Terasol

Liste bibliographique des études sur les technosols construits à partir de terres excavées en milieu urbain

Livres

Créer des sols fertiles : du déchet à la végétalisation urbaine

O Damas, A Coulon, P Bataillard, M Benbrahim, F Brun, P Cannavo, P Chenon, et al. - 2016. Editions du Moniteur. Antony

La construction de sols fertiles à partir des résidus urbains constitue une piste inédite de recyclage. Cercle vertueux s'inscrivant dans une logique de développement durable, cette forme de végétalisation part de la ville pour revenir à… la ville !
Fruit d'une réflexion pluridisciplinaire conduite par le collectif SITERRE – programme de recherche sur la construction de sols fertiles pour les aménagements d'espaces verts urbains soutenu par l'ADEME –, cet ouvrage propose des techniques novatrices de construction de sol basées sur le recyclage de matériaux issus du bâtiment et des activités de la ville (ballasts, bétons concassés, terres de déblai, composts et autres matières organiques).
Après une présentation très documentée de la démarche et de ses enjeux, l'ouvrage décortique étape par étape l'élaboration de technosols construits et en analyse la qualité. Les nombreuses fiches techniques qui ponctuent l'ouvrage, les cas pratiques aussi variés qu'illustrés, ainsi que les « fiches projet », permettent de comprendre et de mesurer le potentiel des matériaux recyclés, substituts efficaces et renouvelables à la terre végétale et aux granulats de carrière.

Articles de revue de la littérature

Existing evidence on the potential of soils constructed from mineral wastes to support biodiversity: a systematic map

DY Ouédraogo, A Lafitte, R Sordello, F Pozzi, I Mikajlo, JHR Araujo, Y Reyjol, TZ Lerch - Environmental Evidence, 2024

Background
The development of cities and transport infrastructure produces a large volume of mineral waste (e.g. excavated earth material). At the same time, cities are increasingly trying to develop green infrastructures, given the ecosystem services they provide to people, but this comes with considerable economic and environmental costs associated with the transfer of fertile soil from rural areas to cities. In a circular economy approach, the reuse of mineral waste to build fertile soil is a substantial opportunity to reduce the economic and environmental costs of both mineral waste management and green infrastructure development. Soils constructed from these materials (constructed Technosols) must be able to support vegetation growth and become a suitable living environment for soil organisms. This requires ecological engineering to maximise the potential of constructed soils for biodiversity, both from a taxonomic and functional perspective. In this context, we systematically mapped the evidence related to the ability of soils constructed from mineral wastes to support biodiversity.

Methods
We gathered published and grey literature through searches in two publications databases (Scopus and Web of Science Core Collection), one search engine (Google Scholar), nine organisational websites and through a call for literature. Titles, abstracts, and full-texts were successively screened using eligibility criteria. All included studies were described with coded variables and a database was produced. The extent of evidence was assessed and knowledge clusters and gaps were identified.
Review findings
The searches yielded 9265 articles, and 153 articles were retained after the screening process. More than half of these articles were from European countries, with France leading the field with 40 articles, followed by Spain (15 articles) and Italy (10 articles). Most of the articles (75%) were produced after 2015. The main reasons for constructing soils from mineral waste were for mine rehabilitation (35%), waste recycling (16%) and experimental purpose (15%). The 153 articles were divided into 1962 studies, a study being a combination of a taxon, an intervention (i.e. soil construction) and a measured outcome. Among these studies, the most studied biological group is plants (69% of studies) and especially herbaceous species (32%), followed by microorganisms (17%) and invertebrates (14%). The most used type of mineral waste is mine waste (31% of studies) followed by excavated soil (16%) and demolition waste (14%). Finally, the most frequently measured outcome is plant growth (42% of studies), followed by organism abundance (16%) and diversity (10%).
Conclusions
Three main knowledge clusters were identified which could be addressed in the future for full synthesis of the results: (1) How well do plants grow in soils constructed from mineral wastes? (2) What is the potential of soils constructed from mineral wastes to support biodiversity? and (3) How do microbial communities develop in soils constructed from mineral wastes? There is a lack of studies investigating several biological groups at the same time: only 6 articles out of 153 investigated the response of both plants, invertebrates and microorganisms to soil construction. More research is therefore needed on the ability to support a diversity of organisms.

Constructed technosols: A strategy toward a circular economy

D Fabbri, R Pizzol, P Calza, M Malandrino, E Gaggero, E Padoan, F Ajmone-Marsan - Applied Sciences, 2021

Soil is a non-renewable natural resource. However, the current rates of soil usage and degradation have led to a loss of soil for agriculture, habitats, biodiversity, and to ecosystems problems. Urban and former industrial areas suffer particularly of these problems, and compensation measures to restore environmental quality include the renaturation of dismissed areas, de-sealing of surfaces, or the building of green infrastructures. In this framework, the development of methodologies for the creation of soils designed to mimic natural soil and suitable for vegetation growth, known as constructed soils or technosols, are here reviewed. The possible design choices and the starting materials have been described, using a circular economy approach, i.e., preferring non-contaminated wastes to non-renewable resources. Technosols appear to be a good solution to the problems of land degradation and urban green if using recycled wastes or by-products, as they can be an alternative to the remediation of contaminated sites and to importing fertile agricultural soil. Nevertheless, waste use requires analysis to ensure the salubrity of the starting materials. Moreover, materials produced on site or nearby minimize the cost and the environmental impact of transport, thus the involvement of local stakeholders in the urban land management must be encouraged.

Using constructed soils for green infrastructure – challenges and limitations

M Deeb, PM Groffman, M Blouin, SP Egendorf, A Vergnes, et al. - Soil, European Geosciences Union (EGU), 2020

With the rise in urban population comes a demand for solutions to offset environmental problems caused by urbanization. Green infrastructure (GI) refers to engineered features that provide multiecological functions in urban spaces. Soils are a fundamental component of GI, playing key roles in supporting plant growth, infiltration, and biological activities that contribute to the maintenance of air and water quality. However, urban soils are often physically, chemically, or biologically unsuitable for use in GI features. Constructed Technosols (CTs), consisting of mixtures of organic and mineral waste, are man-made soils designed to meet specific requirements and have great potential for use in GI. This review covers (1) current methods to create CTs adapted for various GI designs and (2) published examples in which CTs have been used in GI. We address the main steps for building CTs, the materials and which formulae should be used to design functional CTs, and the technical constraints of using CTs for applications in parks and square lawns, tree-lined streets, green buffer for storm water management, urban farming, and reclaimed derelict land. The analysis suggests that the composition and structure of CTs should and can be adapted to available wastes and by-products and to future land use and environmental conditions. CTs have a high potential to provide multiple soil functions in diverse situations and to contribute to greening efforts in cities (and beyond) across the world.

Modelling pedogenesis of Technosols

S Leguédois, G Séré, A Auclerc, J Cortet, H Huot et al. - Geoderma, 2016

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.

Articles de recherche publiés sur revue à comité de lecture

Technosol made with urban and industrial waste: potential for improving soil quality and growing tree seedlings

LGO Gambi, RA Junior, LS Vanzela, ER Tagliaferro et al. - Soil Advances, 2024

This study evaluated the use of waste materials to produce Technosol, a "tailor-made" soil consisting of construction and demolition waste (CDW), solid waste from stone mining (WSM), natural soil (NS), and compost from plant pruning (CPP), for improving soil quality in forest recovery projects. Samples of CDW were characterized using X-ray fluorescence and X-ray diffraction. The potential of the Technosol as a substrate was assessed using a mixture of "Class A" CDW, WSM, NS, and CPP in the following proportions: *(a)* 10 % CDW + 42.5 % WSM + 42.5 % NS + 5 % CPP, *(b)* 20 % CDW + 37.5 % WSM + 37.5 % NS + 5 % CPP, and *(c)* natural soil as a control. A randomized block design was used with nine treatments and three replications using 5.5 L pots. The experimental treatments consisted of two proportions of mixtures, natural soil, and three tree species: pioneer, *Cecropia pachystachya*, secondary, *Handroanthus impetiginosus* and climax, *Copaifera langsdorffii*. The activity of the enzymes β-glucosidase and arylsulfatase was determined in the Technosol and natural soil at the end of the experiment. During 180 days, the height of the plants and the diameter of the stem were determined at intervals of 30 days and, at the end of the experiment, the aerial part dry mass (leaves and trunk) and roots were evaluated. The Technosol constructed from the mixture *(a)* proved to be viable for improving soil quality, as indicated by a greater enzymatic activity compared to other soils, and for the growth of ***H. impetiginosus*** seedlings, showing the capacity to gain plant height over 180 days after planting.

