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Use of dredged sediments for soil creation in the Seine estuary (France): Importance of a soil functioning survey to assess the success of wetland restoration in floodplains

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ABSTRACT

The creation and restoration of new wetlands to mitigate wetland losses is a newly developing science whose success still needs to be assessed. This study focuses on the ecological restoration of a gravel-pit in the low valley of the Seine estuary (France). Restoration consisted in filling the gravel-pit using a hydraulic technique with dredged sediments from the Seine river and covering it with alkaline peat from adjacent wet meadows. Our objectives were to survey the functions of recreated soil 3 years after the gravel-pit was filled and assess whether it regained typical wetland functionality and to determine which soil functioning parameters are the most efficient for assessing restoration success. To address these questions, an approach combining analyses of *in situ* and *ex situ* soil functioning was used. The survey was conducted on recreated soil as compared to a control soil (*i.e.* soil before gravel extraction). Four topographic zones were sampled corresponding to 4 types of recreated soil functioning in terms of waterlogging conditions: Hemic Histosol without waterlogged periods, Hemic Histosol with temporary waterlogged periods, Hemic Histosol with the longest waterlogged periods and Interstratified Histosol without waterlogged periods. Soil respiration and SIR results showed that large stocks of organic matter are maintained after 3 years of restoration and proved able to sequester C in recreated soils. 3 years after restoration, nitrogen removal function measured through denitrification technique was restored in the Hemic Histosol with the longest waterlogged periods. These results demonstrate that waterlogging regime maintain the C stock and accelerate the restoration of denitrification process.

1. Introduction

Wetlands are among the most important ecosystems on earth. They are broadly defined by Mitsch and Gosselink (2000) as ecosystems providing substantial ecosystem services to human societies and also as having important ecological and environmental functions that contribute to human well-being. These include water quality improvement (Moreno et al., 2007), biological productivity (Van Roon, 2012), and carbon (C) sequestration (Coletti et al., 2013; Wylynko, 1999). Nitrogen (N) cycling in wetlands has received considerable attention because of the potential of wetlands for decreasing Nitrogen inputs (Chen et al., 2009; Pinay et al., 2007). Nitrogen in wetlands is removed by both denitrification (Bachand and Horne, 1999; Mander et al., 2008) and plant uptake processes (Gottschall et al., 2007; Tan et al., 2013). Pinay et al. (2007) report that denitrification is one of the important processes occurring in the wetlands, which uses nitrogen oxides as alternative electron acceptors when oxygen is limited. Denitrification is the reduction of NO_3^- to nitrogen gaseous forms such as N_2O, and the main process responsible for the buffering capacity of riparian zones against diffuse nitrate pollution. Wetlands also play an important role in global C cycling by acting as natural C sinks (Bernal and Mitsch, 2008; Bridgham et al., 2006; Davidson and Janssens, 2006; Trettin

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et al., 2011). High C accumulation rates are related to their typically high vegetation productivity (Mitsch and Gosselink, 2000; Zhang et al., 2011) and low organic C decomposition (Coletti et al., 2013). Low C decomposition rates are promoted by waterlogged conditions that limit oxygen (O_2) diffusion through the soil, thus decreasing the efficiency of decomposition pathways (Mitsch and Gosselink, 2000).

However, owing to human activities, more than half of the wetland ecosystems that existed in the early 20th century have been lost (Mitsch, 2005; Neue et al., 1997). The degradation and loss of these ecosystems all over the world, and the subsequent recognition of their ecological value, has led to considering the restoration of wetlands as a top priority (MA, 2003). According to the Society for Ecological Restoration (SER, 2004), restoration attempts to return ecosystems to their historical dynamics trajectory. Nevertheless, the historical dynamics trajectory can prove hard or even impossible to determine with accuracy according to how deeply the ecosystem was impacted. So the use of reference sites/ecosystems that can serve as models for designing ecological restoration projects and later assessing restoration success is of primary importance (SER, 2004). Reference sites should be located in the same edaphic, climatic and historical zone as the restoration project, and should be exposed to similar natural disturbances (SER, 2004). Usually, ecosystems that require ecological restoration are degraded, damaged or transformed as a direct or indirect result of human activities. However when ecosystems have been entirely destroyed, questions arise, such as (1) how to define a reference site in this case and (2) how to find the appropriate strategy for estimating restoration success. Various authors suggest that restoration success could be based on the survey of one ecosystem component such as vegetation structure (Matthews et al., 2009; Spieles, 2005; Stefanik and Mitsch, 2012), hydrological characteristics (Hohensinner et al., 2007) or macro-invertebrate communities (Spieles et al., 2006), while others promote a more integrated approach including many variables in order to provide a better assessment of restoration success (Andersen et al., 2006; Hobbs and Norton, 1996; Passoni et al., 2009). Nevertheless, few authors have attempted to use soil functioning as an indicator of wetland restoration success, although soils perform multiple ecological functions such as being a carbon sink and a nitrogen removal (Mitsch and Gosselink, 2000).

