Long-term soil landscape modelling in a Mediterranean agricultural environment

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Abstract

Nowadays, soil is subjected to rapid evolutions induced by climate changes and humans disturbances. Modeling is an appropriate methodology to analyse, understand space time evolution in soil and landscape processes and to test the effect these climatic and anthropogenic variations on soil cover evolution at short and medium term. And indeed to propose future technologies and landscape management practices to conserve soil. This study presents the LandSoil model, which is an event based model, dimensioned for fine spatial [1 m] and medium [10 –100 years] temporal scales, taking into account a detailed representation of the agricultural landscape structure. The aims of this research were to use pedological knowledge coupled with the LandSoil model to simulate soil evolution as affected by soil redistribution processes e.g. water-erosion processes and mechanical erosion. The model has been calibrated and validated under the current environmental conditions and landscape structure. Results confirm the observed patterns in terms of soil development and redistribution, as well as the preponderant effect of landscape structures to reduce climatic effects.

Key Words

Quantitative pedology, quantitative modelling, landscape evolution, landscape scale, long-term soil redistribution modelling, soil erosion, tillage erosion.

Introduction

Early soil scientists had already sought to identify the dynamic dimension of soils (Dokuchaev 1883; Kossovich 1911; Shaw 1932). Soil evolution over time was integrated as a factor of soil formation by Jenny (1941, 1961). This perception of soil evolution over time, often achieved at the profile scale, was accessed during last decades by studies focusing on quantitative pedology at the landscape scale. It appears that soils and landscapes evolve simultaneously (Hall, 1983): soil organization evolution is mainly controlled by soil redistribution processes due to water and tillage erosion (Hairsine and Rose 1992a; 1992b; Lindstrom *et al.* 1992; Quine *et al.* 1999), influenced by topographic and climatic parameters, but with a major contribution of management strategies. The perennial landscape features have also a strong influence on soil spatial distribution (geometry) and soil genesis (Follain *et al.* 2006).

In recent studies, soil was subjected to rapid evolutions. Two ways of fast soil cover changes can be identified: changes induce by climate and those induce by humans. Human induced changes are those which can be implemented by the farmers individually at the field or farm scale and those which can be imposed by policy- and decision-makers (land planners, natural resource managers) at a range of scales (farm, municipality, catchments, region). Climate induced changes are those related to changes in the seasonal distribution of climate factors and in the frequency of extreme events predicted by the projections of future climate change.

All theses fast modifications may have large consequences on cultivated ecosystem productivity and impose wider use of technologies and landscape management practices to conserve soil. Modeling is an appropriate methodology to analyse, understand and simulate space time evolution in soil and landscape processes. We need quantitative models for soil formation and distribution in the landscape to test the effect of different scenarios of land management and climate evolutions.

In recent years, landscape modelling (Coulthard 2001; Willgoose 2005) has been a matter of increasing interest for many researchers, with a few models focused on agricultural environment evolution. The intended uses of these models were to predict and manage erosion and the transport of soil matter on the terrain surface. The cumulative effect of erosion and sediment yield has been considered as a key to understanding landscape evolution.

Geo-morphological modelling is a topic of research that takes into account the main hydrological and sediment erosion transport rules to describe the processes and evolution of terrain physiography. Some recent models deal with soil redistribution under agricultural practices such as SPEROS (Van Oost *et al.* 2000; Van Oost *et al.* 2005a; 2005b; Govers *et al.* 2006), based on the Watem/Sedem model (Van Oost *et al.* 2000; Van Rompaey *et al.* 2001). Other modelling study proposed soil mechanistic model combining soil redistribution processes and soil production function at the landscape scale (Minasny and McBratney, 1999, 2001). These modelling gives an evaluation of soil redistribution utilizing mechanistic rules for diffusion and water erosion (Kirkby 1985) and use soil production function similar to those proposed by Heimsath *et al.* (1997).

Even if principles of soil evolution over space and time are acquired, less modelling was done to simulate soil evolution over the landscape at fine spatial [1 m] and medium [10 –100 years] temporal scales. Moreover, despite the effort to represent in the existing models the most part of the environmental features e.g. hedges, ditches etc., involved in processes and landscape, some of them have not been yet fully considered.

In the presented study, we propose a model, the LandSoil model, which is an event based model, dimensioned for fine spatial [1 m] and medium [10 –100 years] temporal scales, taking into account a detailed representation of the agricultural landscape. The aims of this study is to use pedological knowledge acquired from a field study coupled with the LandSoil model to simulate soil evolution at fine spatial and medium temporal scales. We model water-erosion and mechanical erosion within a landscape, taking into account anthropogenic landscape structures. Subsequently we apply this model to study the effect of different scenarios of land management and climate changes on soil cover and landscape evolution.

Methods

The study area

The field experiment was carried out at Roujan (Languedoc-Roussillon –FRANCE 43°30’N – 3°19’E). The Roujan watershed unit of 91 ha is located in the south of France (Hérault, France), submitted to a sub-wet Mediterranean climate type characterized by a long dry season (P = 650 mm/y; PET = 1090 mm/y). Its first justification is to allow the study of global changes affecting hydrosystems in agro-systems located in Mediterranean context. The Mediterranean context is well adapted to study the system vulnerability to anthropic and climatic changes. Mediterranean climate is characterized by hydrological constraints (flooding, droughts, water erosion) having a strong impact on the evolution of soils. Land use is almost exclusively vineyards but may drastically change over years.

