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Growth and nutrient uptake of perennial crops in a paludicultural approach in a drained Mediterranean peatland

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ABSTRACT

Combining peatland rewetting with biomass cropping (paludiculture) is one strategy to remove nutrient surpluses from soil/water and stimulate peat-forming vegetation. This approach was tested in the Massaciuccoli Lake Basin (Tuscany, Italy), a coastal floodplain artificially drained for agricultural purposes since 1930, where land reclamation and continuous cropping have contributed to considerable peat degradation and water eutrophication due to nutrient enrichment of surface waters. An experimental trial was established in spring 2012 with three perennial rhizomatous grasses (PRG) (*Phragmites australis*, *Miscanthus* × *giganteus*, *Arundo donax*) and two woody species managed as short-rotation coppice (SRC) (*Salix alba* "Dimitrios", *Populus* × *canadensis* "Oudenberg"), aimed to provide biomass for various bioenergy supply chains. A conventionally cultivated annual crop (maize) was the control. The aim of this study was to compare the sustainability of the proposed paludiculture systems to that of conventional annual crops on the basis of yield and nutrient-removal capability. This two-year field study evaluated yields, nutrient concentrations and uptake (N and P) of the crops. Over the two years, *A. donax* had the highest mean biomass yield (35 Mg ha^{-1}), N uptake (367 kg ha^{-1}), and P uptake (54 kg ha^{-1}). SRCs had the lowest nutrient uptake in both years. Among grasses, the highest N concentration was recorded in *A. donax* leaves in 2013 (N: 2.41%), while P concentration was greater in *S. alba* branches (P: 0.39%). The average aboveground biomass of maize was 17.5 Mg ha^{-1}, while the nutrient uptakes were equal to 194 and 27 kg ha^{-1} for N and P, respectively.

Thus, the performances of paludiculture systems were generally encouraging and could represent an important alternative for restoring and managing former drained peatlands in a suitable product chain.

1. Introduction

Peatlands are the most widespread wetland types in the world, representing 50–70% of global wetlands. They cover over four million square kilometer, equal to 3% of the land and freshwater surface of the planet (Joosten and Clarke, 2002), and represent not only a major stock of carbon (C) and nitrogen (N) but also a resource of high ecological, historical, recreational and/or agricultural values (Mitsch and Gosselink, 2000).

In previous centuries, many peatlands were artificially drained as a consequence of increasing land demand for agriculture and forestry (i.e., land-hunger) and the urgent need to improve sanitary conditions (i.e., malaria eradication) for the people living there (Holden et al., 2006). As a consequence, significant changes occurred in physical and chemical properties of peat (Litaor et al., 2008) such as (i) acceleration of organic-matter oxidation, with a consequent increase in greenhouse gases (GHG) emissions into the atmosphere of up to 25 t CO_2 equivalent ha^{-1} y^{-1} (Wichtmann and Wichmann, 2011); (ii) increase in NO_3^- concentrations in pore water due to higher oxygen availability and the consequent mineralization and nitrification of organic N (Tiemeyer et al., 2007) and (iii) mineralization of organic P compounds and increase of absorbed and Fe-bound P pools (Zak et al., 2004). The continual recurrence of these phenomena has negatively affected the land, for example, progressively lowering the soil level (subsidence), increasing nutrient loads delivered to receiving water bodies (eutrophication) and decreasing ecosystem biodiversity and functionality (loss of ecological stability), especially in land-reclamation districts (Schipper and McLeod, 2002; Foley et al., 2005; Tiemeyer et al., 2007; Wichtmann and Joosten, 2007; Verhoeven and Setter,

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2010). For these reasons, rewetting of drained peatlands has been identified since the mid-1990s as an important mitigation strategy to reverse this self-perpetuating process, which is definitely unsustainable (Erwin, 2009). Restoring saturated conditions reduces GHG emissions from the soil, especially CO_2 and NO_x (Joosten and Augustin, 2006). The use of biomass from plants growing on rewetted peatlands (paludiculture) was evaluated to avoid further CO_2 emissions by replacing raw fossil materials and fuels.

Paludiculture is defined as the agricultural use of wet and rewetted peatlands to produce biomass for bioenergy (e.g., direct combustion, biogas, biofuels) or other purposes (e.g., feed; fiber; raw materials for industrial biochemistry, pharmaceuticals and cosmetics), which slows subsidence and nutrient release from the peat soil (reduction of mineralization rate, plant uptake and harvest) and improves ecosystem services (e.g., habitat restoration, aquifer recharge, nutrient cycling) (Wichtmann and Tanneberger, 2011; Joosten et al., 2012; Abel et al., 2013; Günther et al., 2014).

In Mediterranean areas, especially in Italy, this approach is quite new because of a historical tradition that always considered the drainage of wetlands (land reclamation) a necessary condition for the development and well-being of human communities. Although peatlands cover less than 1% (about 300 km^2) of Italy's national territory, the vast majority was drained for agricultural purposes in the 1920s–1930s.

