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Research article

Good for sewage treatment and good for agriculture: Algal based compost and biochar

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ABSTRACT

In this study we test a novel approach to closing the anthropogenic nutrient cycle, by using the freshwater macroalga, *Oedogonium intermedium*, to recover dissolved nitrogen (N) and phosphorous (P) from municipal wastewater. We then convert this cultivated algae into two types of soil ameliorant; compost and biochar. To produce compost, algae was combined with sugarcane bagasse and left to mature for 10 weeks, and to produce biochar, algae was processed through slow pyrolysis at 450 °C. The mature compost had a total N and P content of 2.5% and 0.6%, which was 2- to 4-times lower than the algal biochar, which had a total N and P content of 5.5% and 2.5% respectively. Composting stabilized the N and P recovered from wastewater, with 80% of the initial N and >99% of the initial P retained in the mature compost. In contrast, only 29% of the initial N and 62% of the initial P was retained in the biochar. When the mature compost was added to a low fertility soil it significantly increased the production of sweet corn (*Zea mays*). Treatments receiving 50 and 100% compost produced 4–9 times more corn biomass than when synthetic fertilizer alone was added to the low fertility soil. When biochar was applied in conjunction with compost there was an additional 15% increase in corn productivity, most likely due to the ability of the biochar to bind labile N and P and prevent its loss from the soil. This study demonstrates a unique model for recovering N and P from municipal wastewater and recycling these nutrients into the agricultural industry. This could be an ideal model for regional areas where agriculture and water treatment facilities are co-located and could ultimately reduce the reliance of agriculture on finite mineral sources of P.

1. Introduction

The world's population is predicted to increase from 7.4 billion in 2015 to 9.7 billion by 2050 (UN, 2015). Global food production will need to increase by 60% across the same time frame to keep pace with the predicted increase in demand for food (Childers et al., 2011; Alexandratos and Bruinsma, 2012; Lal, 2006). This will require up to 1 billion hectares of new arable land dedicated to food production (Tilman et al., 2011), yet at the same time the productivity of existing arable land will decline in the coming decades due to land degradation and the effects of climate change (Lal, 2006). Currently agricultural crop production is heavily reliant on synthetic fertilizers to deliver sufficient nitrogen (N) and phosphorous (P) to maintain productivity (Tilman et al., 2011). However, these fertilisers are often used inefficiently and there is a clear need to develop sustainable amendments that can both improve the productivity of marginal land and increase the efficiency of fertilizer applications (Cassman et al., 2002; Raun and Johnson, 1999). Moreover, the P component of synthetic fertilizers is derived from finite mineral resources (rock phosphate) that may become limiting in the near future (Childers et al., 2011; Cordell et al., 2009). Approximately 90% of all mined rock phosphate is used in food production, with 20% of this P ultimately consumed and then excreted as human waste (Childers et al., 2011). Closing this “anthropogenic P loop” by recovering P from human waste and improving the efficiency of P use in agriculture would have significant ramifications for soil health, farm gate productivity, and the sustainability of agriculture (Childers et al., 2011). Arguably, the most direct means of closing the P loop is to recover P from municipal wastewater.

Conventional sewage treatment processes rely on flocculants to bind P and create an insoluble metal-phosphate complex that can

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be removed from wastewater via precipitation (Morse et al., 1998). There is limited potential for P recovery and re-use as the strength of these complexes make P largely inaccessible for agricultural applications and the metals used as flocculants pose risks to soil macrofauna and plants (Morse et al., 1998; Roy et al., 2011). An alternative approach to recover P that is suitable for re-use is to exploit the ability of algae to extract N and P from wastewater (Craggs et al., 2012; Cole et al., 2016a; Neveux et al., 2016). For example, the freshwater macroalga *Oedogonium intermedium* (hereafter *Oedogonium*) can be cultivated at wastewater treatment plants to recover and concentrate N and P up to 5.4% and 1.1% in the biomass respectively (Cole et al., 2016a; Neveux et al., 2016). These concentrations, coupled with the high productivity of *O. intermedium* (Cole et al., 2015), make the integrated production of this macroalga a scalable mechanism to recover N and P from municipal wastewater (Cole et al., 2016a; Neveux et al., 2016).

There are several methods to transform the cultured algal biomass, and the recovered N and P, into a stable form that is suitable for recycling into agriculture. The most familiar approach is composting, or the aerobic decomposition of biomass through microbial activity. Composting results in a humus-rich material that is an excellent medium for plant growth (Bernal et al., 2009). Any biomass can be successfully composted with the correct balance of carbon (C), nitrogen (N) and moisture (Bernal et al., 2009). Macroalgae, cultured in high nutrient wastewater, is an ideal source of N, while agricultural crop residues can be used as the source of C for composting (Cole et al., 2016b). Phosphorous and other mineral elements that are present in the feedstock biomass do not influence the composting process itself and are to a large extent retained within the mature compost, making compost a relatively efficient technique to stabilise organic phosphorous (Tiquia et al., 2002; Cole et al., 2016b). Mature compost can then be applied to soils to improve water holding capacity (WHC), increase soil organic matter (SOM) and carbon (SOC), and provide a substrate for microbes (Bullock and Ristaino, 2002), ultimately increasing the growth rates of plants and their resistance to pests and diseases (Larkin, 2015; Akhter et al., 2016).

