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Using a dune forest as a filtering ecosystem for water produced by a treatment plant – One decade of environmental assessment

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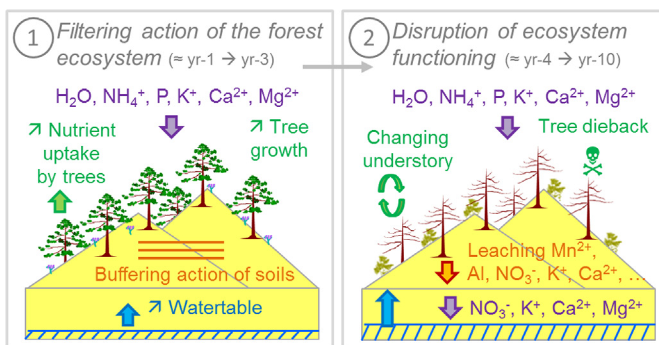
HIGHLIGHTS

- We evaluated the effects of applying wastewater from a treatment plant on a forest.
- In the short-term, the wastewater improved tree growth.
- Long-term application led to soil alkalinisation and eutrophication.
- Nutrient imbalances in the soil caused pine dieback and modified understory composition.
- Wastewater application polluted the water table.

GRAPHICAL ABSTRACT



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ABSTRACT

A dune forest in SW France composed of maritime pines was irrigated with treated wastewater for a decade in an experiment (including irrigated plots versus control plots) to evaluate the environmental impact of applying wastewater on the water table, soil properties, and plants. The amount of treated wastewater (1921 mm yr^{-1}) applied was twice the annual precipitation. Nutrient inputs were also very high, particularly nitrogen (N: 539 kg-N ha^{-1} yr^{-1}), phosphorus (P: 102 kg-P ha^{-1} yr^{-1}), and calcium (Ca: 577 kg-Ca ha^{-1} yr^{-1}). Irrigation caused a rise in the water table, and increased its sodium (Na), NO_3^-, potassium (K), and calcium concentrations. Soil properties were affected by irrigation at least down to a depth of 1.2 m. After eight years of irrigation, soil pH had increased by 1.4 units, and soil available P content (P_{Olsen}) increased nearly 8-fold. In the short-term (i.e. 1–3 years), irrigation with treated wastewater improved growth, standing biomass, and the nutritional status of the vegetation. But tree dieback started in the fourth year of irrigation and worsened until the end of the monitoring period when almost all the irrigated trees were dead or moribund. The understory composition was drastically modified by irrigation, with an increase in α-biodiversity and in the biomass of herbaceous species, and a reduction in woody species abundance. The factor that best explained tree dieback was manganese nutrition (Mn): (i) the Mn content of the tree foliage was negatively affected by irrigation and below the deficiency values reported for pine species, and (ii) soil available Mn ($CaCl_2$ extraction) decreased by half in the topsoil layer.

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Manganese deficiency was probably the consequence of the increase in soil pH, which in turn reduced soil Mn availability. Tree dieback was not related to either to a macronutrient deficiency or to toxicity caused by a trace element.

1. Introduction

As population grows and the demand for food and fibre rises, the pressure on natural water resources increases. Recycling is one of the viable options to achieve sustainable management of water. Application of wastewater (hereafter refers both to "*treated wastewater*" and "*untreated wastewater*") in agriculture is of major importance, since nearly 70% of the water used throughout the world is used for agricultural irrigation (Kummu et al., 2016). The benefits of using recycled water for irrigation are diverse and include *(i)* alleviating the pressure on natural water resources, *(ii)* reducing the discharge of untreated wastewater into the environment, and *(iii)* supplying water-scarce regions (Chen et al., 2012). Treated wastewater is therefore a valuable alternative source of water that should be increasingly used. Before then, however, the real risks and benefits linked to its use for irrigation need to be better understood.

Wastewater originates from a combination of domestic, industrial and agricultural activities. It receives several treatments (sedimentation, filtration, chemical or biochemical oxidation) before being discharged into the receiving environment. Despite these treatments, wastewater usually contains high levels of nitrogen (N), phosphorus (P), potassium (K), and micronutrients thereby giving it a nutritional value. Several examples (e.g. Vazquez-Montiel et al. (1996)) show an increase in crop yield as well as in tree growth in forest systems (e.g. Houda et al. (2016)) when treated wastewater was used for irrigation (see Pedrero et al. (2010) for a review). The nutrient value of wastewater would be particularly advantageous where soils are naturally poor in macro- or micronutrients and when large exports of nutrients in the form of harvested biomass lead to nutrient deficiencies (Achat et al., 2015). In this context, the application of wastewater may increase plant production, as already observed with sewage sludge (Bramryd, 2001).

