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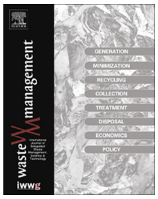

Modelling agronomic properties of Technosols constructed with urban wastes

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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 P_{Olsen}. The fertility of the new substrates is modelled by multilinear regressions for the main soil properties.

1. Introduction

Is it possible to recycle urban wastes for the construction of fertile soils in cities as a substitute for natural soil resources? plants in urban environments present a growing interest in daily life, health and well-being (Nielsen and Hansen, 2007). Indeed, green areas present advantages regarding biodiversity, urban water infiltration and also contribute to the decrease of urban heat island phenomenon (Lorenz and Lal, 2009). However, soils in urban areas are mainly not favourable mediums for plant growth considering their low physical and chemical fertility (Jim, 1998). Urban soils are characterised by a high spatial heterogeneity as a result of the mixture of technogenic artefacts in Technosols (WRB, 2006) with native materials (Morel et al., 2005). These soils are characterised by (i) coarse texture; (ii) extreme values of bulk density that are either high ($>1.6\ \mathrm{g\ cm^{-3}}$) or very low ($<0.5\ \mathrm{g\ cm^{-3}}$); (iii) high pH values (pH > 7.5) resulting from alkalising products mixed in the soil; (iv) high C/N ratio because of a low N content; and (v) potentially enhanced pollution level (Morel et al., 2005). Therefore, to insure the implementation of urban green areas, large quantities of upper soil materials imported from agricultural or forestlands are needed (in France 3 millions of $\mathrm{m^3\ year^{-1}}$). At the same time, cities consume high quantities of raw materials that give rise to great amounts of urban wastes (e.g., rubble, household refuse, industrial wastes and by-products). In France, 770 million tons of wastes and by-products (called "wastes" in the article) were produced in 2009, 5.3 million tons corresponding to municipal wastes (public refuse, sewage sludge, and green wastes), 253 million tons to wastes resulting from civil engineering, 32 million tons to household wastes, 106 million tons to industrial wastes and 374 million tons to wastes from forest and agriculture (ADEME, 2012). These wastes are consistently exported out of cities, part of them being recycled into industrial processes, others directly spread on agricultural soils (e.g., compost, urban and industrial sludge) and most of them landfilled (Marshall and Farahbakhsh, 2013).

The aim of the present work is to limit the exportation of wastes out of cities by recycling them in urban soil construction. Some previous experiments have been led by mixing wastes together

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(e.g., sewage sludge, compost, and paper mill sludge) to restore industrial brownfields (Fierro et al., 1999; Séré et al., 2008) or by adding organic wastes to planting holes (Craul, 1999; Grosbellet et al., 2011). But, in these particular studies few wastes ratios have been well investigated. Thus the complexity of the potential interactions in the wastes combination could not be understood. Moreover, the question of reaching the optimum wastes ratio in the mixture stays unanswered, whereas this step is required to develop at a larger scale pedological engineering by the recycling of urban wastes into constructed soils. The aim of this study is to provide answers to the following questions: (i) Is it feasible to create fertile substrates, which mimic natural soils, exclusively with wastes? (ii) Is it possible to describe with appropriate models the variation of physico-chemical properties of mixtures constituted by various proportions of wastes? (iii) Is the fertility of these mixtures predictable out of the characteristics of the constitutive materials?

2. Materials and methods

2.1. Selection of wastes

A national research program funded by the French environmental agency (programme SITERRE–ADEME) is dedicated to the development of pedological engineering for the construction of soils in urban areas. During this program, eleven wastes have been selected in the European waste catalogue (European commission *n*° 94/3/CEE, 1993). The criteria of selection were: the volume of production, the availability all over the French regions, the low toxicity and the potential fertility as mineral and/or organic constituents for soil construction. The eleven wastes are: excavated acidic and basic earth material from a deep horizon (respectively AE and BE, European classification number: 170504), bricks (BR, 170102-170103), compost made off sewage sludge and green wastes (CO, 190503), concrete (CR, 170101), demolition rubble (DR, 170107), green wastes (GW, 020107-020103), paper-mill sludge (PM, 030305), street sweeping wastes (SS, 200303), sewage sludge (SW, 190812), and track ballast (TB, 170508). Five of them are mainly organic (CO, GW, PM, SS, SW) and six are mainly mineral materials (AE, BE, BR, CR, DR, TB). Among them, only two are fine earth materials, developed on acidic and basic bedrocks (AE, BE). These last are classified as wastes but can be considered as natural soil resources, even if excavated from deeper horizons.

