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Influence of earthworm abundance and diversity on soil structure and the implications for soil services throughout the season

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ABSTRACT

Earthworms help maintain and enhance the physical condition and function of soils. Their contribution to soil services, such as the flow of water, nutrients and gases, is influenced by earthworm abundance and diversity. In this study mesocosms with either low (dominated by epigeic *Lumbricus rubellus*) or high earthworm abundance and diversity (*L. rubellus*, *Aporrectodea caliginosa* and *Aporrectodea longa*) were established to explore the relationship with plant production, soil porosity and soil moisture over 444 days. Mesocosms with an abundant and diverse earthworm community had 5% more micro-pores and 70% more macropores. Volumetric soil moisture contents were consistently lower in the mesocosms with an abundant and diverse earthworm community and above-ground accumulation of plant biomass was 35–70% higher over the last 5 months of the study. There was a strong positive relationship between earthworm abundance and diversity, drainage and plant growth and negative relationship with soil moisture. The influence of earthworms on pasture growth was greatest during winter and spring, while their effect on drainage volume was more pronounced during the drier period. This work provides baseline information demonstrating how to relate earthworm abundance and diversity to soil services, and highlights the need to consider their changing influence throughout the season.

1. Introduction

Intensive agricultural practices worldwide have resulted in the degradation of many soils, with some soils showing decreases in soil organic matter and loss of soil structure (Bellamy et al., 2005; Greenwood and McKenzie, 2001; Houlbrooke et al., 2011; Schipper et al., 2010). The integrity of the soil's physical structure is vulnerable to the loadings of both livestock and machinery under intensifying agricultural systems, and it is soils with limited structural strength which are particularly vulnerable (Hewitt and Shepherd, 1997; Houlbrooke et al., 2011). Soil structure, pore size distribution and the connectivity of the pore network are key properties for many soil functions. Changes in the pore network can adversely affect many soil-based ecosystem services which impact agricultural production (Blouin et al., 2013; Dominati et al., 2010), including the flow of water, nutrients and gases in the soil; and their availability to plants and microorganisms.

Earthworms (Family Lumbricidae) are important ecosystem engineers (Jones et al., 1994), building soil aggregates and associated micropores (Zangerlé et al., 2011). Simultaneously, their burrowing creates macropores, with their burrows typically exceeding 2.5 mm diameter (Francis et al., 2001; Springett, 1983). By physically modifying the soil, earthworms benefit soil structure and reduce the impact of detrimental agricultural practices (Greenwood and McKenzie, 2001). Ultimately, earthworms stimulate water infiltration rates, improve plant-available moisture by increasing field capacity (Stockdill and Cossens, 1966) and benefit pasture production (Baker et al., 1999; Stockdill, 1982; van Groenigen et al., 2014).

The degree to which earthworms modify soil structure is influenced by both their functional role within the soil (Bastardie et al., 2003) as well as their abundance (Capowiez et al., 2014). Among the functional groups endogeic earthworms burrow extensively throughout the top-soil, but have few burrows opening to the soil surface, anecic earthworms have burrows which open at the soil surface and go deeper, while epigeic earthworms form few permanent burrows (Paoletti et al., 1991). The influence of earthworms on soil structure has been well studied (Bastardie et al., 2003; Capowiez et al., 2014; Francis et al., 2001; Paoletti et al., 1991; Springett, 1983). However, how earthworms impact soil structure as their abundance and diversity increases remains poorly understood, in particular in relation to how this might alter their contribution to soil services, and whether their contribution to these soil services change throughout the year.

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There have been few attempts to recommend desired abundances (Freund et al., 2011; Schon et al., 2012b) even though earthworms are recognised as useful indicators of soil health (Breure et al., 2004; Doran and Zeiss, 2000; Römbke et al., 2005). The objective of this study was to determine the impact of a high earthworm abundance and diversity (*L. rubellus, Aporrectodea caliginosa* and *Aporrectodea longa)* in comparison to low earthworm abundance and diversity (dominated by epigeic *Lumbricus rubellus*) and the relationship with soil pore size distribution, soil moisture, drainage volume and plant growth. We examine these relationships, how this changes throughout the year and the implications of this for soil services.

2. Methods

2.1. Experimental design

The mesocosm experiment was established on a flat grassland site in Palmerston North, New Zealand, using 20 L plastic buckets (300 mm diameter, 400 mm deep) filled with sieved soil to a depth of 350 mm with drainage holes cut in the base. The experimental results reported here were part of a larger mesocosm study of earthworm functional group effects on soil properties which ran from June 2011 to August 2012, a total period of 444 days. For further details and results see Schon et al. (2014b). The soil used was a Maramarua silt loam (Ultic, New Zealand Soil Classification, (Hewitt, 2010)), which had been under a perennial ryegrass (*Lolium perenne* L.) dominant pasture for 40+ years. The top 200 mm of soil (A horizon) was excavated from a site in the Waikato region and used to fill the mesocosms (16.4 kg dry soil) after being sieved (5 mm) and hand-sorted to remove any earthworms and cocoons.