A second approach for recycling waste N and P using algae is to transform the biomass into biochar via slow pyrolysis. This process involves combusting biomass in an oxygen free atmosphere to create a recalcitrant charcoal known as biochar. Biochar is a C-rich material that can increase the SOC content of soils (Agegnehu et al., 2015). Biochar produced from macroalgae, as opposed to woody material, has a high N, P and K content and may act as a minor source of essential nutrients in soils (Bird et al., 2011; Roberts et al., 2015b). However, the main benefit of biochar is that it has a high cation exchange capacity (CEC) and can bind labile N, P, and trace elements such as Fe, K, Zn and Mo, from pore water (Roberts et al., 2015b). Soils amended with biochar lose less nutrients through leaching and can therefore support more efficient use of these nutrients by plants (Chan et al., 2008; Roberts et al., 2015a, 2015b). While compost can improve the health and fertility of soil, these benefits may be short lived, especially in the humid tropics which have high turnover rates of organic matter (Ghosh et al., 2015). One opportunity is to exploit the ability of biochar to bind labile nutrients is to use it as a stabilising element to retain nutrients within the soil structure. In this way, applying small quantities of biochar in tandem with compost may enhance the benefits of the nutrients in compost and prolong the timeframe over which these benefits occur.

In this study we use biomass from the filamentous macroalga *Oedogonium* that was cultivated in municipal wastewater to produce compost and biochar as soil ameliorants. We then test the effects of both types of ameliorants in isolation and together on the physical characteristics and fertility of a sandy loam in a pot trial experiment using sweet corn (*Zea mays*). Specifically, we quantify the physico-chemical properties of compost and biochar produced from freshwater macroalgae and then evaluate the potential synergistic effects of compost and biochar on the growth of corn in a low fertility soil. Ultimately this study aims to develop a model system where nutrients can be recovered from municipal wastewater treatment plants and effectively converted into a form that is beneficial to the production of agricultural crops.

2. Methods

2.1. Production of algal biomass

Oedogonium was cultivated in treated municipal wastewater at the Cleveland Bay Purification Plant (CBPP) in Townsville, north Queensland, Australia (19°17′20.8″S; 146°51′20.2″E). CBPP has a capacity of 29 ML and the treated water is discharged into the ocean. While this discharge water complies with regulations, it does contain residual N and P, with mean concentrations of approximately 4 and 0.8 mg L^{-1}, respectively (Cole et al., 2016a). A portion of this discharge water was intercepted prior to discharge and diverted into three large parabolic troughs (25 m long x 2 m surface area 50 m^2; ~27 000L capacity per trough) located at the facility. The biomass was cultured continuously over a 12 month period, providing a tertiary treatment service that reduced the concentrations of total N and P by 36% and 68% in the treated water, respectively (Cole et al., 2016a). In total 491 kg DW of *Oedogonium* was cultivated over a 12 month period, with this biomass recovering 24.4 kg of N and 4.8 kg of P from the water. This algae was harvested weekly, air-dried and then used as the feedstock to produce compost and biochar. Further details regarding the cultivation of biomass and the characteristics of the wastewater can be found in Cole et al. (2016a).

2.2. Production and characterisation of compost

To make the compost *Oedogonium* biomass was mixed with sugarcane bagasse, a fibrous by-product of the sugar extraction process, sourced from the Home Hill sugar processing facility (19°39′40″S; 147°24′50″S) in north Queensland, Australia. Representative samples of the algae and bagasse were collected prior to the compost trials, dried at 60 °C and analysed for N and C using an elemental analyser (OEA Labs, UK). Trace elements (Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mn, Mg, Mo, Na, Ni, P, Pb, S, Se, V, Zn) where analysed with Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) by A2 Analises (Portugal). The pH and electrical conductivity (EC) of the algae and bagasse were measured using a HACH HQ40d portable probe in a 1:5 (w/volume) solution with deionized water. The ash content of the algae and bagasse was quantified in duplicate through the combustion of 500 mg of each sample at 550 °C in a muffle furnace until constant weight was reached. The proportion of OM in the subsamples was calculated as the fraction that is lost on ignition.

Three replicate composts were made by mixing the *Oedogonium* with bagasse to achieve an initial C to N ratio (C:N) of 20:1. As the *Oedogonium* was taken from multiple harvests and was pre-dried, we chose to mill the biomass (to < 5 mm particle size) before mixing it with the bagasse. Milling the biomass increases the surface area available for microbial activity and reduces the time taken to produce mature compost (Bernal et al., 2009). The proportion of *Oedogonium* in the composts was 31% on a dry weight (DW) basis. The algae and bagasse were mixed together with water until a moisture content of 70% was reached. The mixtures were then placed into three 400 L compost bins with a passive aeration pipe in the centre and a 15 L leachate collection tray in the bottom. The