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Modelling pedogenesis of Technosols

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ABSTRACT

Technosols, soils subjected to a strong human influence and containing significant amounts of artefacts, are characteristic of the Anthropocene. In order to better apprehend their growing importance in our current environment, our knowledge of the evolution and fate of these soils must be improved. The aim of this article is to promote pedogenic modelling for Technosols by proposing an appropriate framework. The paper first defines the characteristics of Technosol pedogenesis, and then considers the requirements for its modelling in light of general concepts of pedogenesis, modelling tools and techniques, and 18 selected existing quantitative models. This mixed technical and conceptual analysis allows us to address at once the modelling approach, the choice of processes, the integration of control variables, the time scales, the spatial representation, and the data needed for such a framework. Technosol pedogenesis is characterised by the soils' anthropic creation, a young age, a climate globally favourable for soil evolution, a surprising level of biological activity, and mostly reactive artefacts as parent materials. Pedogenic processes observed in Technosols are similar to those occurring in more natural soils; however, they generally have fast kinetics and occur in unusual assemblages. We propose that the modelling framework for Technosol evolution should be based on the coupling of process-based models of soil functioning processes and accommodate the peculiar properties of technogenic materials. Our work also highlights modelling features needed for pedogenesis in general: development of biological and physical models, selection of a comprehensive energy unit, dual-time scale modelling, and multi-scale representation of the soil profile. We propose (i) an adaptation of existing energy metrics (entropy, exergy, emergy or EEMT), (ii) a dual-time scale approach, our original concept, based on resilience patterns in soil changes, and (iii) the development of an existing spatial representation. Constructed Technosols are a relevant experimental model which supplies reliable data on soil evolution, data which are required for the development of pedogenic models. Technosols are emblematic of the issues we face for the management of the soils of the Anthropocene. The design of a modelling framework for Technosol evolution should therefore bring interesting developments for pedogenic modelling in general.

Contents

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1. Introduction

In the latter part of the 18th century, we entered a geological era, referred to as the Anthropocene, in which human activities have become the major driving force affecting the environment (Crutzen, 2002). Factors such as dramatic population growth and subsequent land use modifications, massive urbanisation, increasing use of energy, intensification of agriculture, and climate change have induced significant and rapid alterations of the environment in general, and, more particularly, of the soils (Blum & Eswaran, 2004; Bullock, 2005; Norra, 2009). The Anthropocene is also characterised by increasing social expectations toward the soils, as revealed by the emergence of concepts like ecosystem services, soil quality, or soil security.

In this context, anthropic soils are spreading. In fact, if we consider urban expansion as a proxy of the human impact on soil like Capra et al. (2015), up to 3% of the world land surface is already considered urbanised and this area is increasing around the globe (Liu et al., 2014; Schneider et al., 2009; Seto et al., 2011). In Europe, up to 4% of the land is covered by artificial areas (EEA, 2010). Mining also generates large surfaces of Technosol with an annual production of soil material of about 21 $Gt.yr^{-1}$ (Hayes et al., 2014). These numbers highlight the increasing significance, in the Anthropocene, of Technosols, i.e., "soils dominated or strongly influenced by human-made material" (IUSS, 2006, 2014). Technosols are closely associated with the growing human influence on the environment as well as the development of soil reclamation and soil construction activities like green roofs, site decontamination, or ecological engineering (Morel et al., 2014; Séré et al., 2008; Shein et al., 2009). They are characteristic Soils of Urban, Industrial, Traffic, Mining, and military Areas (SUITMAs). Thus, Technosols are representative soils of the Anthropocene (Certini & Scalenghe, 2011) and improved knowledge of their evolution and possible fate is needed to better apprehend the main issues of this era.

Pedogenesis refers to soil evolution from the profile scale to the regional scale and it encompasses the significant changes occurring in the physical, chemical, or biological conditions of soil. Soils have long been considered to be relatively stable natural bodies that evolve over periods of centuries to millions of years. However, increasing evidence indicates more rapid soil changes are now occurring over a time scale of decades (van Breemen & Buurman, 2002; De Kimpe & Morel, 2000; Howard & Olszewska, 2011; Tugel et al., 2005; Richter, 2007). Thus pedogenesis should be viewed on this shorter time scale. The definition of pedogenesis we propose here is broader than views generally shared by other authors which imply better soil organisation, higher complexity or a loss of entropy and isotropism (see, for example, the review in Chapter 11 by Schaetzl and Anderson (2007b)).

In the Anthropocene, quantitative modelling of the evolution of soil, and more particularly of Technosols, is an important step necessary for cognitive, applied, and communication goals.

Firstly, pedogenesis modelling is an effective cognitive tool to synthesise our current knowledge and to better comprehend the evolution processes (Hoosbeek & Bryant, 1992; Kline, 1973; Minasny et al., 2008; Samouëlian & Cornu, 2008). The investigations on Technosol evolution are recent (Capra et al., 2015) but have led to significant results and data that could already be used as a base for modelling (De Kimpe & Morel, 2000; Huot et al., 2013; Scalenghe & Ferraris, 2009; Scholtus et al., 2009; Séré et al., 2010). Secondly, soil evolution modelling can be used as an applied tool, in a changing environment, for assessment of (i) the future of soil systems per se, (ii) the potential alterations of the supported ecosystem services, and (iii) the role of soil in global environmental issues like climate change or the nitrogen cascade (Bryant & Olson, 1987; Bullock, 2005; Hoosbeek & Bryant, 1992; Lin, 2011; Lorenz & Lal, 2009). In addition to those general challenges, there are other relevant expectations for models of Technosols evolution such as the design of sustainable soil rehabilitation techniques or assessment of the potential spreading of pollutants (Huot et al., 2014a; Lal, 2009; Lorenz & Lal, 2009; Macías & Camps Arbestain, 2010; Morel et al., 2014). Finally, pedogenesis modelling could also be promoted as a communication medium to raise soil awareness and education and ensure soil connectivity (McBratney et al., 2014). Simulations with pedogenic models can be the basis of the necessary co-learning among stakeholders about soil and the related ecosystem services (Bouma, 2014), like in the companion modelling approach (Etienne, 2011). In case of Technosols, which are involved in urban development, urban agriculture, brownfield reclamation, and decontamination, this co-learning is essential for developing and promoting innovative solutions that are both technically reliable and socially acceptable.

Hence, there is a need to conduct quantitative modelling of anthropic pedogenesis (Huang et al., 2015). Soil evolution modelling is still underdeveloped (Minasny et al., 2008; Samouëlian & Cornu, 2008) and, to our knowledge, no models yet exist of Technosol pedogenesis. The objective of this review is to promote the development of pedogenic modelling for Technosols by proposing an appropriate modelling framework. With this objective, the paper begins by identifying the specific