Reuse of Tunisian excavated material into composite soil for rainwater infiltration within urban green infrastructure

G Snoussi, B Nasri, E Hamdi, O Fouché-Grobla - Geoderma Regional, 2024

Excavated material or soil is one of the most abundant types of waste produced by civil works. The study draws a methodology for assessing through selected standard tests the environmental, geotechnical, and agronomical features of excavated material to highlight the most ecological way to reuse it. In view of making a constructed soil to be implemented within green infrastructure part of new urban landscape, imperative skills of soil or material are referred to as SWOFI: safety, workability, fertility, infiltrability, and guidelines are derived accordingly. As a practical case of the application of the methodology, a non-cohesive sedimentary parent rock with a sandy loam texture excavated at Bou Argoub in Tunisia has been characterised. This excavated material is a negligible source of pollution hazard by heavy metals. It classifies in a category very sensitive to compaction and strongly influenced by the clay content, so difficult to reuse in road applications. It is very poor in organic matter and too much alkaline, so grape marc waste is used to improve its fertility, thus making a composite soil that prefigures a constructed soil. This allows the valorisation of local agriculture waste throughout the designed strategy.
Novelty resides in the selection of tests and the association of technics issued from usually separated disciplines and the integrated workflow of the soil at three stages of the value-chain: excavated-homogenised, amended, then repacked at a given bulk density as a composite soil. Immediate compactibility changes as a linear function of repacked bulk density BD; from the literature, this result is assumed true in the composite soil as well as the excavated material. Based on required intervals of permeability for the projected use in green infrastructure requiring rainwater infiltration, a decision-making table is applied with, as input, the most probable value of permeability determined from

pedotransfer function as topsoil or as subsoil. Combining pollution hazard assessment, geotechnical improvement, agronomical amendment, an innovative approach leads to pedological and hydrological functionality for constructed soil, a nature-based solution.

Predicting soil hydraulic properties for binary mixtures–concept and application for constructed Technosols

M Willaredt, T Nehls, A Peters - Hydrology and Earth System Sciences, 2023

Constructed Technosols are an important means of substituting natural soil material, such as peat and geogenic material, for use in urban green infrastructure. One characteristic of Technosols important to their role in urban green infrastructure, specifically with respect to urban water management, is their soil hydraulic properties (SHPs). The SHPs depend on the composition of the constructed Technosols (e.g. their components and their mixing ratio). The diversity of possible components and the infinite number of mixing ratios practically prohibit the experimental identification of the composition needed to achieve suitable soil hydrological functions. In this study, we propose a compositional model for predicting the water retention curves (WRCs) of any binary mixture based on the measured WRCs of its two pure components only (basic scheme) or with one additional mixture (extended scheme). The unsaturated hydraulic conductivity curves (HCCs) are predicted based on the modelled WRCs. The compositional model is developed from existing methods for estimating the porosity of binary mixtures. The model was tested on four data sets of measured WRCs of different binary mixtures. The distribution of water and air in 50 cm high soil columns filled with these mixtures was predicted under hydrostatic conditions in order to assess their suitability for typical urban applications. The difference between the maxima of the pore size distributions (m) of the components indicates the applicability of the compositional approach. For binary mixtures with small , the water content deviations between the predicted and the measured WRCs range from 0.004 to 0.039 cm cm. For mixtures with a large , the compositional model is not applicable. The prediction of the soil hydraulic properties of any mixing ratio facilitates the simulation of flow and transport processes in constructed Technosols before they are produced (e.g. for specific urban water management purposes).

Evaluation of Technosols constructed with construction and excavation debris for greenhouse production of ornamental plants

TF Abbruzzini, L Mora, B Prado - Journal of Soils and Sediments, 2022

Purpose

The overexploitation of the O horizon, or the litter layer of the soil profile, in the production of ornamental plants, causes the disintegration of the landscape and the loss of soil productivity in preserved areas, which calls for new approaches to address the need for substrates in soilless culture systems. Thus, this study examined the construction of purpose-designed Technosols from construction waste as substrates in the production of ornamental plants.

Methods

The evaluated treatments were as follows: (CCW) 40% concrete waste, 30% compost, 30% wood chips; (ECW) 40% excavation waste, 30% compost, 30% wood chips; and (AOW) 40% compost, 60% wood chips. A control treatment (CTL) was composed of 50% compost and 50% natural exported soil. The plant species used were *Heliotropium arborescens*, *Lobularia maritima*, and *Lavandula angustifolia,* which were grown for one cycle in an 8-week greenhouse experiment. The pH, electrical conductivity (EC), carbon and nutrient (N, P, and exchangeable cations) contents, and water availability of the Technosols and control treatment, as well as the survival rate, presence of flowers, number of

flowers per plant and shoot diameter of the ornamental plants, were evaluated over the experimental period.

Results

All treatments had slightly alkaline pH, yet their EC decreased to the levels recommended for growing media considering the evaluated species. The AOW presented the highest initial contents of total C, total N, and available P, and the highest concentration of DOC at the end of the experiment, followed by the CCW Technosol. There were no differences within treatments regarding their initial and final available P contents, and the final available P and mineral N contents in Technosols and control did not differ, thus showing their ability to supply both N and P adequately to plants. A high plant survival rate was observed throughout the experimental period, and the frequency of blooming plants increased for all species regardless of the treatment.

Conclusions

The Technosols produced from construction and excavation waste had been shown to provide favorable chemical, physical, and physicochemical conditions for the vegetative development and blooming of ornamental plants with different fertilization requirements and, thus, could be used as alternative to reduce the exploitation of exported natural soils. The plants used in the study had different nutritional requirements, yet they all grew adequately. The Technosol made from concrete waste had the most promising outcome in terms of C and available nutrients (N, P and exchangeable cations) as well as water retention and availability to plants compared to the excavation-based Technosol, besides having comparable results with the control treatment that is commonly used by the producers to grow ornamental and flower plants. Considering that no mineral fertilization was used in this study, further research may assess the use of a controlled fertilization schedule in order to reduce and optimize the use of agrochemical inputs, from small to large-scale growers of flower plants.

Predicting water retention curves for binary mixtures–concept and application for constructed technosols

M Willaredt, A Peters, T Nehls - Hydrology and Earth System Sciences Discussions, 2022

Constructed Technosols are important means to substitute natural soil material such as peat and geogenic material to be used in urban green infrastructure. One of the most important features of such soils is related to the water cycle and can be described by the soil water retention curve (WRC). The WRC depends on the composition of the constructed Technosols e.g. their components and their mixing ratio. The diversity of possible components and the infinite number of mixing ratios practically prohibit the experimental identification of the optimal composition regarding the targeted soil functions. In this study we propose a compositional model for predicting the WRC of any binary mixture based on the measured WRCs of it's two pure components only (basic scheme) or with one additional mixture (extended scheme). The model is developed from existing methods for estimating the porosity in binary mixtures. The compositional model approach was tested for four data sets of measured WRCs for different binary mixtures taken from the literature. To assess the suitability of these mixtures for typical urban applications, the distribution of water and air in 50 cm high containers filled with the mixtures was predicted under hydrostatic conditions. The difference between the maxima of the pore-size distributions ΔPSD_{max} of the components indicates the applicability of the compositional approach. For binary mixtures with small ΔPSD_{max}, the water content deviations between the predicted and the measured WRCs range from 0.004 to 0.039 $m^3\ m^{-3}$. For mixtures with a large ΔPSD_{max}, the compositional model is not applicable. The knowledge of the WRC of any mixing ratio enables the quick choice of a composition, which suits the targeted application.

Assessing soil-like materials for ecosystem services provided by constructed technosols

K Ivashchenko, E Lepore, V Vasenev, N Ananyeva et al. - Land, 2021

Urbanization results to a wide spread of Technosols. Various materials are used for Technosols' construction with a limited attention to their ecosystem services or disservices. The research focuses on the integral assessment of soil-like materials used for Technosols' construction in Moscow megalopolis from the ecosystem services' perspective. Four groups of materials (valley peats, sediments, cultural layers, and commercial manufactured soil mixtures) were assessed based on the indicators, which are integral, informative, and cost-effective. Microbial respiration, C-availability, specific respiration, community level physiological profile, and Shannon' diversity index in the materials were compared to the natural reference to assess and rank the ecosystem services and disservices. The assessment showed that sediments and low-peat mixtures (30% of peat in total volume) had a considerably higher capacity to provide C-sequestration, climate regulation and functional diversity services compared to peats and high-peat mixtures. Urban cultural layers provided ecosystem disservices due to pollution by potentially toxic elements and health risks from the pathogenic fungi. Mixtures comprising from the sediments with minor (30%) peat addition would have a high potential to increase C-sequestration and to enrich microbial functional diversity. Their implementation in urban landscaping will reduce management costs and increase sustainability of urban soils and ecosystem.

Early colonization of constructed technosol by microarthropods

L Santorufo, S Joimel, A Auclerc, J Deremiens, G Grisard, M Hedde, J Nahmani, C Pernin, J Cortet - Ecological Engineering, 2021

Technosols are defined by the World Reference Base as soils subjected to a strong human influence and containing at least 20% of artefacts. The construction of Technosol using recycled waste material is considered an appealing sustainable use of both natural and anthropic resources. Constructed Technosol can attract and host a multitude of soil organisms, forming a reserve of biodiversity. In this study, we assessed the early colonization – in successional stages – of a constructed Technosol supporting grassland vegetation by the microarthropod community, in particular Collembola. To do this, the taxonomic and functional characteristics of microarthropod communities in a newly constructed Technosol in northeast France were studied for a period of four years. Collembola communities also increased in density and taxonomic richness, as well as in functional richness and dispersion. However, hemiedaphic Collembola dominated the community, particularly in the fourth year. Findings at the end of the survey indicated that the Collembola community in the studied Technosol remained very different to that of natural grassland, while it shared some characteristics with arable land. However, the present research clearly showed that waste material recycling to construct a Technosol could be an opportunity to support soil microarthropod biodiversity.