Land application systems are systems that treat and recycle wastewater through soil infiltration and groundwater recharge (Crites, 1984). They are based on the capacity of soil to store the nutrients contained in the wastewater. However, the nutrient retention capacity of soils is limited as is their capacity to protect groundwater from nutrient contamination. Usually, irrigation results in high nutrient removal because the rate of wastewater application is low and the vegetation uses part of the applied wastewater (Crites, 1984). If not properly managed, irrigation with wastewater may cause runoff of nutrients (particularly of N and P) from irrigated areas and eutrophication of surface water. Moreover, soils which receive treated wastewater may accumulate salts and trace elements at higher levels than soils which receive fresh water. In the case of salts, this may lead to increased salinity in the root zone and cause drought-like symptoms in plants (Saur et al., 1993), especially in regions where the evapotranspiration:precipitation ratio is high. In the case of trace elements, due to their sorption onto the soil solid matrix, wastewater application can lead to their accumulation in the topsoil layer with subsequent possible phytotoxic effects. Environmental concerns related to wastewater reuse for irrigation are mainly associated with the risk of an imbalanced supply of nutrients (and trace elements) caused by repeated applications of wastewater. It is thus of major interest to monitor the long-term effect of treated wastewater on the biogeochemistry of irrigated areas to avoid the degradation of natural resources (soil, groundwater and surface water).

In France, forests cover more than one quarter of the surface area of the country. These ecosystems are consequently often considered as possible receptacles for waste products. This is notably the case of the coastal fringe of the *Landes de Gascogne* region (1.4 Mha in south-western France). The area attracts many tourists in summer. The large population of tourists is partly responsible for the production of large quantities of wastewater, which it is impossible to discharge into surface waters or into the nearby ocean, mainly because of the presence of swimmers. The area is mainly composed of pine forests growing on soils which are naturally poor in macro- and micronutrients (Augusto et al., 2010; Saur, 1989). Because high rates of biomass and nutrient removal are expected in the near future to supply the region in fuelwood (Augusto et al., 2015; Mora et al., 2014), the nutritional value of wastewater could be of special interest in these oligotrophic forests. In this context, some stakeholders responsible for water management hope to solve the wastewater problem by applying it in local forests, and hope that these ecosystems have a long-term filtration capacity. On the other hand, the *Landes de Gascogne* soils are characterised by low pH, a sandy texture, low organic matter content and low cation exchange capacity (Augusto et al., 2010). This raises the question of whether such soils have sufficient retention capacity to filter wastewater nutrients (and trace elements) down to acceptable levels before they reach the groundwater, especially in the long term. Because applying wastewater in forests is currently forbidden in France, an experiment was initiated by a State service to test the practice. This study reports the results of this experiment, which focused on the filtering capacity of a dune forest which was sprinkler irrigated with wastewater produced by a treatment plant. This study used data collected during a 10-year period of monitoring the vegetation (trees and understory), soil, and water table to assess how irrigation with wastewater affects the forest ecosystem, and to identify possible functional causes of the observed effects of irrigation using wastewater. Based on *(i)* the limitation of tree growth by nutrients and water in the *Landes de Gascogne* region (Trichet et al., 2008), *(ii)* short-term experiments conducted on the application of waste products in this region to monitor tree growth and the leaching of elements (BenBrahim et al., 2003; Combes, 2000; Oller, 1974), and *(iii)* the inherent low capacity of these soils to retain nutrients after the application of fertiliser in croplands (De Wit et al., 2005; Juste et al., 1982; Vernier et al., 2003), we hypothesised that the repeated application of treated wastewater would improve tree growth, but at the expense of an undetermined rate of groundwater pollution. We further hypothesised that, because of specific element-soil interactions, several macronutrients (N, K, Ca) would easily migrate down to the water table whereas several trace elements (Cu, Ni, Pb) would be retained in the topsoil because this soil layer contains organic matter known to immobilize these elements (Benbrahim et al., 2006; Labrecque et al., 1998; Lazdina et al., 2007; Medalie et al., 1994).

2. Materials and methods

2.1. Study area

The coast of south-western France is characterised by long primary dune ridges located in the backshore area. These dunes originated from Aeolian deposits during the Holocene period (Penin, 1980). Most of the area is now a Maritime pine forest (*Pinus pinaster*), which was progressively installed by sowing during the 18th and 19th centuries to stabilise the dunes.

The study area (approx. 44°N 23′ 10″ – 01°W 12′ 10″) was a 50.1 ha polygon on a forested dune ridge. The climate is mild and oceanic. Mean