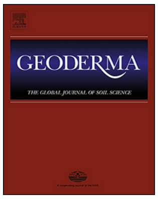
Geoderma 334 (2019) 113–123

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma



Circular economy fertilization: Testing micro and macro algal species as soil improvers and nutrient sources for crop production in greenhouse and field conditions

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ARTICLE INFO

Handling Editor: Alex B. McBratney

Keywords:
Circular economy
Agricultural soil
Algae
Soil nutrient status
Plant nutrition
Yield

ABSTRACT

Nutrient losses from agricultural land to freshwater and marine environments contribute to eutrophication and often to the growth of algal blooms. However, the potential benefits of recycling this algal biomass back to agricultural land for soil quality and crop nutrition in a "circular-economy" has received little attention. We tested the effects of algal additions to arable soil in greenhouse-grown garden peas, and field plots of spring wheat, on plant growth and nutrition and physical and chemical properties of the soil. Representatives of five algal species, which contrasted in elemental composition, were applied at 0.2, 2 and 4 $g\,kg^{-1}$ in the greenhouse and at 24 $g\,m^2$ in the field. These included the cyanobacteria *Arthrospira platensis* (*Spirulina*), the unicellular green algae *Chlorella* sp., the red seaweed *Palmaria palmata*, and the brown seaweeds *Laminaria digitata* and *Ascophyllum nodosum*. In the greenhouse at the highest application rates (4 $g\,kg^{-1}$), *Chlorella* sp., and *Spirulina* increased soil total nitrogen and available phosphorus, and *Spirulina* also increased soil nitrate concentrations. *P. palmata* and *L. digitata* significantly increased soil inorganic (NH_4^+ and NO_3^-) concentrations under all three application rates. *Chlorella* sp. significantly increased soil total P, N and C, available P, NH_4^+-N, and pea yield. Soil water-stable aggregates were unchanged by the algal additions in both the greenhouse and field study. In the field, 4 species (*Chlorella* sp. *Spirulina*, *P. palmata* and *L. digitata*) increased soil inorganic nitrogen concentrations, confirming their potential to recycle mineralizable nitrogen to agricultural soils, but no significant effects were found on wheat yields under the application rates tested.

1. Introduction

Soil quality plays a critical role in crop productivity and both soil and crop resilience to drought and heavy rainfall, but there is increasing concern that intensive arable farming has degraded soil water and nutrient holding-capacity as a result of organic matter loss (Department for Environment, Food and Rural Affairs, 2009; Graves et al., 2015). Soil quality constraints are implicated in the yield plateau seen in wheat and oilseed rape, the most important field-grown crops in the UK (Knight et al., 2012). Soil degradation is estimated to cost the UK between £0.9 billion and £1.2 billion annually, in onsite and offsite non-market 'external' costs (Graves et al., 2015). This value is mainly attributed to the loss of soil organic carbon (47%), compaction (39%) and erosion (12%) (Graves et al., 2015). These changes are reflected in soil physical and chemical attributes such as soil aggregate stability and nutrient status. Water-stable aggregates are key indicators of soil quality since they deliver good soil structure and function by: (i) physically protecting soil organic matter against rapid decomposition, (ii) increasing soil water-holding capacity, (iii) providing pore space for root growth and water infiltration, and (iv) enhance resistance to erosion, and ultimately reducing surface crusting and runoff, which leads to aquatic pollution (Paul et al., 2013).