Feasibility of urban waste for constructing Technosols for plant growth

B Prado, L Mora, T Abbruzzini, S Flores, S Cram, P Ortega, A Navarrete, C Siebe - Revista Mexicana de Ciencias Geológicas, 2020

An alternative for sustainable urban development is to revegetate cities with the construction of planters as well as to recover degraded sites. The objective of this work was to characterize urban waste materials produced in Mexico City and to evaluate their potential for constructing Technosols for plant growth, as an alternative to use in revegetating the city without affecting natural landscapes. Construction and demolition waste materials amended with different application rates of compost made out of gardening wastes from Mexico City green areas were tested. Nine mixtures were prepared;

three based on concrete, three based on demolition waste and three based on excavation waste. Changes on physical, chemical and physicochemical properties of these mixtures, namely nutrient contents, water retention and aeration capacity, were monitored in a twelve-month experiment. The mineralogy and the risk regarding the release of heavy metals and trace elements were also evaluated in the soluble fraction. The constructed Technosols were appropriate, to a greater or lesser extent, for tomato plant growth. Soil pH and soil electrical conductivity (EC) were the main factors defining their suitability; both parameters changed over time due to the washing of salts. The particle size of the mineral materials as well as the application rates of compost used in the construction of the Technosols resulted in adequate water holding capacity and soil aeration for plant growth. The type of parental materials defined the majority of the Technosol characteristics as well as their ability to function as a plant support. The concentrations of readily available heavy and trace metals were not a limitation for plant growth. However, potential co-transport of these elements with soluble organic matter should be considered in further research.

Tree growth and macrofauna colonization in Technosols constructed from recycled urban wastes

C Pruvost, J Mathieu, N Nunan, A Gigon, A Pando, TZ Lerch, M Blouin - Ecological Engineering, 2020

Urban greening is a growing societal demand but consumes large amounts of soil. This massive transfer of soil, typically imported from peri-urban and rural areas, raises questions about the environmental sustainability of such projects. It has been suggested that artificial soils made with urban wastes, also called constructed Technosols, might be a sustainable alternative. In this article, we examined during three years, different mixtures of excavated deep horizons of soil, crushed concrete and green waste compost, in order to (i) identify the most suitable mixture for growing trees; (ii) identify tolerant tree species among six different species; and (iii) assess macrofaunal colonization, a major driver of soil fertility, from the surrounding macrofaunal pool.
The mixture of excavated deep horizons and green waste compost led to the highest tree mortality. The best tree survival and growth, and quickest soil macrofaunal colonization were obtained with a mixture of 20% of excavated deep horizons, 10% of green waste compost and 70% of crushed concrete (*v*/v). The survival rate of species *Acer campestre* and *Prunus avium* was 100% but only 58% for *Carpinus betulus*. Our results show the construction of Technosols with urban wastes is a promising alternative for planting trees and hosting soil biodiversity within cities.

Storage of carbon in constructed technosols: in situ monitoring over a decade

F Rees, R Dagois, D Derrien, JL Fiorelli, F Watteau, JL Morel, C Schwartz, MO Simonnot et al. - Geoderma, 2019

Artificial soils constructed from wastes and by-products have been considered as a sustainable option for land reclamation. In particular, they could contribute in a complementary manner to natural soils to global climate regulation by storing large quantities of carbon (C). However, the evolution of C stocks in such newly formed soils remains largely unknown. This work aimed at evaluating the dynamics of C in constructed Technosols, focusing on two experimental sites in Lorraine, France, where Technosols were constructed from thermally-treated industrial soil, papermill sludge and green waste compost, and planted with grasses. Soil samples were collected over 12 years, and stocks of C were calculated, taking into account the increase in soil bulk density and the associated decrease in soil thickness over the years. The evolution of the stocks of organic C was compared to the evolution reported for natural grassland soils from the same region and for other Technosols. Initial organic C stocks in the two constructed Technosols were 50% higher than in natural analog soils when calculated over 30 cm, and up to 5 times

higher when calculated over 100 cm. Organic C stocks in the two Technosols decreased over the first three years, but increased during the following years, most likely due to the accumulation of plant-derived C. A similar evolution was observed in other planted Technosols. We conclude that Technosols constructed from an adequate set of parent materials can keep large amounts of organic C over time and sequester additional C under permanent plant cover.

A micromorphological analysis for quantifying structure descriptors in a young constructed Technosol

F Watteau, NS Jangorzo, C Schwartz - Boletín de la Sociedad Geológica Mexicana, 2019

Evaluating soil structure dynamics is a major challenge when analysing or modelling pedogenesis. Constructed Technosols are considered, by definition, to be good candidates for pedogenetic studies, insofar as their initial characteristics and implementation conditions are controlled. Thus, we developed an approach based on image analysis of soil microstructures in order to specify the structure dynamics of a constructed Technosol. We described and quantified porosity and aggregation descriptors on a microscale (1) from pictures of mesocosms performed during 14 months, using an innovative automatic high-resolution image-acquisition device (Soilinsight®), and (2) from thin sections sampled in situ in a 1 ha field experiment at t0 and t2 (17 months). Plant root system architecture of Lupinus albus and the behavior of introduced earthworms (Lumbricus castaneus) were described using the Soilinsight® device. After 14 months, the pore surface was 10 times greater in the presence of plants and macrofauna than in the control samples. Although the biological activity promoted the genesis of aggregates, their dynamics were irregular. In fact, the proportion of aggregates varied depending on both root age and worm action. In situ, the soil was progressively compacted due to a significant decrease in the number of> 2000 µm pores. In the same way, three aggregate descriptors-number, area and shape-were selected as the most significant indicators of soil aggregation evolution during the early stages of pedogenesis. In conclusion, this approach, based on the quantification of microstructure parameters, did indeed allow the description and monitoring of 2D soil structure dynamics in both field and mesocosms conditions. Completed with 3D soil structure data, this micromorphological analysis could advantageously contribute to the impact of climatic and biological agents modelling on a structural evolution of Technosols during initial pedogenesis.

Influence of connectivity & topsoil management practices of a constructed technosol on pedofauna colonization: A field study

C Burrow, C Pernin, A Lepretre - Applied soil ecology, 2018

At the present time, rehabilitation of polluted urban areas and the restoration of their soil are environmental priorities. The creation of constructed soils appears to be a tempting way to restore, lastingly, a contaminated urban soil provided that they can become fertile and host a functional biodiversity delivering essential ecosystem services.
To ensure this, the recolonization of newly established technosols composed of a mixture of compost and *in situ* deep alluvion was monitored using judiciously chosen bioindicators: springtails, mites, earthworms, carabid beetles and woodlice. These technosols were part of an experimental plot located inside the future “Ecoquartier de l’Union” (Roubaix, France).
The results show that, if the connection of the technosols with an element of the local landscape (in this case a railway hedgerow) plays a part chiefly in aiding the first stages of recolonization, notably for earthworms and springtails, technosols management has a lasting impact on the colonization dynamics and the implantation of the different taxa.

Establishing an herbaceous cover (flowering meadow, lawn) or a hedge was especially profitable to the pedofaunic communities, which were richer and more abundant, as well as to the technosols functioning (better litter degradation, diversified collembolan communities with regards to functional traits). The same is true for the addition of RCW (Ramial Chipped Wood) which benefits earthworm and mesofauna through the organic components released and the associated fungal development.

Technosols made with various urban wastes showed contrasted performance for tree development during a 3-year experiment

P Cannavo, R Guénon, G Galopin, L Vidal-Beaudet - Environmental Earth Sciences, 2018

Vegetation in urban areas is generally living in a stress-inducing environment. Sustaining good soil quality is crucial to improve tree development and heath in such (artificial) environment. This study investigates the dynamics of the physico-chemical properties of Technosol, and compares tree development performances in various waste mixtures. A 3-year experiment was conducted with *Acer platanoïdes* L. grown in three distinct constructed soils, in three replicates, in 0.480-m^3 lysimeters in Angers (France). Four combinations of artefacts were studied either as "growing material" (GM) or "structural material" (SM). Three different SMs were used: (1) a mixture of fine mineral material, demolition rubble and green waste (SM-DR/GW), (2) a mixture of fine mineral material, track ballast and sewage sludge (SM-TB/SS), and (3) the SM currently used by Angers city for green space settlements (SM-CT). Waste characteristics and mixing proportions both affected tree development. Physical properties were not a limiting factor for tree development, despite a relatively low soil water reservoir due to high stone content. Moreover, the chemical properties of the materials, more particularly low water pH and CEC, led to poor tree development in SM-CT, whereas the other two SMs did not affect tree development. SM-TB/SS was the most suitable constructed soil after 3 years because it exhibited satisfactory soil nutrient contents that promoted the best tree crown quality. Waste mixtures can sustain soil functions for tree development. As for urban street tree pits that are 2–8 m^3 in volume, soil water, and nutrient autonomy should satisfactorily sustain tree development.

