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Milled cereal straw accelerates earthworm (*Lumbricus terrestris*) growth more than selected organic amendments

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ABSTRACT

Earthworms benefit agriculture by providing several ecosystem services. Therefore, strategies to increase earthworm abundance and activity in agricultural soils should be identified, and encouraged. *Lumbricus terrestris* earthworms primarily feed on organic inputs to soils but it is not known which organic amendments are the most effective for increasing earthworm populations. We conducted earthworm surveys in the field and carried out experiments in single-earthworm microcosms to determine the optimum food source for increasing earthworm biomass using a selection of crop residues and organic wastes available to agriculture. We found that although farmyard manure increased earthworm populations more than cereal straw in the field, straw increased earthworm biomass more than manures when milled and applied to microcosms. Earthworm growth rates were positively correlated with the calorific value of the amendment and straw had a much higher calorific value than farmyard manure, greenwaste compost, or anaerobic digestate. Reducing the particle size of straw by milling to <3 mm made the energy in the straw more accessible to earthworms. The benefits and barriers to applying milled straw to arable soils in the field are discussed.

1. Introduction

Earthworms are the most abundant animal, by biomass, in most soils (Lavelle and Spain, 2001) and are responsible for providing numerous ecosystem services and functions (Blouin et al., 2013) that benefit crop growth (Bertrand et al., 2015). Earthworms increase the rate of water infiltration (Bouché and Al-Addan, 1997), the availability of nutrients (Devliegher and Verstraete, 1996), and can increase crop yield by 25% (van Groenigen et al., 2014). Many agricultural practices such as tillage (Chan, 2001), pesticide application (Pelosi et al., 2014), and the removal of crop residues (Karlen et al., 1994) decrease the biomass and abundance of earthworm populations. Conversely, the addition of organic amendments to soils increases earthworm populations in arable soils (Edwards and Lofty, 1982), even when tillage operations and pesticide applications are maintained (Blanchet et al., 2016; Whalen et al., 1998).

Earthworm population dynamics can be explained by modelling the energy budgets of individuals within a population, and the interactions between the individuals (Jager et al., 2006; Johnston et al., 2014a; Johnston et al., 2014b). The models describe how individuals acquire and utilize energy, based on a set of simple rules for metabolic organisation, treating individual earthworms as a system with a closed mass and energy balance. Earthworms must reach a minimum mass to mature sexually and be able to reproduce (Lofs-Holmin, 1983). The quantity of food supplied (assuming all else is equal) also influences its reproduction rate because it converts food into offspring (Johnston et al., 2014b). It is possible to reduce the time taken for earthworms to reach maturity and intensively rear earthworm communities in laboratory cultures by optimising population density, temperature and moisture (Butt et al., 1992; Lowe and Butt, 2007; Lowe and Butt, 2005). However, these parameters cannot be easily manipulated in field populations.

The quality of food fed to laboratory reared earthworms affects earthworm biomass, time taken to reach sexual maturity and

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cocoon production (Butt, 2011). There is also considerable evidence that the abundance and biomass of earthworms in arable fields can be increased by the application of organic amendments such as straw (Kennedy et al., 2013), poplar bark (Pérès et al., 1998) and cattle slurry (Pommeresche and Løes, 2009). Reducing the particle size of organic amendments to < 2 mm increases the growth rate of laboratory-reared earthworms (Boström and Lofs-Holmin, 1986; Lowe and Butt, 2003). However, growth rate can differ to a large extent depending on the type of organic amendment applied. For example, livestock manures increase earthworm populations more than composts, reportedly because the organic carbon in the composts is more humified and stable due to microbial degradation (Leroy et al., 2008). However, despite crop residues (e.g. cereal straw) being less humified and less degraded by microorganisms at the time they are incorporated into the soil, they do not seem to increase earthworm biomass to the same extent as livestock manures (Blanchet et al., 2016).

In the UK, and many other nations, the availability of animal manures to cereal growers for land application is limited because of the geographical distance between livestock and arable farms, as evidenced by lower use of farmyard manure in the Eastern region (13% of crop and grass area), compared to the South West region (41% of crop and grass area) (DEFRA, 2016). Therefore, we investigated ways of increasing earthworm populations using cereal straw produced on most arable farms and contemporary soil amendments that are becoming increasingly available in arable regions (compost and anaerobic digestate). We hypothesised that earthworm biomass could be increased in soils by manipulating the type(s) of organic amendment(s) applied and their particle size.

