupling of physically-based equations and transition matrices (Equation 1&2). The transition matrices express the physics of the processes acting on a layer (e.g. erosion, weathering; Equation 1) and the interactions between the profile layers (material rearrangement as a function of erosion, deposition or translocation; Equation 2). This allows for a simpler calculation of the processes with minimal compromise of the processes physics (*Cohen et al.,* 2009 & 2010a).

$$\begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_k \end{bmatrix}_{t+1} = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_k \end{bmatrix}_{t} + \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1k} \\ A_{21} & A_{22} & \cdots & A_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ A_{k1} & A_{k2} & \cdots & A_{kk} \end{bmatrix} \cdot \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_k \end{bmatrix}_{t}$$

__Equation 1__: Soil grading (represented in k number of groups (g)) in time step t+1 is calculated by multiplying the soil grading vector at time t by the transition matrix **B**. *The transition matrix entries are physically-based and express the dynamic between the grading class as a function of the simulated process (e.g. weathering, erosion).*

$$\begin{bmatrix} \underline{g}_s \\ \underline{g}_1 \\ \vdots \\ \underline{g}_n \\ \underline{g}_\infty \end{bmatrix}_{t+1} = \begin{bmatrix} \underline{g}_s \\ \underline{g}_1 \\ \vdots \\ \underline{g}_n \\ \underline{g}_\infty \end{bmatrix}_{t} + \begin{bmatrix} [\mathbf{B}]_{ss} & [\mathbf{B}]_{s1} & \cdots & [\mathbf{B}]_{sn} & [0] \\ [\mathbf{B}]_{1s} & [\mathbf{B}]_{11} & \cdots & [\mathbf{B}]_{1n} & [0] \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ [\mathbf{B}]_{ns} & [\mathbf{B}]_{n1} & \cdots & [\mathbf{B}]_{nn} & [\mathbf{B}]_{n\infty} \\ [0] & [0] & \cdots & [0] & [0] \end{bmatrix} \cdot \begin{bmatrix} \underline{g}_s \\ \underline{g}_1 \\ \vdots \\ \underline{g}_n \\ \underline{g}_\infty \end{bmatrix}_{t}$$

Equation 2**: Transition matrices are also used to calculate the dynamics between the profile layers. Each vector here is a super vector which describe the grading vector in each layer ($\underline{g}$). The matrix here is a super matrix in which each entire* **[B]is a layer specific transition matrix* **B** *(Equation 1). This super matrix describe how the grading of each layer interacts with each other layer.*

3. The Model's Physics

(1) <u>Weathering</u> is expressed by a mass conservative mechanical breakdown of bedrock and soil particles into two equally sized daughter particles (p_1 and p_2 in Figure 1). The diameter of the two daughter particles, d_1 and d_2, is calculated by $d_1 = d_2 = \frac{d_0}{(1+\alpha^3)^{1/3}}$ where d_0 is the diameter of the parent particle and α is the proportion between parent and daughter (0.5 in this case). This process is calculated in each profile layer (and the surface layer) for each particle size-class (g_k in Equation 1).

(2) Sediment flux (q_s) from each pixel is calculated at every iteration by $q_s = e\frac{q^{\alpha_1} S^{\alpha_2}}{d_{50}^{\ \beta}}$ ere e is the erodibility factor, q is discharge per unit width , S is slope, d_{50} is the median diameter (m) of surface layer and α_1, α_2 and β are calibration parameters. **Erosion rate** (E) is the budget between inflowing (q_{sUS} - upstream sediment flux) and outflowing sediment in each pixel: $E = \Delta q_s = q_s - q_{sUS}$.

<u>**Armouring**</u> is calculated by selective removal of surface particles when E>0 (erosion). The **entrainability** of each size-class (g) is expresses in the erosion transition matrix (**A**): $A_{kk} = \begin{cases} \frac{a}{d_k^{\ m}} g_k & for \quad k < M \\ 0 & for \quad k > M \end{cases}$ where A_{kk} is the diagonal entries of **A**, d_k is the mean diameter (m) of size class k, the power m needs to be calibrated, a is scaling factors, and M is a size threshold that determines the largest particle diameter that can be entrained in the flow (determined by the Shield stress threshold).