Constructed soils for mitigating lead (Pb) exposure and promoting urban community gardening: The New York City Clean Soil Bank pilot study

SP Egendorf, Z Cheng, M Deeb, V Flores, A Paltseva, D Walsh, P Groffman, HW Mielke - Landscape and Urban Planning, 2018

Gardening provides a wide range of benefits to urban residents but may also increase risks of exposure to contaminants in soils. Here we evaluate the use of clean excavated glacial sediments and locally produced compost, to create soils for urban gardens in New York City, NY, USA. The objectives of this study are to examine contaminants in compost and manufactured soil, assess safety of produce, and evaluate the agronomic value of soil mixes with different ratios of sediment and compost. Methods of analysis include quantifying metal/metalloid concentrations in sediments, composts, and plant tissues, soil agronomic parameters (pH, salinity, organic matter, total nitrogen, total carbon), and crop yield. Contaminant levels in sediments from the New York City Clean Soil Bank (CSB) (<10 mg Pb kg^{-1}) were far below background levels of soils in two selected gardens (66 and 1025 mg Pb kg^{-1}), while available composts had highly variable levels of contamination (10–232 mg Pb kg^{-1}). A relatively clean compost was used for this study (19 mg Pb kg^{-1}). Metal/metalloid levels did not increase in constructed soils during the 1-year pilot study period, and crops were well below EU safety standards of 0.1 and 0.3 mg Pb kg^{-1} for fruits and leafy greens, even when surrounded by contaminated soils. Sediment/compost mixtures produced yields comparable to control plots. Results suggest that CSB sediments have high potential to serve as manufactured topsoil. Creating these soil mixtures diverts

materials from expensive waste disposal, reduces contamination risks for urban residents, and promotes the myriad benefits of urban agriculture and community gardening.

Ranking of wetting–drying, plant, and fauna factors involved in the structure dynamics of a young constructed Technosol

NS Jangorzo, F Watteau, C Schwartz - Journal of Soils and Sediments, 2018

Purpose

Dynamical in situ observation of biological and climatic structuring factors involved in pedogenesis has not previously been possible in a way that would consider the early stages of pedogenesis. If studies have explored the effect of pedogenetic factors on soil structure, none have succeeded in ranking them in view of the intensity of their effects. We propose a novel approach for describing the aggregation process for a constructed Technosol obtained from a process of pedological engineering.

Materials and methods

We focus on agents including plants, macrofauna, and water, and we use (i) a dynamic in situ observation and (ii) the quantification of the evolution of selected descriptors of pores and aggregates. They are quantified from high-resolution images obtained with the Soilinsight® device. Associating those images with each other, movies of interactions between soil and organisms over a 14-month non-destructive soil evolution experiment are made.

Results and discussion

Agents influencing aggregation—plant roots, earthworms, and water—can be ranked according to their impact on soil structure. During the studied period of evolution, wetting–drying cycles are the first to operate. The intensity of their action on soil structure is dominant at the very first stages of pedogenesis. Despite this ranking of agents, over the long term, plants and earthworms have a more intense effect on soil structure than wetting–drying cycles.

Conclusions

The method applied to observe and quantify soil structure dynamics is thus proposed as a helpful approach to modeling other processes involved in soil functioning and evolution in relation to their ability to fulfill ecosystem services.

Aggregation and availability of phosphorus in a Technosol constructed from urban wastes

L Vidal-Beaudet, S Rokia, T Nehls, C Schwartz - Journal of soils and sediments, 2018

Purpose

To preserve natural soil resources and in order to create fertile constructed Technosols for plant cultivation, wastes and by-product mixtures were studied in relation to their pedogenic properties and especially soil organic matter contents. We assessed interactions between aggregation and nutrient availability, focusing on phosphorus (P) transfer in the soil-water-plant system.

Materials and methods

Four typical urban wastes, dried and sieved to pass 2 mm, were mixed selectively to mimic a fertile topsoil material: excavated subsoil AE, compost from sludge and green wastes CO, green wastes GW, and bricks BR. After characterization of the wastes for physico-chemical and toxicological parameters, we focused on four mixtures: AE/CO, AE/GW, BR/CO, and BR/GW. The mixtures were tested in a 55-day long pot experiment under controlled conditions in a climate chamber. Pots were bare and planted with *Lolium perenne* (ryegrass) and *Brassica napus* (rape). The two plant species were selected for contrasting root activities and architectures and phosphorus (P) acquisition strategies. The aggregate formation was tested using the mean weight diameter method at the end of the experiment.

Results and discussion

We have measured intense aggregation in mixture AE/GW, low aggregation in AE/CO, and no aggregation in BR/CO and BR/GW. After 55 days, neither Technosol aggregation nor aggregate stability was significantly affected by plant development. Available phosphorus (P_{Olsen}) content was sufficient for plant development in all the mixtures (from 0.28 to 0.58 g kg^{-1}). The P_{Olsen}/P_{total} ratio was higher in mixtures with GW, even if the mixtures with compost (AE/CO and BR/CO) induced the highest biomass production for ryegrass and rape.

Conclusions

The nutrient availability in constructed Technosols and the transfer of P to plant were highly dependent on organic matter type, with high or low delivery of P_{Olsen} linked to the mineralization potential and the size and distribution of aggregates. Therefore, pedological engineering processes can be improved by the selection of adapted constitutive wastes and by-products to create a fertile substrate allowing high biomass production.

Rapid changes in soil nematodes in the first years after technosol construction for the remediation of an industrial wasteland

C Villenave, G Séré, C Schwartz, F Watteau, A Jimenez, J Cortet - Eurasian Soil Science, 2018

Technosol construction is an emergent technology that uses an assemblage of technogenic materials for the ecological reclamation of derelict land and waste recycling. Knowledge about the colonisation of Technosols by soil biota is limited, despite the latter's central role in ecosystem functioning. In this four-year field (2008 to 2011) study, we characterized the development over time of the diversity and the abundance of soil nematodes in two types of Technosols in North-Eastern France. We also studied the nematode community structure, abundance of taxa and functional groups in both Technosol profiles in the third year of the study. Samples were collected from the top soil layer (0–20 cm) each year in the spring (April), on a one ha. field experiment that had spatially divided in 24 sampling areas. For soil profiles, three samples were collected in three horizons within six pits (three pits per Technosol). Nematodes were extracted from soil and identified at the family or genus level and then classified into functional feeding guilds. In the first year, the community was dominated by opportunistic bacterial feeders. The taxonomic and functional nematode diversity increased with time, with a dominance of non-opportunistic bacterial feeders after four years, but also the significant presence of fungal feeders, omnivorous and carnivorous, as well as plant parasites and insect parasites. No significant difference was observed between the two Technosols. Each layer showed distinct communities, with nematode diversity and abundance decreasing with depth. Abundance and diversity, coupled with the analysis of several indexes, commonly used for nematodes, including Maturity index (MI), Enrichment index (EI), Structure index (SI) and Nematode channel ratio (NCR), lead to the conclusion that the high organic matter content, particularly in the upper horizon of both Technosols, guaranteed nematode colonization and progressive diversification, and is likely to be the key for successful biodiversity reclamation.

Physical properties of structural soils containing waste materials to achieve urban greening

D Yilmaz, P Cannavo, G Séré, L Vidal-Beaudet, M Legret, O Damas, PE Peyneau - Journal of soils and sediments, 2018

Purpose
The densification and expansion of urban areas will increase the streams of waste materials such as bricks, concrete and street sweeping waste. In parallel, green areas offer the potential to overcome many challenges that face growing/expanding cities but require the use of large amounts of natural resources such as natural topsoil and aggregates. In this work, various waste materials mixed with organic debris are tested for greening applications in urban environments as an alternative to the consumption of natural resources.
Materials and methods
Five combinations of artefacts were studied either as “growing material” (i.e. dedicated to plant growth) or “structural material” (as support for traffic). These constructed Technosols were studied in situ in lysimeters under two sets of contrasting climatic conditions at two sites in France (Angers, oceanic climate, and Homécourt semi-continental climate). They were planted with trees (Acer platanoides) and with ryegrass (Lolium perenne L.).
Results and discussion
Compared to natural soils, the constructed Technosols exhibited high porosities and highly saturated hydraulic conductivities (up to 0.76 m3 m−3, and to 34.74 cm h−1, respectively). The physical properties–i.e. macroporosity and microporosity–of these artificial soils revealed high water supply for plants, with available soil water ranging from 0.5 to 2.9 mm cm−1. Tree and ryegrass roots were able to grow in the entire soil volume available in the lysimeters. Organic matter nature and soil pH conditions appeared to be the main drivers of plant development.
Conclusions
Constructed Technosols are suitable for vegetation growth and constitute a valuable alternative to the consumption of natural arable earth for urban greening applications, e.g. gardens, parks, and tree lines. Furthermore, they can provide high levels of relevant ecosystem functions in cities such as water retention and infiltration, plant settlement, carbon sequestration and even biodiversity habitats.