Our case study is located in a reclamation district on the coastal plain of west-central Italy and is characterized by large-scale, intensive agriculture and the presence of a vulnerable receiving water body, Lake Massaciuccoli. Since the 1930s, a complex network of artificial drains and pumping stations has been used to drain the superficial aquifer and excess rainfall, thus ensuring a water table depth suitable for cultivation (Ciccolini et al., 2013). The lake and surrounding marches are Wetlands of International Importance according to the Ramsar Convention since 2014, but their status is seriously harmed by severe eutrophication. Furthermore, the traditional agricultural use of the land-reclamation district is seriously compromised by increasing difficulties in maintaining the unsaturated zone for crop growth (Zuccarini et al., 2011; Pistocchi et al., 2012). For these reasons, it is necessary to identify suitable alternative management options for this area.

Paludiculture based on perennial species has been tested at the field scale as a possible solution and aims to simultaneously maintain water quality and agricultural use of the land. The perennial nature of these crops dramatically reduces agronomic input requirements (e.g., primary and secondary tillage, seeding, fertilization) compared to those of annual crops, making their cultivation possible in fields that are not easily accessible due to the presence of water-saturated soil.

Perennial crop productivity should be an important criterion for selecting species for paludiculture. High and steady biomass production, along with high nutrient concentrations, may increase nutrient recovery from the surrounding water, thus reducing eutrophication risk for the receiving water body. Furthermore, high yields may increase farmers' incomes and possibly ensure economic sustainability of the system (Tzanakakis et al., 2009). Increasing fixation of carbon dioxide in organic compounds decreases GHG emissions into the atmosphere and provides more matter to renovate the peat stock, which limits subsidence (Joosten et al., 2014).

The species selected for our paludiculture experiment, aiming for high biomass production, rapid development and crop hardiness (Bonari et al., 2004; Angelini et al., 2009; Rowe et al., 2009; Mirza et al., 2010), were perennial rhizomatous grasses (PRG) and short-rotation coppice (SRC) crops. The objective of this study was to evaluate the suitability of the selected crops to paludiculture in a drained Mediterranean peatland, on the basis of their aboveground biomass production and their nutrients (N and P) uptake. These results were compared with those related to the most cultivated crop in the area (maize), which is used as the control.

2. Materials and methods

2.1. Study site

The research was conducted over two years (2013–2014) as part of a larger phytotreatment system located in Vecchiano, about 10 km from Pisa, Italy (43°49′59.5″N; 10°19′50.7″E) in the Migliarino-San Rossore-Massaciuccoli Natural Park (http://www.parcosanrossore.it).

This 15 ha experimental area was used to compare the efficiency of three different systems in treating the eutrophic drainage water coming from a sub-watershed in the reclamation district. In the area, P has been recognized to be the primary limiting factor for eutrophication and the losses of this nutrient from cultivated fields (dissolved + particulate fractions) are estimated in 2–4 $kg\,ha^{-1}\,y^{-1}\,ha^{-1}$ (Pensabene et al., 1997; Bonari et al., 2013). The three systems have different types of water management (water level and path) and plant management (species, cultivation and harvesting) (Ciccolini et al., 2013). The tested systems were a constructed wetland system (CWS), a natural wetland system (NWS) and a paludiculture system (PCS) (Fig. 1). The last of these was based on growing different non-food crops and harvesting their biomass periodically to ensure nutrient removal from the fields. The system was not dammed and was crossed by a dense network of small channels (about 8 m apart) that supplied both drainage (in autumn and winter) and irrigation (in spring and summer) for the crops through lateral infiltration. The soils of the PCS (Table 1) were classified as Histosol according to the USDA system (Soil Survey Staff, 1975) and as Rheic Histosol according to the FAO system (IUSS, 2006). They are representative of the soils of the land-reclamation district, which are also defined as peat and peaty soils (Pellegrino et al., 2014). The main difference between the PCS and the surrounding areas concerns the water table level. The water table in the watershed is artificially lowered to allow the farmers to cultivate, with noticeable fluctuations during the year (from −0.10 to −0.60 m) depending also on cultivation practices. In the rewetted PCS, the water table depth is kept higher because of the continuous supply of water to be treated and thanks to the weirs, which are not moved except for management needs (e.g., harvest or maintenance of drainage ditches). Then, in the experimental fields, the water table depth is only dependent on the meteorological conditions (e.g., rainfalls or dry periods), ranging from 0.00 to −0.05 m during the winter and from −0.10 to −0.25 m during the summer. The climate is Mediterranean (Csa) according to the Köppen–Geiger climate classification map (Kottek et al., 2006). Summers are dry and

Table 1
Physical and chemical characteristics of paludiculture system soils (0–30 cm depth).

Parameter	Unit	Value
pH		5.0
EC	($dS\,m^{-1}$)	1.46
Sand (USDA)	(%)	56
Silt (USDA)	(%)	25
Clay (USDA)	(%)	19
Bulk density	($g\,cm^{-3}$)	1.44
SOM (Walkey-Black)	(%)	30.1
N_{tot} (Kjeldahl)	($g\,kg^{-1}$)	13.2
P_{avail} (Olsen)	($mg\,kg^{-1}$)	79
K_{exch}[a]	($g\,kg^{-1}$)	516
CEC	(meq 100 g^{-1})	75
Fe[b]	($g\,kg^{-1}$)	12.2
Al[b]	($g\,kg^{-1}$)	5.5

[a] Atomic absorption.
[b] Extractable with ammonium oxalate.