2. Materials and methods

2.1. Field surveys

Earthworm surveys were carried out on two long term field experiments at Rothamsted Experimental Farm near Harpenden, UK (51.813N, 0.381 E) during spring 2014. All 16 plots of the Long Term Straw Incorporation Experiment, described by Powlson et al. (2011) were surveyed. The experiment has grown winter wheat continuously and had wheat straw incorporated annually for 28 years at a rate of none, once, twice, and four times the yield of straw the previous year (approximately 0, 5, 10 and 20 t ha^{-1}) in a complete randomised block design (Table 1). A 2 m × 3 m area was designated specifically for sampling on the southern end of each plot. Two earthworm surveys were conducted in each plot (as described below), resulting in 32 surveys in total.

Selected plots on the Broadbalk experiment, described by Blair et al. (2006), that have grown winter wheat continuously for 171 years (apart from occasional fallow years) were also surveyed but, due to the age of the experiment, treatments are not replicated. Surveys were conducted on four plots that have either (i) received 35 t ha^{-1} of farmyard manure annually for 171 years, (ii) received wheat straw for the last 28 years by incorporating the straw of the previous crop harvested from the same plot (approximately 5 t ha^{-1}), (iii) received both farmyard manure and wheat straw annually, as described above, or (iv) received no manure or straw applications for at least 171 years. All plots received 144 kg N ha^{-1} since 1852. A 1 m × 14 m area was designated specifically for sampling along the northern edge of each plot and this area was divided into four equal sub-plots that are considered here statistically as true replicates (Table 1). In each sub-plot two earthworm surveys were conducted, resulting in 32 surveys in total.

Earthworm surveys were conducted by excavating a 20 × 20 × 20 cm cube of soil, bringing it back to the on-site laboratory and sorting it to find all the earthworms and identify them following (Sherlock, 2012). Deep burrowing (anecic) earthworms were extracted by pouring a 5 L aqueous solution containing 6 g l^{-1} of Colman's mustard flour, following (Bartlett et al., 2008; Murchie and Gordon, 2013) into the excavated hole and waiting up to 1 h to collect any emerging earthworms. All earthworms were washed by submerging them in water, blotted dry, identified to the species level and then its mass determined. All adults and some juveniles were identified but if the species of a juvenile earthworm was unclear then it was classified as 'unidentified'.

2.2. Microcosm experiments

2.2.1. Materials

A silty clay loam soil of the Batcombe Series (Avery and Catt, 1995), a Chromic Luvisol according to FAO classification, was collected from Fosters field of Rothamsted Experimental Farm. Fosters field has been in continuous arable production for more than 200 years. and has a soil organic carbon content of 14.3 g kg^{-1} (Johnston et al., 2009). The soil was air dried and sieved to <2 mm.

Barley and wheat straw was also sourced from Rothamsted Experimental Farm. Farmyard manure was obtained from a farm

Table 1
An outline of the individual experiments conducted in this investigation.

Experiment	Field/ Laboratory	No. of treatments	Factors	No. of replicates	No. of units
Long Term Straw Incorporation Experiment	Field	4	Straw rate 0, 5, 10 and 20 t ha^{-1}	4	16
Broadbalk	Field	4	Organic matter type Farmyard manure, straw, mixture, nil	4 [a]	16
Microcosm experiment 1	Laboratory	65	Organic matter type Straw, farmyard manure, anaerobic digestate, compost Organic matter rate 0, 2, 4, 6 and 8 g C kg^{-1} soil Straw-manure mixtures	4	260
Microcosm experiment 2	Laboratory	11	Straw type Wheat straw, barley straw Straw rate 0, 2, 4, 6, 8 and 10 g kg^{-1} $month^{-1}$	4	44
Microcosm experiment 3	Laboratory	17	Straw particle size < 1 mm, <3 mm, 1 cm and chopped Straw rate 0, 2, 4, 6 and 8 g kg^{-1} $month^{-1}$	4	68

[a] Subplots are considered here as true replicates.