2.2. Sampling of wastes

Ten cubic meters of each waste have been collected from local cities and companies and stored on a platform before sampling (Angers, France, 47°47′ N, 00°56′ W). Fifty kilograms of homogeneous samples representative for each pile of waste have been obtained by the mixing of 20 sub-samples.

2.3. Selection of waste mixtures

To reduce the complexity of the systems, the number of wastes mixed together was limited to 3. Using the 11 wastes, they were 45 binary and 120 ternary possible combinations. For technical reasons in relation with the size of the experiment, we decided to limit the number of characterised mixtures to 25. The first filter was to eliminate the nonsensical associations regarding the construction of fertile soils. Obviously, the mixtures of materials with very similar properties and the binary combinations of two mineral or two organic materials were not studied. In prevision of the construction of dose–response curves, fifteen binary combinations have been prepared at 5 different ratios ranking from 0/100, 20/80, 50/50, 80/20, to 100/0 (volume waste 1/volume waste 2) (Table 1). For the ternary mixtures, we followed the model of structural soils including systematically 60% v/v of coarse mineral material (CR, DR, TB) (Grabosky et al., 2002). They were added with 40% v/v of binary mixtures constituted by 10%, 20% or 30% (volume waste 1/volume waste 2) of two other materials: organic wastes (CO, GW, PM, SS, SW) and earth materials (AE, BE) (Table 1). This procedure allowed preparing, at all, 75 mixtures contrasted for their composition (25 combinations) and different ratios.

2.4. Mixing procedure

At a first step, all the wastes have been air-dried. Coarse wastes (CR, DR, BR, TB) have been crushed at 5 mm. All the materials have then been sieved at 5 mm. The experimental devices used for the mixing procedure were 2 L cylinder shaped flasks (Nalgene, 100 mm diameter, 250 mm height). This size has been selected because the maximum grain diameter of mixed materials should be at least 10 times smaller than the diameter of the experimental device (Paute et al., 1994). The wastes have been moistened at 80% w/w of their water field capacity. They have been weight, mixed, and homogenised manually during 5 min, before being incorporated in the 2 L flasks and put successively vertically (16 rpm, for 10 min) and horizontally (16 rpm, for 10 min) on a rotating shaker (Guyon and Troadec, 1994; Khakhar, 2011; Severson et al., 2007). Bulk density has been determined on these samples following a method adapted from the standard NF EN 13041.

2.5. Agronomic characterisation

The mixtures of wastes have been investigated for their ability to support plant biomass production. Both wastes and mixtures have been air dried and sieved at 2 mm. Classical soil indicator attributes have been selected to characterize the fertility of the mixtures of technogenic materials. The samples have been characterised for total C (C_{tot}), available phosphorus (P_{Olsen}), cation exchange capacity (CEC), pH (water), and characteristic humidity at field capacity (matrix potential: -10 kPa) ($\mathrm{WC}_{-10\ \mathrm{kPa}}$) using standard methods for soils (NF ISO 10694, NF ISO 11263, NF X 31130, NF ISO 10390, NF ISO 11464 respectively). The characteristics of the mixtures have been compared to statistics calculated from the 2200 sites of the French National Soil Monitoring Network "Réseau de Mesures de la Qualité des Sols" (Jolivet et al., 2006; Arrouays et al., 2002), which consists of soil property observations on a 16-km regular grid covering the French metropolitan territory (5550,000 km^2).

2.6. Statistic tools

Data relative to the waste characterisation (C_{tot}, P_{Olsen}, CEC, pH, $\mathrm{WC}_{-10\ \mathrm{kPa}}$, bulk density) were submitted to principal component analysis using XLSTAT software (2011.2.06 version).

2.7. Modelling details and validation

Waste mixtures characteristics were modelled using second order polynomial models without interaction terms (Matlab, R2010a). Models include the 11 factors describing the composition of each waste material. One model was determined for each characteristic (C_{tot}, P_{Olsen}, CEC, pH, $\mathrm{WC}_{-10\ \mathrm{kPa}}$, bulk density). Each experience was repeated three times. The linear regression was performed on a set of 86 samples including pure (11), binary (45) and ternary (30) mixtures. Model quality was assessed using determination coefficient (R^2). As a validation step, the model was tested with characterisation data for 4 organic wastes (CO, GW, SS and SW) from a new origin. Twelve mixtures (four binary

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