From atmospheric-to pedo-climate modeling in Technosols: a global scale approach

R Dagois, P Faure, P Bataillard, R Bouzouidja, S Coussy, S Leguédois, N Enjelvin et al. - Geoderma, 2017

It is now certain that soil evolution will be strongly influenced by climate change. In particular, young soils, such as anthropogenic soils, show evolution patterns that change faster than natural soils. They can contain large quantities of organic pollutants (in the context of industrial activities) which mobility in the environment might differ under the impact of several environmental factors, particularly climate. To better quantify the link between climatic fluctuations and their impact on soil properties, it is important to understand how meteorological records can be derived into pedoclimates. Using HYDRUS-1D, we converted fluctuations of water content and temperature into pedoclimatic events over time as a function of climatic conditions, soil properties and depth. First, using data collected from lysimeters and a local weather station, we calibrated the fluctuations in soil water content and soil temperature. The model efficiently predicts the evolution of soil temperature (index of agreement > 0.97 and RMSE < 1.8 °C) with a simple convection-dispersion equation. Regarding water content, empirically-estimated hydraulic properties were slightly satisfactory compared to inverse-solution obtained parameters. In a second step, we used the pedoclimate simulated from 10-year datasets collected from 6 global weather stations (Nancy - Nantes - Marseille – France, Darwin – Australia, Denver – USA and Helsinki – Finland)

to estimate the occurrences of freeze-thaw cycles (FTC), wetting-drying cycles (WDC), the temperature regimes and the number of days when the soil temperature rose above 28 °C. The frequency of occurrence of pedoclimatic events decreased with depth and was strongly controlled by climate type. The developed transcription calculus could potentially be used to predict the evolution over time of Technosol properties, such as the fate of the organic matter or organic pollutants under different climatic conditions.

Interactive effects of compost, plants and earthworms on the aggregations of constructed Technosols

M Deeb, T Desjardins, P Podwojewski, A Pando, M Blouin, TZ Lerch - Geoderma, 2017

Aggregation is an important physical process to study during the early formation of Technosols. It is known to be influenced both by the organic matter content and soil biota. Constructed Technosols represent good models to test the importance of these factors since their composition can be easily manipulated by mixing different proportions of parent materials and introducing soil organisms. In this study, we performed a 5 month mesocosm experiment, using excavated deep horizons of soils (EDH) as mineral material mixed with green waste compost (GWC) at six different proportions (from 0 to 50%) in the presence or absence of plants and/or earthworms. After 21 weeks of incubation, aggregation was characterized by: 1) determining the size fraction and morphology, 2) measuring the distribution of organic carbon (OC) in each fraction and 3) testing the aggregate stability. Results showed that organisms accounted for 50% of soil aggregation variance while GWC was responsible for only 5% of the variance. The percentage of total variance of OC distribution in aggregates explained by organisms, GWC, and the interaction of the two was similar (28%, 22% and 26%, respectively). The effect of GWC on structural stability was negligible (2%) compared to that of organisms (70%). The effect of earthworms combination with plants was complex: plants had a dominant effect on the distribution of the size of aggregates by disrupting earthworm casts, but earthworms had a dominant effect over plants for aggregate stability under fast wetting only when the percentage of compost was low. This study underlines the importance of considering the interaction of the organic matter and soil biota: in this case, increasing compost proportion in a Technosol has significant effects on aggregation only in the presence of plants or earthworms.

How lysimetric monitoring of Technosols can contribute to understand the temporal dynamics of the soil porosity

M Tifafi, R Bouzouidja, S Leguédois, S Ouvrard, G Séré - Geoderma, 2017

Soil poral architecture controls soil functioning and is submitted to temporal changes. The monitoring of soil structure dynamics is complicated by inherent technical constraints in its measurement that are either punctual or complex. In this study, four soils, from a natural one to incrementally anthropized (including three Technosols: Spolic Toxic, Terric Transportic, Spolic Garbic Hydric), have been studied. Seven 2-m3 lysimetric columns have been setup to compare planted and non-planted treatments over 3 to 6 years. Data on the water balance and the hydrodynamics were continuously acquired. Differences were observed between the various soils as a function of their texture. The presence of vegetation also led to significant differences, especially in hot periods, between the vegetated and the bare soils treatments: the amount of water stored into the soil was up to 210 L m− 2 higher for bare soil. Furthermore, the analysis of the “critical water storage capacity” highlighted differences in the hydrodynamics at two time scales. For vegetated soils, similar seasonal variations depending on the climatic conditions were observed for all soils, with higher SCRIT values in cold periods compared to hot periods (differences were up to 190 L m− 2). These results were attributed to roots development over

the climatic year that decreases water storage capacity and increases preferential flows. Besides, significant trend evolution was also observed but only for the youngest i.e. the most anthropized soils. Their total water storage capacity decreased down to 52%. It is possibly due to soil compaction, the increase of pore connectivity related to root development and the formation of organo-mineral associations. Our work promotes the association of monitored lysimeters as tool and the study of soils within a gradient of anthropization in order to describe a pedogenetic process like the dynamics of soil porosity.

Initial conditions during Technosol implementation shape earthworms and ants diversity

A Vergnes, M Blouin, A Muratet, TZ Lerch, M Mendez-Millan, M Rouelle-Castrec, F Dubs - Landscape and Urban Planning, 2017

Soils in urban parks are mainly manmade and called Technosols. These Technosols are made of backfill with or without a topsoil addition, which may affect both the physicochemical properties of these soils and the success of soil fauna colonization. The effects of these initial soil management conditions on colonization dynamics of Technosols have not been evaluated yet.
To fill this gap, we sampled earthworms and ants in 20 Technosols covered by lawn and located in urban parks around Paris (France). We selected Technosols constructed with or without an initial addition of topsoil and distributed along an age gradient since construction ranging from 2 to 64 years. Surrounding greening index around Technosols, management practices and physicochemical soil properties have also been recorded.
Surprisingly, no significant differences were observed in the physicochemical properties of Technosols regardless of the absence/presence of topsoil. Communities were composed of few ubiquitous species, which could explain the lack of species richness response to any of our variables. Earthworm and ant abundances increased significantly along the age gradient only in Technosols with initial addition of topsoil. In Technosols, initial conditions apparently determine in part soil macrofauna.
Thanks to a close collaboration between scientist and managers, we highlighted that managers should add topsoil during the creation of Technosols in order to sustain abundance of ecosystem engineers and potentially the ecosystem services they provide.

Interactions between organisms and parent materials of a constructed Technosol shape its hydrostructural properties

M Deeb, M Grimaldi, TZ Lerch, A Pando, A Gigon et al. - Soil, 2016

There is no information on how organisms influence hydrostructural properties of constructed Technosols and how such influence will be affected by the parent-material composition factor. In a laboratory experiment, parent materials, which were excavated deep horizons of soils and green waste compost (GWC), were mixed at six levels of GWC (from 0 to 50%). Each mixture was set up in the presence/absence of plants and/or earthworms, in a full factorial design (n= 96). After 21 weeks, hydrostructural properties of constructed Technosols were characterized by soil shrinkage curves. Organisms explained the variance of hydrostructural characteristics (19 %) a little better than parent-material composition (14 %). The interaction between the effects of organisms and parent-material composition explained the variance far better (39 %) than each single factor. To summarize, compost and plants played a positive role in increasing available water in macropores and micropores; plants were extending the positive effect of compost up to 40 and 50 % GWC. Earthworms affected the void ratio for mixtures from 0 to 30 % GWC and available water in micropores, but not in macropores. Earthworms also acted synergistically with plants by increasing their

root biomass, resulting in positive effects on available water in macropores. Organisms and their interaction with parent materials positively affected the hydrostructural properties of constructed Technosols, with potential positive consequences on resistance to drought or compaction. Considering organisms when creating Technosols could be a promising approach to improve their fertility.

Influence of organic matter content on hydro-structural properties of constructed Technosols

M Deeb, M Grimaldi, TZ Lerch, A Pando et al. - Pedosphere, 2016

Constructed Technosols may be an alternative for creating urban green spaces. However, the hydro-structural properties emerging from the assembly of artefacts have never been documented. The soil shrinkage curve (SSC) could provide relevant structural information about constructed Technosols, such as the water holding capacity of each pore system (macropores and micropores). The objectives of this study were (i) to evaluate the SSC and water retention curve (WRC) to describe the structure of constructed Technosols and (ii) to understand the influence of organic matter content on soil hydro-structural properties. In this study, Technosols were obtained by mixing green waste compost (GWC) with the material excavated from deep horizons of soil (EDH). The GWC was mixed with EDH in six different volumetric percentages from 0% to 50% (GWC/total). The GWC and EDH exhibited highly divergent hydro-structural properties: the SSC was hyperbolic for GWC and sigmoid for EDH. All six mixture treatments (0%, 10%, 20%, 30%, 40% and 50% GWC) exhibited the classical sigmoid shape, revealing two embedded levels of pore systems. The 20% GWC treatment was hydro-structurally similar to the 30% and 40% GWC treatments; so, a large quantity of expansive GWC is unnecessary. The relation with the GWC percentage was a second-degree equation for volumetric available water in micropores, but was linear for volumetric available water in macropores and total volumetric available water. Total volumetric available water in the 50% GWC treatment was twice as high as that in the 0% GWC treatment. By combining SSCs and WRCs, increasing the GWC percentage increased water holding capacity by decreasing the maximum equivalent size of water-saturated micropores at the shrinkage limit and increasing the maximum equivalent size of water-saturated macropores, resulting in an increased range of pore diameter able to retain available water.

Nondestructive monitoring of the effect of biological activity on the pedogenesis of a Technosol

NS Jangorzo, F Watteau, D Hajos, C Schwartz - Journal of Soils and Sediments, 2015

Purpose

Pedogenesis is a set of steps which leads to the formation and evolution of soils under pedogenetic factors and processes (e.g., aggregation, weathering, transfer). To describe them quantitatively for a modeling end, constructed Technosols are suitable candidates to be studied, because their initial composition can be controlled. The challenging objective of our work was then to monitor and study nondestructively, visually, and quantitatively the effect of biological agents on the evolution of a constructed Technosol.