<u>**Deposition**</u> is calculated by selective settling of particles from the inflowing sediment when E<0. The relative deposition rate of each size-class is expresses in the deposition transition matrix (**D**): $D_{kk} = \frac{b}{g_{fk} V_{sk}}$ where D_{kk} is the diagonal entries of **D**, g_{fk} is the particle size-class of the inflowing sediment, V_s is the settling velocity for size class k and b is a scaling factors.

4. Selected Results

Below we present selected results from a small-scale simulation of a 7ha catchment (pixel resolution of 4m). Soil evolution is simulated over 300,000 years. Initial conditions were set as full bedrock profile and the simulation ended at a state of dynamic equilibrium between weathering and erosion.

We present these results to showcase mARM4D as a detailed and dynamic modelling platform.

Three-dimensional Soil Grading (d_{50})

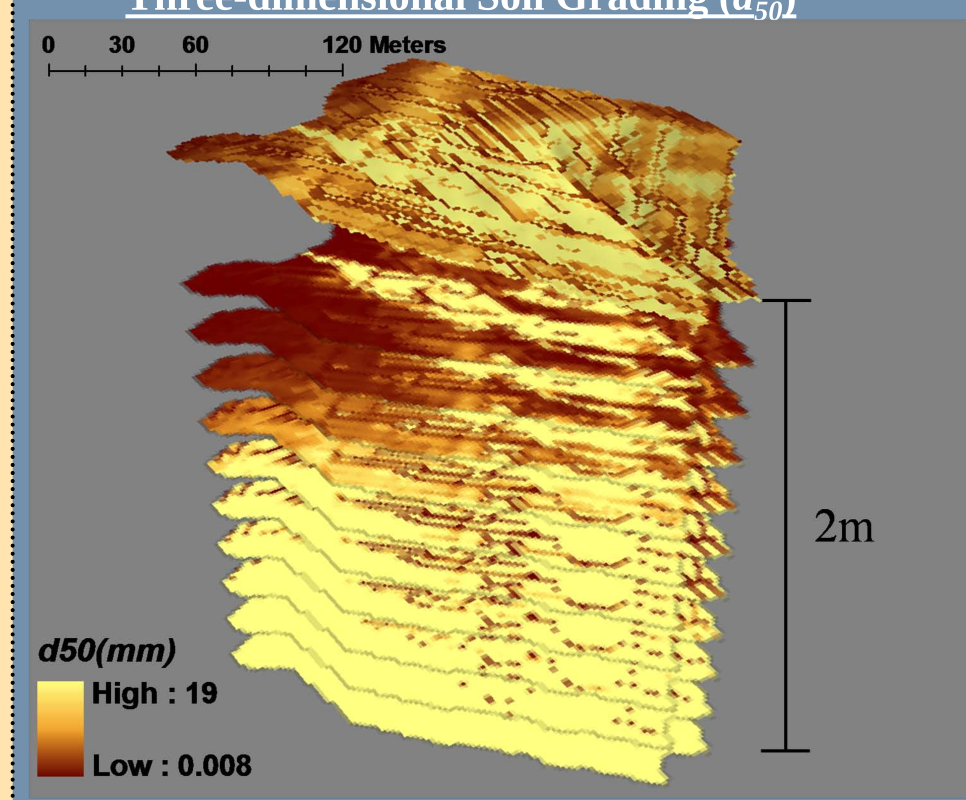

Figure 2: *This figure show the soil grading (expressed by median diameter- d_{50}) in every second layer (out of 20) down the profile. It illustrates the detailed description of the soil profile for each pixel on the landscape.*

It shows that the bottom layer is completely occupied by bedrock. The soil profile has a general morphology of a very fine-grained B horizon (about 60-80cm thick) underneath a coarser surface and overlaying a coarse C horizon.

This detailed description of the soil profile has a lot of potential for hydrological modelling.