Intensification of arable production with continuous annual cropping using high mineral nutrient inputs has depleted soil organic matter (Mulvaney et al., 2009), which is responsible for storing nutrients and maintaining soil structure, ultimately leading to nutrient losses to water bodies. This has been compounded by nutrient-rich topsoil being eroded from continuously cropped arable land at an average rate of 9.5 tonnes per hectare across the EU 28 countries (Eurostat, 2017). This has caused preferential loss of the finer particles, such as the nutrient-retaining organic matter and clays, exacerbating the risk of nutrient export from land to water bodies and eutrophication (Department for

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https://doi.org/10.1016/j.geoderma.2018.07.049
Received 28 March 2018; Received in revised form 13 July 2018; Accepted 28 July 2018

Environment, Food and Rural Affairs, 2014). Despite the implementation of the Water Framework Directive (WFD) and the active management of nitrate vulnerable zones, there has been a decrease in the overall number of water bodies in the UK being awarded high or good surface water status between 2011 and 2016 (Joint Nature Conservation Committee, 2017). In England alone, 28% of failures to meet the WFD standards are directly attributed to diffuse water pollution from agriculture and rural land use (Department for Environment, Food and Rural Affairs, 2014). The urgency of this situation has grown with increasing awareness of the fossil-fuel energy costs in the production and use of chemical fertilisers. Each year, 100 million tonnes of fertiliser is used globally, contributing to greenhouse gas emissions. A recent study conducted by the Grantham Centre for Sustainable Futures at The University of Sheffield showed that more than half the environmental impact of producing a loaf of bread is attributed to the use of ammonium nitrate fertiliser during the wheat cultivation process, which accounts for 43% of the sample loaf's greenhouse gas emissions (Goucher et al., 2017).

In order to reduce dependency on inorganic fertiliser use, organic fertilisers such as animal manure, biosolids from human wastes, anaerobic digestate, biochar and crop residues are used as alternatives (Farrell et al., 2014; Rady, 2011; Walsh et al., 2012). Of these, the manures, biosolids and digestates are potentially the most important nutrient sources, but these complex materials have caused pollution/ecological risks associated with veterinary antibiotics, use of growth promoting heavy metals such as (Cu and Zn) in pigfeed (Ciesinksi et al., 2018) and other contaminants such as arsenic (Heimann et al., 2015; Wuang et al., 2016; Zhang et al., 2015). Alternative sources of organic fertilisers that can provide plants with an optimal mix of macro and micronutrients as well as benefit the structural characteristics of soil would be hugely beneficial for the agricultural industry. The European Commission disclosed a legislative proposal in March 2016 on organic and waste-based fertilisers as part of their Circular Economy Action Plan (European Commission, 2016). The aim is to promote resource efficiency with regards to the fertiliser sector in order to create new business opportunities for farmers, as well as help them become more competitive in recycling organic nutrients compared to purchasing inorganic fertilisers (European Economic and Social Committee, 2016). It seeks to reduce waste, energy consumption and environmental damage (Messenger, 2016).

Algae are the main primary producers in most water bodies, and their growth is naturally stimulated by organic effluents and mineral nutrients (Sen et al., 2013). As incidences of diffuse pollution increase due to anthropogenic activity, the size and frequency of algal blooms is on the increase. Furthermore, climate change has been predicted to exacerbate the problem. One potential solution to limit the detrimental impacts of nutrient runoff from agriculture is to divert nutrients to water bodies where it is possible to exploit the natural ability of microalgae to grow much quicker than land plants (Wuang et al., 2016), and actively cultivate and harvest the biomass. The biomass can be used as a sustainable source of organic fertiliser, returning both nutrients and carbon to soil, potentially improving soil quality, crop growth and nutrition. Moreover, research in large-scale algal biomass production has increased in recent years, for diverse applications including biofuels, animal feed (Yaakob et al., 2014) and as nutrient scavengers in wastewater treatment processes (Zhu et al., 2013). This has also created opportunities for the development of by-products such as algal-based fertiliser that could contribute to a more sustainable circular-economy for nutrients in arable farming systems.