Materials and methods

The Technosol is constructed in three horizons. From bottom to top of the mesocosms, horizons are: (1) gravels, (2) treated industrial soil mixed with paper mill sludge (2/3, 1/3 mass ratio), and (3) green waste compost. Pedogenetic factors are organized according to two modalities each repeated three times: “Plant and Fauna,” where six adult earthworms, Lumbricus castaneus, and five seeds of white lupin, Lupinus albus, are inoculated, and a “control” without any plant and macrofauna. Moisture of

60/80 % field capacity is maintained in all treatments throughout a 14-month experiment. Soil evolution is studied by recurrent image acquisition of the soil profile.

Results and discussion

At the beginning, roots grew preferentially through fissures and cracks at 10 mm·day-1 speed during the first 3 weeks. Then they grew exponentially until reaching a plateau and decreased when plants were at the end of their life cycle. Earthworms prospected the top of the soil first before exploring the deeper horizons preferentially along roots. During their round-trip between the two horizons, earthworms translocated compost. The porosity increased in the first hours of experience and decreased when the system was irrigated. In the Control, porosity continuously decreased while it increased in Fauna–Plant treatment. The evolution of aggregation is root system-dependent. Aggregation was constant in control but significantly increased in Fauna–Plant treatment (about 10 times at 268 days compared with the control).

Conclusions

The use of nondestructive observation of soil profiles is therefore an innovative way of monitoring and quantifying the impact of pedogenetic factors on the functioning and evolution of Technosols. Porosity and aggregation increased with time under the influence of biological factors. Constructed Technosols could be used as model soils for studying the dynamics of soil structure. Although their composition is likely to be different from natural soils, the pedogenetic evolution of Technosols is similar to that of natural soils when facing the impact of biological factors.

Image analysis of soil thin sections for a non-destructive quantification of aggregation in the early stages of pedogenesis

NS Jangorzo, C Schwartz, F Watteau - European Journal of Soil Science, 2014

One major challenge facing soil micromorphology is the direct quantification of aggregation. This study proposes a generic protocol to quantify aggregation properties directly in undisturbed soil samples by image analysis of soil thin sections. We worked on a constructed Technosol proposed as an experimental model with controlled characteristics. Two sampling campaigns were conducted in 2008 and 2010 on an in situ plot, where 24 undisturbed soil samples were collected each year. Thin sections were prepared, scanned to generate images and processed using the protocol developed. Aggregates from 50 to 2000 µm equivalent diameters were monitored. Six aggregate properties were quantified: number, area, perimeter, eccentricity, shape and equivalent diameter. A synthetic mean index of aggregation (MIA ia) was calculated from image analysis. We confirmed that aggregation is closely related to porosity, as highlighted by the MIA ia. Three aggregate properties: number, area and shape were selected as the indicators most representative of aggregation evolution during the early stages of pedogenesis. In further developments, direct (image analysis) and indirect (stability tests) methods for the quantification of aggregation could be proposed as complementary ways of describing and quantifying total quantities of stable macroaggregates in soils.

Modelling agronomic properties of Technosols constructed with urban wastes

S Rokia, G Séré, C Schwartz, M Deeb, F Fournier, T Nehls, O Damas, L Vidal-Beaudet - Waste Management, 2014

The greening of urban and suburban areas requires large amounts of arable earth that is a non-renewable resource. However, concentration of population in cities leads to the production of high amounts of wastes and by-products that are nowadays partly recycled as a resource and quite systematically exported out of urban areas. To preserve natural soil resources, a strategy of waste recycling as fertile substitutes is proposed. Eleven wastes are selected for their environmental harmlessness and their contrasted physico-chemical properties for their potential use in pedological

engineering. The aim is (i) to demonstrate the feasibility of the formulation of fertile substrates exclusively with wastes and (ii) to model their physico-chemical properties following various types, number and proportions of constitutive wastes. Twenty-five binary and ternary combinations are tested at different ratios for total carbon, Olsen available phosphorus, cation exchange capacity, water pH, water retention capacity and bulk density. Dose–response curves describe the variation of physico-chemical properties of mixtures depending on the type and ratio of selected wastes. If these mixtures mainly mimic natural soils, some of them present more extreme urban soil features, especially for pH and POlsen. The fertility of the new substrates is modelled by multilinear regressions for the main soil properties.

Structure of earthworm burrows related to organic matter of a constructed Technosol

B Pey, J Cortet, F Watteau, K Cheynier, C Schwartz - Geoderma, 2013

Literature considering earthworms as a biological agent of Technosol functioning, especially those constructed in order to reclaim degraded areas (e.g. industrial wasteland), is scarce. The main objectives of the following work is: (i) to describe the structure of burrows produced by two different eco-morphological groups of earthworms in a constructed Technosol and (ii) to link their burrowing activity to Technosol organic matter transfers and carbon content in one-species and two-species combinations. For these purposes, the contributions of Lumbricus terrestris as an epi-anecic earthworm and Aporrectodea caliginosa as an endogeic one to such functioning aspects of a constructed Technosol, resulting from soil engineering processes (e.g. choice of proportions, parent materials) were assessed using laboratory microcosm experiments. The Technosol studied was composed of green waste compost, treated industrial soil and paper mill sludge. Earthworms were inoculated separately and together in the constructed Technosol over a period of 75days. Ultra-structural analysis of randomly selected burrows of the one-species treatments and the soil of the control treatment were sampled to describe their structure. Functional consequences on the organic matter in the Technosol were assessed by studying remaining surface litter mass, transfer of surface organic matter to depth and by measuring soil carbon content. At the ultrastructural scale, the burrowing activity of the two eco-morphological groups of earthworms locally modified the organo-mineral associations of the Technosol. Burrows presented a similar structure for both species, with a looser internal cutan including some organic elements and microbial activity tracks (closed to the lumen) and a compacted external mineral cutan (distant from the lumen). However, structural differences were observed between species. L. terrestris burrows contained a visible organo-mineral interface, resulting from the interface between the internal cutan, which was much more organic than for the A. caliginosa one, and the external mineral cutan. For L. terrestris, mucus was present as a large stratum visible between the interface and the external mineral cutan, whereas the mucus was scattered for A. caliginosa. Aggregation also differed between species. Even though both burrows presented some organo-mineral aggregates, plant organic matter particularly contributed to the aggregates for L. terrestris, whereas aggregation was essentially bacterial for A. caliginosa. As is the case for “natural soils”, these results confirmed the notions of i) “ecosystem engineers” in constructed Technosols, by demonstrating that earthworms create organo-mineral structures with a similar structure and ii) eco-morphological groups by distinguishing differences between these structures. At a larger scale (microcosm scale), L. terrestris buried significantly more surface organic matter into depth than A. caliginosa. However, almost no effect of either of the two earthworms (one-species and two-species treatments) on soil carbon content was noticeable. It is suggested that not enough soil carbon measures were made given the temporal and spatial scales of this experiment or earthworm effects may have been masked in the man-made soil built with materials with high initial carbon content. Although sometimes slight at the microcosm scale, differences suggested that earthworm combinations of dissimilar eco-morphological groups led to different effects

on organic transfers and carbon content of the constructed Technosol. Developing knowledge about effects of soil fauna diversity in constructed Technosols using reliable tools (e.g. trait-based approaches) is required. It would better predict the effects of biological agents such as earthworms in soil engineering and in turn improve the ecological restoration of such Technosols.

Predictability of the evolution of the soil structure using water flow modeling for a constructed technosol

G Séré, S Ouvrard, V Magnenet, B Pey, JL Morel, C Schwartz - Vadose Zone Journal, 2012

This paper focuses on the relation between the structure of a constructed Technosol and its hydraulic characteristics during its early pedogenesis. The method is based on a 3-yr comparison of, on one hand, experimental measurements from an in situ gravitation lysimeter and, on the other hand, a modeling approach with HYDRUS-1D. The change of water flow patterns with time was described. It was consistent with previous results for constructed Technosol aggregation. Apart from seasonal variations, the specificity of the hydraulic functioning of the constructed Technosol was shown to be due to the nature of its technogenic parent materials. The in situ evolution of the hydrodynamics has been established and partly linked to external factors (climate, vegetation). The direct modeling and the optimization of the parameters over first a 3-yr period and then three 9-mo periods accurately represented global water flow trends at the pedon scale. However it failed to simulate precisely the main events, such as massive leachate outflow. An evolution with time of some of the hydraulic properties was shown, expressing the structuring of the soil. The existence of two distinct time-scales (slow and steady/fast and cyclic) of the evolution of hydraulic parameters was then formulated as a new hypothesis.