Equilibrium Surface Soil grading (d_{50})

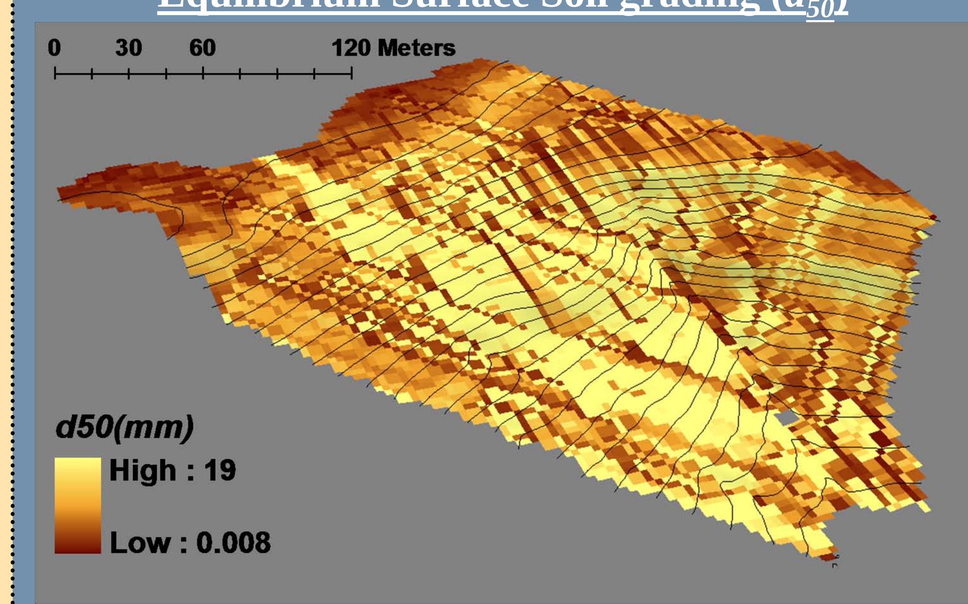

Figure 3: *Equilibrium surface soil grading (expressed by median diameter- d_{50}). It shows a complex spatial dynamics of very fine soil at the less erosive sections of the catchment (hilltops), varying degree of coarse and fine soils along the erosive and deposition regions and very coarse (armoured) soils along the flow paths.*

This spatially detailed description of surface soil conditions has a lot of potential for geomorphological modelling (e.g. landform evolution).

Proportion of Sand at the surface

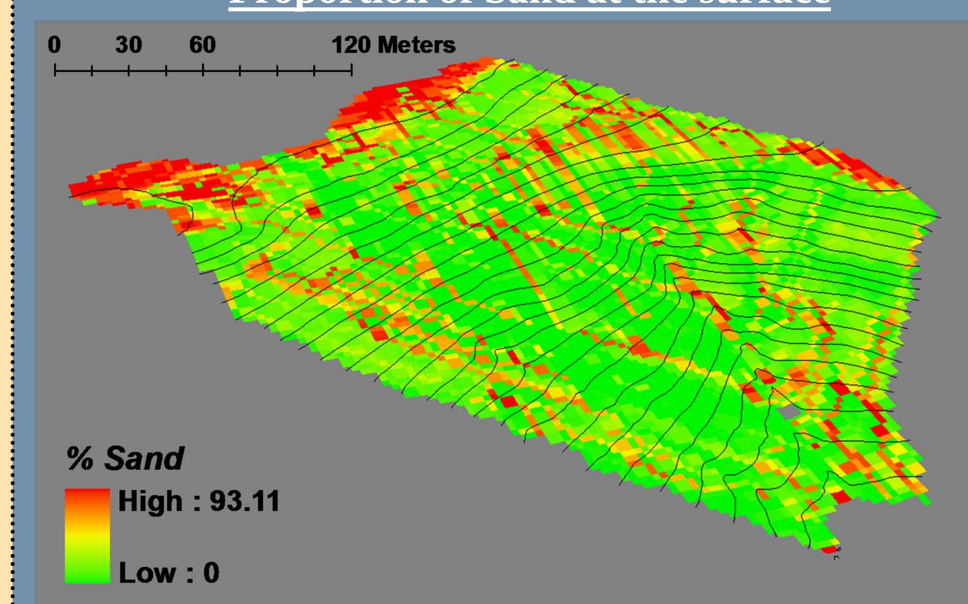

Figure 4: *The percentage of sand-sized particles at the surface. There is a notably high concentration of sandy texture at the upslope regions of the catchment. This illustrate the importance of detailed description of soil as some soil properties may have different spatial dynamics then others.*

Quantifying soil texture dynamics is important for quantifying many environmental processes such as hydrological and vegetation dynamics.