Data collection

A geological and a pedological map (1/25 000) on the watershed were established by Coulouma *et al.* (2008). We decided to increase the pedological database with data collected during two pedological survey on the wathershed. First, we implemented a 25 m square sampling scheme and described the soil profiles to assess the general soil organization over the landscape. To take into account the short-distance variability of soil geometry in the vicinity of landscape structures, we added soil profile description in their neighborhood. The topography of the area has been surveyed by a LiDAR system and is represented by the derived digital elevation model with [1m] of spatial resolution. The use of area is characterized mainly by vineyard, cereals, and some scrubland/wildlands. The spatial field structure is described by parcels with a medium size of 0.4 ha. An analysis of historical documents was performed to determine the age of hedges and ditched structures. This was done by comparing historical documents: the land registry from the year 1833, called "Napoleonic registries"; aerial photographs from 1946 to 2009.

The Model

The proposed *LandSoil model* (Landscape model for soil conservation under land use and climate change) is an expert-system based on a raster distributed-approach. It is, in fact, an evolution of the STREAM soil erosion model (Souchère *et al.* 1998; Cerdan *et al.* 2001) and new functions and modules are introduced in order to evaluate more soil and landscape specific characteristics. The model has been developed in order to characterize the dominant surface processes leading to overland flow in relation to soil surface properties following laboratory and field researches carried out in France (e.g. Fox and Le Bissonnais 1998; Le Bissonnais *et al.* 1998). Runoff and soil erosion reference data have also been collected in a variety of weather conditions, land use and soil surface state.

The model is rainfall event based and runoff and infiltration are evaluated at every event starting from the characteristics of the rain and the soil surface. It is composed of three modules for soil erosion/redistribution: rill erosion (Souchère *et al.* 2003); interrill erosion (Cerdan *et al.* 2002); and tillage erosion based on the mechanistic rules developed by Govers *et al.* 1994. Soil deposition is accounted by two modules (rill and interrill) following the rules of the local maximum transport capacity. After each rain and tillage event a new topography is evaluated as well as all the geometric landscape parameters. For a more detailed characterisation of the soil surface conditions, a monthly input parameterisation of the properties has been implemented and the rules concerning the soil susceptibility to erosion have been defined for all the main soil types of the area.

Specificities of the model are: i) long-term landscape analysis and topography balance after each rainfall; ii) evaluation of water erosion and soil mechanistic redistribution (tillage erosion); iii) taking in consideration of the landscape geometry, especially the connectivity, as a significant information in describing the landscape and useful in modelling (Landscape structure management and landscape design); and iv) utilisation of various and different climate scenarios thanks to the event based model.

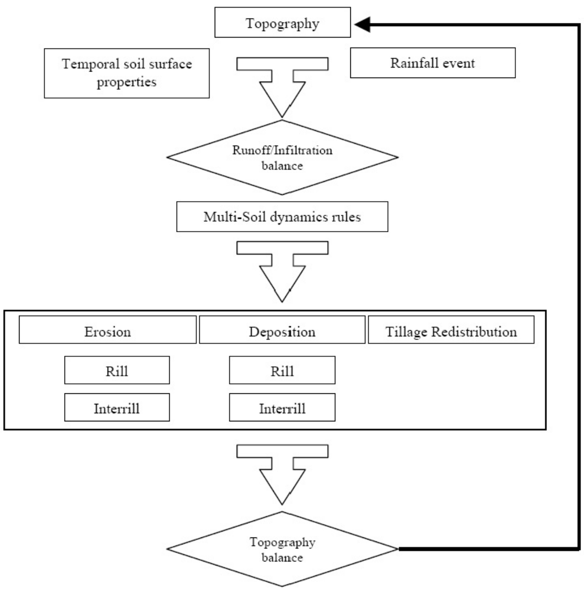

Figure 1. LandSoil module scheme.

Results and conclusion

The model has been calibrated and validated under the current environmental conditions and landscape structure. It has been observed a significant contribution in soil conservation by the landscape geometry even in short term simulations. The simulated soil depth evolution, compared with the present soil cover detailed by the surveying, confirm the observed patterns in terms of soil development and redistribution. Land use, cultural practices and agricultural landscape structure are also able to directly influence sediment fluxes, then the related topographic evolution.

Starting from the analysis of historical rainfall series, different climate scenarios have been tested in order to understand and analyse the resulting effects. The present landscape structure, tested under the perspective of climate changing showed a mitigating effect in terms of soil erosion confirming the importance of a detailed representation of the system geometry. This modelling constitutes a first approach to integrate over time the complexity in soil-landscape evolution. Further improvements should integrate the results of dating techniques (137Cs, 14C) to adjust for the process dynamics. And future developments will manage soil organic carbon redistribution and dynamic over the landscape.

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