Early pedogenic evolution of constructed Technosols

G Séré, C Schwartz, S Ouvrard, JC Renat, F Watteau, G Villemin, JL Morel - Journal of Soils and Sediments, 2010

Purpose
Constructed soils are Technosols resulting from the deliberate combination of various artefacts. Similarly to natural soils, technogenic parent materials are transformed by pedogenic factors contributing to their evolution. This work was conducted to study the first stages of the pedogenesis of constructed soils.
Materials and methods
Two soils were constructed in lysimetric plots (10 × 10 m) using an engineering process by the combination of paper-mill sludge, thermally treated soil material and green waste compost. Evolution of the soil profiles, composition of soils and leachates were studied for 3 years.
Results and discussion
A strong evolution of the profiles was observed over the 3 years with rapid changes in the number and characteristics of the horizons. Significant changes in chemical weathering (decarbonatisation) and physical status (aggregation), i.e. processes similar to those occurring in natural soils were observed. Other processes specific to the technogenic materials were recorded, e.g. massive dissolution of gypsum or drainage of constitutive water. Apart from constructed Technosols classification, prediction was made on their future pedogenic evolution.
Conclusions
Constructed Technosols made of finely divided reactive organic and mineral compounds were observed to evolve quickly. Evidences of original pedogenic processes have been highlighted that could be considered as a general diagnostic characteristic of Technosols. Finally, some considerations about the

application of the World Reference Base for Soil Resources to the classification of Technosols are proposed, taking into account some aspects of their pedogenesis that have been highlighted by our work.

Thèses de Doctorat

Construction de Technosols fonctionnels et fertiles à partir de matériaux, déchets et sous-produits urbains pour un usage en micro-maraîchage bio-intensif

P Cheval 2023

La construction de Technosols permet de créer des sols à partir de matériaux non valorisés (déchets ou produits résiduels) pour remplir une ou plusieurs fonctions ou services écosystémiques. Cette thèse s'inscrit pleinement dans cette démarche et vise à concevoir des Technosols fonctionnels et fertiles pour un usage en maraîchage urbain. Deux Technosols ont été construits, en collaboration avec Veolia, à partir de matériaux, de déchets et de sous-produits urbains tout en s'inspirant de sols maraîchers réputés pour leurs bonnes potentialités agronomiques. L'objectif du travail consiste à étudier la fertilité de ces deux Technosols, différenciés dans leur composition par la présence ou l'absence de bentonite au regard de (i) leurs paramètres physiques, chimiques et biologiques, (ii) leur capacité à assurer la production de cultures maraîchères, et (iii) leur aptitude à assurer la fonction d'habitat de bioindicateurs de la faune. Les résultats mettent en évidence l'initiation de premiers processus pédogénétiques favorables (i) à l'amélioration de leur fertilité et (ii) à la production de cultures maraîchères de qualité et en quantité comparables à celles d'un sol maraîcher professionnel au cours de deux saisons culturales. Une distinction est toutefois établie avec, dans l'ensemble, des cultures de meilleure qualité dans les modalités incluant de la bentonite. L'analyse de la composante biotique permet, quant à elle, de montrer que les Technosols sont susceptibles d'être rapidement colonisés par des organismes pionniers et qu'ils ont la capacité à assurer la fonction d'habitat d'organismes ingénieurs de l'écosystème avec une propension globale des organismes à privilégier les modalités incluant une part de bentonite. Ces travaux représentent une opportunité d'imaginer une alternative aux prélèvements de terres rurales fertiles pour assurer les aménagements urbains, mais aussi d'accroître l'implantation de systèmes à l'origine de nombreux services écosystémiques (e.g. support de biomasses, approvisionnement de denrées alimentaires, régulation). Ils représentent également la possibilité de reconnecter production alimentaire et zone urbaine, deux termes encore antinomiques jusqu'à récemment.

Fabrication d'agrégats à partir de déchets : recherche sur l'incorporation d'argiles réactives dans des matériaux dédiés aux filières de construction de sol

S El Farricha 2022

La construction de sols à partir de déchets encourage la transition d'une économie linéaire vers une économie circulaire en recyclant les matériaux pour produire des sols fertiles pour les communautés. Dans ces travaux de thèse, nous explorons l'incorporation de déchets riches en argiles réactives dans le processus de construction de sol pour mieux comprendre comment la nature des déchets, les propriétés physiques et les méthodes de construction de sol influencent l'agrégation à l'échelle du laboratoire et d'un site-pilote. Les résultats de laboratoire montrent que la minéralogie et la proportion d'argiles incorporées influencent principalement la production d'agrégats de 1 à 3 mm et la stabilité structurale à sec, tandis que l'ajout de compost mature influence principalement les agrégats de plus

de 3 mm. Le mouvement rotationnel automatisé d'un disque bouletteur permet un mélange uniforme des déchets et la production significative d'agrégats entre 1 et 5 mm. Ces résultats valident le potentiel d'agrégation de la méthode de construction de sol par bouletage et son principe de fonctionnement. La stabilité structurale humide des agrégats peut être améliorée en augmentant l'humidité dans leurs espaces poreux ou en augmentant l'hydrophobicité globale pour réduire la pression interne des agrégats. L'expérience en pot à l'échelle du laboratoire démontre l'influence de la croissance de la végétation sur l'agrégation du sol. Les racines impactent la formation des agrégats au-delà de 5 mm, et le couvert végétal protège les agrégats de surface évitant ainsi une réduction de la taille des agrégats. Pour cette raison, la mise en place de végétation sur les sols construits peut être très bénéfique, car les racines peuvent favoriser l'agrégation et la stabilité, tandis que la couverture végétale peut protéger la surface du sol, lui donnant suffisamment de temps pour améliorer sa stabilité. L'étude à l'échelle du site-pilote utilise un cylindre bouletteur et examine l'impact des argiles et de la matière organique sur l'évolution de la stabilité des agrégats humides sur sept mois. La teneur en argiles peut être bénéfique pour stabiliser les microagrégats, mais seulement lorsqu'un pourcentage suffisant de compost est ajouté. L'amélioration de la stabilité des agrégats humides dans le temps est un indicateur positif de la viabilité biologique et de la fertilité de ces sols construits. Ceci est encore confirmé par la production de biomasse, principalement corrélée au pourcentage de compost ajouté. Les matériaux parentaux sélectionnés se sont révélés avoir un potentiel d'agrégation élevé et ont fourni un support végétal, remplissant le rôle d'un sol fertile.

Potentiel de la Biodiversité dans la construction de Technosols à partir de déchets urbains

C Pruvost 2018

Les besoins en terre végétale pour l'aménagement d'espaces verts urbains induisent un prélèvement de sols agricoles ou naturels. D'autre part, des volumes considérables d'horizons profonds excavés lors de la construction de bâtiments sont mis en décharge en périphérie des villes, avec un impact sur l'environnement. Le recyclage de ces déchets inertes pour la construction de sols des espaces verts apparaît comme une solution prometteuse. Il est toutefois nécessaire de s'assurer que ces Technosols construits peuvent accueillir une diversité végétale et animale pour délivrer des services écosystémiques, comme propose de le faire ce travail de thèse. La composition des mélanges de matériaux (horizons profonds, compost de déchets verts, béton concassé) a été manipulée dans une expérimentation de 4000 m² en collaboration avec l'entreprise ECT et le CD 93. Un suivi de quatre ans a montré que le compost utilisé était responsable de la mort de certains arbres, mais qu'associé au béton, il augmentait fortement leur vitesse de croissance et de colonisation par la macrofaune. En usage prairial, l'ajout de compost a augmenté la production de biomasse et modifié l'assemblage de la communauté végétale, en favorisant les espèces compétitives, mais pas de la macrofaune. Dans une expérience en mésocosmes visant à étudier le lien entre diversité végétale et productivité, une complémentarité entre espèces a été observée pour une des trois communautés, à un niveau de fertilité intermédiaire. Il est donc possible d'améliorer la productivité primaire de nouveaux écosystèmes en manipulant la composition des mélanges de matériaux tout en évitant la dominance de certaines espèces, afin de conserver des communautés diversifiées

Influence des plantes, des vers de terre et de la matière organique sur la structure de technosols construits

M Deeb 2016

Pour répondre à la demande sociétale et aux contraintes environnementales, la création de Technosols à partir de déchets organiques et minéraux est une alternative à l'importation de sols agricoles fertiles au profit des espaces urbanisés. Si le rôle de la matière organique (MO) et des organismes est reconnu sur la fertilité des sols naturels, il reste peu connu en ce qui concerne les Technosols. Ce travail de thèse s'intéresse en particulier à l'influence du taux de MO et des interactions avec les vers de terre et les plantes sur les propriétés physiques et hydriques des Technosols construits. Les matériaux utilisés pour construire nos Technosols sont le compost de déchets verts et des remblais d'horizons profonds excavés. Dans une première expérience, nous avons testé l'influence du taux de MO sur les propriétés hydrostructurales des Technosols, en réalisant 6 mélanges contenant des proportions volumiques croissantes de compost (de 0 à 50%). Les courbes de retrait et de rétention montrent que les propriétés hydrostructurales des Technosols sont similaires à celles de sols naturels et proches de celles de sols argileux, alors que nos Technosols n'en contiennent qu'une très faible quantité (2%). L'augmentation de la quantité de matière organique s'accompagne d'effets positifs sur la micro et la macro porosité, ainsi que sur l'eau disponible pour les plantes.Dans un deuxième temps, ces différents mélanges ont été incubés en chambre de culture avec ou sans vers de terre (Aporrectodea caliginosa) et avec ou sans plantes (Lolium perenne). Après 5 mois d'expérience, nous avons mesurés les propriétés hydrostructurales, l'agrégation, et la distribution du carbone dans chaque fraction. La présence de plantes et/ou vers explique 19% de la variance des propriétés hydrostructurales du sol, et la dose de compost influe à 14%. L'interaction entre organismes et compost explique davantage la variance (40%) que les effets de ces facteurs isolés. Le compost et les plantes jouent un rôle positif sur l'eau disponible en agissant à la fois sur la macroporosité et sur la microporosité, alors que les vers jouent un rôle positif uniquement sur cette dernière. Par ailleurs, la proportion d'agrégats >3mm est plus importante dans les traitements sans organisme (témoin) et avec des vers de terre, tandis que la proportion d'agrégats <3mm est plus importante en présence de plantes, indépendamment de la présence de vers de terre. Les organismes ont un effet plus fort sur la stabilité structurale (77%) que le compost (4%). Tous ont un effet positif sur la quantité de Corg dans les différentes fractions d'agrégats. Enfin, la minéralisation du Corg augmente en présence de vers ou de compost, mais diminue en présence de plantes. Nos résultats démontrent l'intérêt de valoriser des matériaux urbains tels que les horizons profonds excavés et le compost de déchets verts pour construire des Technosols. Une synthèse des résultats nous permet de conseiller une teneur volumique en compost comprise entre 20 et 30% pour obtenir des propriétés structurales intéressantes, sans trop alourdir le coût induit par le compost et maximiser les volumes d'horizons excavés ainsi utilisés. Constatant l'effet positif des vers de terre, des plantes et des interactions plantes-vers de terre sur la porosité, la stabilité structurale et le stockage de carbone, il semble opportun de favoriser la présence des organismes