Equilibrium Soil Depth

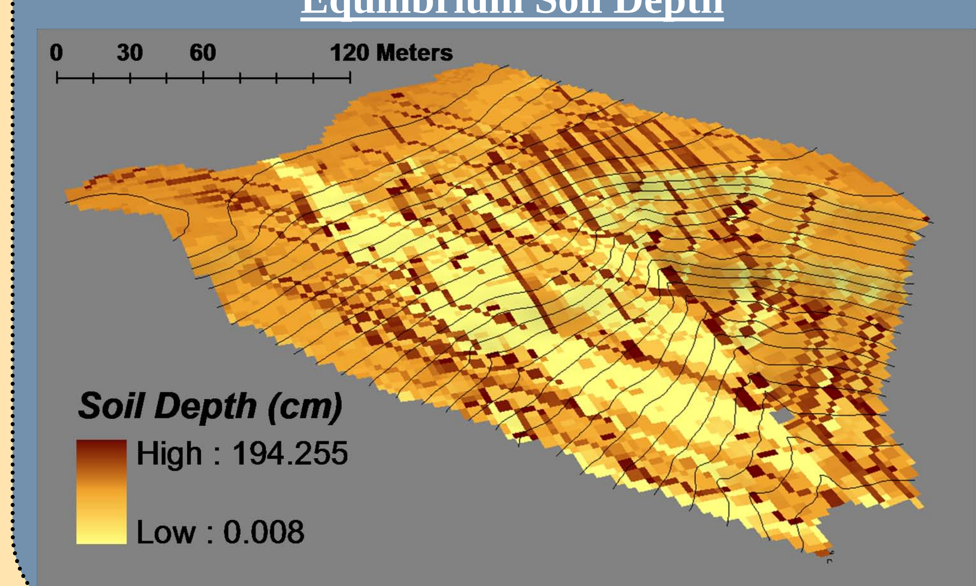

Figure 5: *Equilibrium soil depth. It shows a complex distribution of soil thickness throughout the catchment. Very low soil thickness is observed along the flow paths. There are many bands of high soil thickness in various parts of the catchment, mostly due to deposition.*

Soil depth is an important soil property which is difficult to measure or predict. It has a large impact on most hydrological processes.

5. mARM4D as a virtual-laboratory

The computational efficiency of mARM4D allows for long-term and large-scale simulations of landscape-pedogenesis dynamics. The detailed description of soil grading and profile layers allows explicit and high-resolution description of 3D soil distribution. These futures makes mARM4D a useful platform for examine a wide range landscape-pedogenesis concepts.

In the past we used earlier versions of the model to study:

1. The weathering-erosion relationship (Cohen et al., 2009);
2. The effect of various soil production and soil weathering functions on soil evolution and distribution (Cohen et al., 2010a);
3. The effect of Late Quaternary climatic fluctuations on soil evolutionary trends (Cohen et al., 2010b).

Using mARM4D, we are currently studying the impact of the development of human civilisation (in the last 10,000 years) on soil distribution.

Future work will focus on adding and examining additional soil-landscape processes such as **chemical weathering, bioturbation, translocation, vegetation dynamics** etc.

6. Conclusions

The mARM4D was designed to improve our ability to quantify spatio-temporal dynamics of functional soil properties. One of the major obstacles we had to overcome was the immense complexity of the soil-landscape interaction. This was achieved in mARM4D by a novel combination of physically-based equations and matrices numerics which makes mARM4D an extremely modular and computationally efficient model (10^5 faster then an equivalent physically-based model; Cohen et al., 2009).

Here we briefly described the model and showcased some of its capabilities. We are currently using mARM4D as a virtual-laboratory to improve our understanding on key soil-pedogenesis concepts. Our vision is that with additional development and validation mARM4D will be used as a digital soil mapping tool and as an explicit soil evolution component in other landscape models (e.g. landform evolution; TelluSim).

References

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•**Cohen, S.,** Willgoose G. R., and Hancock G., (2010b), Using the mARM3D soil-landscape model to study the affect of climate dynamics on soil processes and properties, EGU meeting 2010- abstract number 3869.

•<u>TelluSim model</u>: Willgoose, G.R, (2008), TelluSim: A Python Plug-in Based Computational Framework for Spatially Distributed Environmental and Earth Sciences Modelling. AGU Fall meeting 2008: abstract number H41G-0957