This study focuses on the ecological restoration of a gravel-pit in the low valley of the Seine estuary (France). Restoration consisted in filling the gravel-pit with dredged sediments from the Seine valley and covering it with alkaline peat coming from soils of adjacent wet meadows (Histosols). More than 5 million tonnes of materials are dredged annually to maintain and improve navigation within the Seine estuary. Consequently, dredging and disposal of these materials has become an important issue in the Seine Valley (Samson et al., 2002). In parallel, sand and gravel extraction is one of most important economic activities in the Seine floodplain (Guézennec, 1999). After their exploitation, extraction pits are commonly converted into ponds dedicated to spare-time activities or habitat protection. Extraction is the second cause for wetland loss in the Seine floodplains after damming. In the early 1990s, the "Grand Port Maritime de Rouen", in collaboration with the "Parc Naturel Régional des Boucles de la Seine Normande", started considering the use of dredged sediments to fill gravel-pits as a promising solution to recreate soils aimed at supporting the development of terrestrial wetland ecosystems such as wet meadows or grasslands.

In this context, this paper aims to (i) survey the functioning of recreated soil during 3 years after the gravel-pit was filled with dredged sediments and (ii) assess whether it regained typical wetland functions (C storage, nitrogen transformations and nitrate removal) in order to determine which soil functioning parameters are the most efficient for assessing restoration success. To address these questions, an approach combining analyses of *in situ* and *ex situ* soil functioning was used. For *in situ* soil functioning measurements, we investigated soil respiration, soil net N-mineralization and soil denitrification, using soil CO_2 efflux measurement technique, the buried bag method and the acetylene inhibition technique, respectively. For *ex situ* soil functioning measurements, we used heterotrophic soil respiration, potential C and N mineralization and potential soil denitrification using Substrate-Induced Respiration (SIR), laboratory incubations and Denitrification Enzyme Activity (DEA) methods, respectively. The recreated soil was compared with a control soil corresponding to the soil before gravel extraction. We hypothesized that the rate with which the recreated soil regained typical functions of wetland soil (C storage, nitrogen transformations and nitrate removal) depends on (1) the nature of the materials used to reconstitute the soil (local dredged sediment and alkaline peat) and (2) the topographic position of the recreated soil within the floodplain system (waterlogging conditions and water-table fluctuations).

2. Materials and methods

2.1. Study site

The study was carried out in the gravel-pit of Yville sur Seine, North-West France (49°29′05″ N; 00°52′ 31″ E) (Fig. 1). The climate is temperate oceanic with mean annual temperature of +11 °C and a mean annual precipitation of 800 mm. The gravel-pit (11 ha surface and 1 million m^3 volume) was filled by pumping dredged sediments between 2000 and 2007 (~684,568 m^3 of dry sediments), and then covered with characteristic alkaline peat from adjacent wet meadows in 2008. Mechanical dredges remove material by scooping it out from the channel bottom and then placing it onto a disposal area. Hydraulic dredges suck a mixture of dredged material and water from the channel bottom. The amount of water sucked up with the material is controlled to make the best mixture (90% of water and 10% of dredged sediments). Such work is carried out by pipeline dredges. A pipeline dredge sucks dredged material through one end (the intake pipe), and then pushes it out through the discharge pipeline directly into the disposal site. Excess water in the disposal area (the gravel-pit) is subsequently pumped back to the Seine River *via* another pipeline.

The hydraulic filling of gravel-pits leads to a spatial distribution of sediments that results in the formation of 3 types of recreated soils (RS) according to the "Référentiel Pédologique" (AFES, 2009). An equivalent in World Reference Base for soil resources (IUSS Working Group WRB, 2006) is given between brackets:

(i) An "ANTHROPOSOL RECONSTITUE/HISTOSOL mésique reconstitué sur sédiments de dragage" (Hemic Histosol reconstituted on dredged sediments) occupied 77% of the recreated area: "HISTOSOL mésique", mainly composed of organic soil material but the soil profile is composed of a histic H horizon on its surface (H horizon with 30% organic carbon in weight within a 55-cm depth), a thin layer of mineral Mca1 horizon in its middle (with ~12% organic carbon, 83% sand content within a 25-cm depth) and a deep mineral Mca2 horizon (with 20% organic carbon, 31% silt content) (Table 1).
(ii) An "ANTHROPOSOL RECONSTITUE/HISTOSOL mésique interstratifié reconstitué sur sédiments de dragage" (Interstratified Histosol reconstituted on dredged sediment) occupied 19% of the recreated area: "HISTOSOL interstratifié", characterized by a mineral Mca horizon in the top 10 cm (with 3.7% organic carbon in weight within a 10-cm depth) (Table 1). For this soil, the