Contribution à la modélisation des processus d'agrégation et de transfert d'éléments nutritifs dans les Technosols construits à partir de déchets

S Rokia 2014

La végétalisation d'espaces en zone urbaine nécessite l'utilisation de grandes quantités de ressource naturelle terreuse. Pour préserver cette ressource non renouvelable, le génie pédologique propose une stratégie de construction de Technosols fertiles à partir du recyclage de déchets et sous-produits. Les propriétés des Technosols sont alors fortement influencées par les matériaux technogéniques qui les constituent. La formulation de mélanges performants pour la croissance des végétaux urbains passe par une analyse scientifique préalable. La fertilité des mélanges et leur évolution au cours du temps peuvent

être appréciées par l'étude du processus d'agrégation et du transfert d'éléments nutritifs lors des stades précoces de la pédogenèse. Le modèle expérimental de Technosol construit proposé dans la Thèse développe une méthodologie aboutissant à la sélection de 11 matériaux (ballasts, béton, boues de station d'épuration urbaine, briques, compost de boues et de déchets verts, déchets de balayage de rue, déchets de démolition, déchets verts, terres excavées de profondeur, sous produits papetiers) représentatifs des gisements de déchets recensés au niveau européen et compatibles avec la construction de sol fertile. Le potentiel fertile initial de chaque matériau pur et de certaines combinaisons de mélanges a été mesuré. Puis des expériences menées en conditions contrôlées ont permis d'évaluer l'effet de différents facteurs pédogénétiques (e.g. anthropique, climatique et biologique) sur les processus déterminant de la fertilité des Technosols construits. Les résultats indiquent (i) qu'il est possible de construire un Technosol fertile exclusivement à partir de deux ou trois déchets aux propriétés physico-chimiques complémentaires; (ii) que les propriétés des mélanges sélectionnés peuvent être modélisées à partir des propriétés initiales de leurs matériaux parents.(iii) que lors des premiers stades d'évolution pédogénétique des mélanges, des agrégats stables se forment en fonction de la nature et des propriétés des matériaux parents, (iv) que les transferts d'éléments nutritifs sont fortement dépendants de la nature des matières organiques et du procédé de mélange des particules entre elles. La libération d'éléments nutritifs (e.g. phosphore) serait liée à la taille et la quantité des agrégats formés et en corollaire à la mise en place d'une organisation porale. Les connaissances acquises sur le fonctionnement et l'évolution des Technosols construits à partir de déchets apportent des connaissances nouvelles pour le génie pédologique. La méthode de choix de déchets ainsi que le procédé de formulation de mélanges développés dans ces travaux permettent d'obtenir des mélanges voire des sols construits performants par rapport à des usages attendus. Les modèles d'évolution des mélanges permettent de prédire au cours du temps la fertilité physico-chimique des Technosols construits. Dans le cadre du programme SITERRE-ADEME (2010-2015), les résultats acquis constituent des bases incontournables dans le développement d'un outil d'aide à la décision pour les gestionnaires (e.g. collectivités, bureaux d'étude, entreprises) auquel doit être associée une expertise sur la construction de sol pour la production de biomasse végétale

Quantification du processus d'agrégation dans les Technosols

SN Jangorzo 2013

Les Technosols forment une nouvelle classe de sols, caractérisée par une forte influence anthropique dont le fonctionnement est peu étudié. L'agrégat étant l'intégrateur de l'histoire du sol et révélateur de son fonctionnement actuel, l'étude du processus d'agrégation est de ce fait une entrée pertinente pour comprendre le fonctionnement des Technosols et les stades vers lesquels ils peuvent évoluer. A partir d'échantillons de sol prélevés sur une parcelle d'un hectare, un protocole non destructif de quantification directe de la porosité et de l'agrégation par analyse d'images a été mis en place. Les résultats montrent qu'au bout de deux ans, le Technosol construit se compacte avec une réduction de la surface de des pores de diamètre > 25 µm et une augmentation des pores < 25 µm. Malgré cette compaction, l'agrégation augmente avec le temps. Pour suivre la dynamique de la porosité et d'agrégation de ce Technosol en fonction de facteurs choisis de pédogenèse, un dispositif de visualisation in situ a été conçu. Les résultats d'analyse d'images ont montré que dans les stades précoces d'évolution des sols, la porosité et l'agrégation augmentent significativement. Ensuite, elles baissent significativement dans la modalité « humectation-dessiccation» tout en continuant d'augmenter dans les modalités « plante » et « faune + plante ». Cette augmentation est proportionnelle à l'âge des racines et à l'intensité de l'action des vers de terre. Le « Technosol construit » est alors un modèle expérimental dont la constitution organominérale et le fonctionnement sont très largement contrôlés, en comparaison de sols « naturels » évolués dont le point initial de développement est quasi systématiquement inconnu

Contribution de la faune du sol au fonctionnement et à l'évolution des Technosols

B Pey 2010

Les Technosols ont des propriétés et une pédogenèse influencées par des matériaux technogéniques qui les constituent. Le modèle expérimental de Technosol construit a été choisi et résulte de l'utilisation délibérée de matériaux technogéniques au sein d'un profil. L'objectif scientifique est d'évaluer la contribution de la faune du sol aux processus impliqués dans le fonctionnement et l'évolution des Technosols. Des expérimentations en laboratoire (cosmes) et en conditions climatiques réelles (lysimètres, parcelles) ont été menées de l'échelle ultrastructurale à celle du pédon. Les résultats indiquent que (i) le Technosol construit est un support de vie de la faune, (ii) le modèle d'ingénieur de l'écosystème : Lumbricus terrestris, par la création de macroporosité et par ses structures biogéniques contribue à sa structuration, son agrégation et à la décomposition de sa matière organique, (iii) lorsque plusieurs groupes d'organismes assurant des fonctions différentes sont associés, des effets sont mesurés majoritairement sur la décomposition de la matière organique. La forte disponibilité des ressources du Technosol autorise la présence de la faune mais masquent en partie ses effets et inhibent les interactions faunistiques qui auront un effet sur les fonctions des sols. Un modèle d'évaluation de l'effet de Lumbricus terrestris sur la macroporosité est proposé. En termes de génie pédologique, un projet de modèle d'aide à la décision résulte des acquis scientifiques. L'inoculation de la faune contribuerait ainsi à initier des mécanismes d'évolution des sols et à les accélérer

Fonctionnement et évolution pédogénétique de Technosols issus d'un procédé de construction de sol

G Séré 2007

La restauration des fonctions des sols est une étape clé de la requalification des sites dégradés par les activités humaines. Ces opérations nécessitent de disposer de procédés de remise en état du couvert pédologique favorisant la résilience écologique. Ils génèrent de nouveaux sols dont il faut prévoir l'évolution. Notre objectif est de caractériser le fonctionnement et la pédogenèse de sols construits à l'aide d'un nouveau procédé fondé sur la formulation de déchets et sous-produits (terre industrielle traitée, sous-produit papetier, compost). Dans ce but, des colonnes en laboratoire ainsi que des parcelles lysimétriques in situ ont été mises en place. Des paramètres descriptifs des fonctionnalités et de la pédogenèse des sols construits ont été mesurés. Les résultats ont montré que les matériaux parents présentent des propriétés aptes à remplir des fonctions comme la fourniture d'éléments ou la rétention en eau. Les sols construits remplissent les rôles de support de végétation, d'échange/filtre et de support de la biodiversité comme des sols naturels. Les premiers stades de leur évolution pédogénétique se caractérisent par leur intensité, leur rapidité et leur caractère non habituel (e.g. dissolution conjointe de gypse et de calcite). La prospective sur l'évolution des sols construits démontre que, de Technosols, ils évoluent vers des types de sols analogues aux sols naturels. Ce cheminement nous conduit à proposer une évolution de la classification des sols très anthropisés sur des critères génétiques. Enfin, les bases de la modélisation de la pédogenèse des sols très anthropisés sont posées ainsi que celles d'un outil d'aide à la décision pour le génie pédologique

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