Chlorella sp. and *Spirulina* (*Arthrospira platensis* and *Arthrospira maxima*), which are commonly used microalgal species in the treatment of wastewater (Aslan & Kapdan, 2006), are reported to have high nutrient (N and P) removal capabilities from effluents, making them suitable candidates as soil conditioners. *Spirulina platensis* biomass has been shown to improve soil macronutrients (nitrogen, phosphorus and potassium) (Aly & Esawy, 2008), act as a biofortification agent, enhance plant protein content (Kalpana et al., 2014) and increase crop growth, i.e. 5 g *Spirulina* in 500 g^{-1} soil increased the height of Bayam red (red spinach) by 58.3% as well as fresh and dry weights by 110.1% and 155.8% respectively, when compared to the control group (Wuang et al., 2016). Dried algal biomass grown on anaerobic digestate from dairy manure increased plant available N and P in soils within 21 days and thereby improved cucumber and corn seedling growth (Mulbry et al., 2005). Additions of 2–3 g dried *Chlorella vulgaris* kg^{-1} soil significantly increased ($p < 0.0001$) fresh and dry weight of lettuce seedlings (Faheed & Abd-El Fattah, 2008). Extracts or composted marine algal seaweed species have been researched as amendments in crop production systems due to their biostimulatory potential on crop growth and their benefits as sources of organic matter and soil nutrients (Khan et al., 2009). Brown seaweeds (Phaeophyceae) have also been tested, with *Ascophyllum nodosum*, the most studied of the phaeophyceae, shown to improve growth and drought stress tolerance when used as a soil drench or foliar spray in container-grown citrus trees (Spann & Little, 2011). Other positive responses include early seed germination and establishment, improved crop performance and yield, as well as elevated resistance to biotic and abiotic stress (Khan et al., 2009). Brown seaweeds contain high amounts of polyuronides such as alginates and fucoidans, which are known for their gelling and chelating abilities and their ability to combine with metallic ions in the soil. They form high-molecular-weight complexes that absorb moisture and result in better soil aeration and moisture retention, and in turn boost soil microbial activity (Khan et al., 2009). The application of another brown seaweed, *Laminaria digitata*, has been shown to also improve soil physical properties including total pore volume and aggregate stability of a sandy soil (Haslam & Hopkins, 1996).

Algae also represent a source of trace elements, which they acquire via biosorption and bioaccumulation (Michalak et al., 2017) and can therefore contribute to crop micronutrient uptake. Wheat, the second most important cereal crop globally, makes up about 28% of human dietary energy (Velu et al., 2016). It is the most important cereal crop in the UK where it is grown on 1.7 million hectares, yielding 15.2 million tonnes last year (Department for Environment, Food and Rural Affairs, 2017). The ability of algal-fertilisers to increase the often suboptimal concentration in wheat grains of zinc, iron and selenium (Broadley et al., 2006; Stroud et al., 2010) which are essential for human nutrition, needs to be investigated, as this could provide a cost effective, sustainable solution to micronutrient deficiencies (Velu et al., 2016).

There is increasing evidence that the deployment of algae biomass could act as a source of organic fertiliser. There are approximately 280,000 recognised algae species (Chojnacka & Kim, 2015), but the relative merits of different species and functional groups on soil quality and crop improvements, and their key attributes that control their effectiveness remain unclear. Algae vary greatly in their mineral and organic composition and consequently their impact on soil nutrients and aggregate stability are hypothesized to be strongly dependant on the initial concentration of nutrients in their biomass (Flavel & Murphy, 2006).

This study aims to investigate the use of chemically contrasting types (difference in elemental composition) of algal species biomass on soil aggregate stability, nutrients and ultimately growth and yields of crops. In addition, we explore the effects of different types of algae as soil amendments for improving micronutrient (e.g. zinc, iron and selenium) concentrations in wheat. To address these aims, bioassay greenhouse and field experiments were conducted with garden peas and wheat respectively. The five algal species chosen also represented different phylogenetic groups: the cyanobacterium *Spirulina*, the freshwater green alga *Chlorella* sp., a Chlorophyte, and three marine species namely *P. palmata* from the class Rhodophyta and *L. digitata* and *A. nodosum* both representing the class Phaeophyta.