The potential for earthworm preferentially burrowing down the side of the buckets was minimised by scouring the inside wall of the buckets. Earthworm escape below the mesocosms was prevented using a 1 mm mesh across the base of the buckets. Each bucket was placed inside another bucket of the same size to create a 100 mm deep chamber below the soil column where drainage accumulated. The outer bucket had a drainage hole with an attached hose and tap to allow leachate collection. The mesocosms were placed outdoors where total rainfall was 1460 mm and the average air temperature was 12.8 °C during the study period (Schon et al., 2014b). The mesocosms were embedded into the ground to reduce temperature fluctuations. They were spaced approximately 0.5 m apart, with the soil surface level with the surrounding grassland soil surface.

Sixty days (day −60, April 2011) before introducing the earthworms into the mesocosms, the mesocosms were seeded with perennial ryegrass (*Lolium perenne* L. cv. 'Grasslands Nui') at a rate of 40 seeds per mesocosm. The mesocosms were initially left outdoors, but were moved indoors for a month and resown at day −36 due to poor germination rates. At day −10 the grass was cut level with the top of the bucket (~50 mm above the soil surface).

Fertiliser was applied at day −8 at a rate of 300 kg ha^{-1} of single superphosphate (29 kg P/ha) and lime (500 kg/ha). The first application of urea was also applied at day −8 at a rate of 50 kg N/ha, this application was repeated a further three times throughout the course of the trial. Cattle dung was applied to the soil surface of each mesocosm at day 0 (June 2011). The dung had 20% dry matter, 36.3% total C and was applied at a rate of 9250 kg C/ha (900 g wet weight per mesocosm).

Five replicates of two earthworm treatments were arranged in a randomized block design.

- Low: No earthworms added. A few earthworms were detected in later sampling (see Table 1).
- High: Eight epigeic (*Lumbricus rubellus*), forty endogeic (*Aporrectodea caliginosa*) and nine anecic earthworms added (*Aporrectodea longa*) equivalent to 125, 565 and 110 ind./m^2 mimicking typical earthworm densities in the study area (Schon et al., 2012a, 2008).

Table 1
Mean abundance (ind./m^2) and biomass (g wet weight/m^2) of earthworms in two earthworm mesocosm treatments after 444 days. Low: no earthworms added. High: *A. longa, L. rubellus* and *A. caliginosa* added. Standard error of mean given in parenthesis. Bold letters indicate significant difference at α = 0.05 in a given row.

	Abundance		Biomass	
Earthworm treatments	Low	High	Low	High
Lumbricus rubellus (Hoffmeister, 1843)	189 (51)	223 (18)	39 (6)	40 (5)
Aporrectodea caliginosa (Savigny, 1826)	**85 (38)**	**639 (231)**	27 (17)	81 (36)
Aporrectodea rosea (Savigny, 1826)	**3 (3)**	**57 (39)**	1 (1)	5 (3)
Octolasion cyaneum (Savigny, 1826)	3 (3)	0 (0)	3 (3)	0 (0)
Aporrectodea longa (Ude, 1885)	**6 (6)**	**93 (19)**	**2 (2)**	**121 (14)**
Total earthworms	**286 (58)**	**1012(235)**	72 (23)	247 (47)

After earthworms were added to the mesocosm, lids were placed on the buckets overnight to ensure earthworms moved down into the soil. Visibly there was an initially low mortality rate (1 or 2 earthworms in each mesocosm). Surface castings were observed in the low treatment (i.e. no earthworms added) and therefore earthworms were supressed with 1500 mL mixture of water and Carbaryl (7.5 gm Carbaryl/1 L water) on day 198. Carbaryl is toxic to earthworms (Potter et al., 1990) but has a short half-life, so there is little evidence of it influencing soil enzyme activity, other soil fauna (Behera and Mishra, 1989; Coleman et al., 1994; Sannino and Gianfreda, 2001; Schäffer, 1993) and soil mineral nitrogen (Ingham et al., 1994).

2.2. Continual monitoring

Leachate was collected as necessary, typically every 2–4 weeks, with a total of 23 collection periods and volume recorded, samples were frozen before analysis. Herbage was cut at 4–6 week intervals depending on growth rates, with a total of 13 harvests over the period of the experiment. At each harvest the herbage was trimmed to a height of 3 cm, oven-dried at 60 °C for 48 h and weighed. Soil temperature was measured every 6 h using a temperature probe (TMC6-HD) that was placed in one replicate of each treatment only, and was connected to a HOBO external data logger (Onset, USA). Soil water content was determined by weekly weighing of the mesocosm. Over the summer months water was applied to the soil surface through regular weighing so as to maintain soil water content near field capacity.

2.3. Destructive sampling

All mesocosms were destructively sampled at day 444. After removing the soil column from the buckets, the soil column was cut into slices at four depth intervals (0–75, 75–150, 150–225, 225–300 mm) using an aluminium sheet. The number of visible burrows on the base of each slice was recorded. Within each slice, cores (100 mm diameter, 50 mm deep) were collected for pore-size distribution, total porosity and bulk density determinations. Pore-size distribution was determined by measuring volumetric soil water content at particular tensions (Danielson and Sutherland, 1986). Macropores are those pores too large for water to move by capillary force and are defined as > 300 μm in this study (1 kPa). Micropores are defined as < 30 μm in size (10 kPa) and hold plant available water (Letey, 1985). Bulk density was determined by oven-drying at 105 °C for 48 h and weighing. Total porosity (v/v) was calculated using bulk density data and assuming a particle density of 2.65 g/cm^3. Two 50 mm diameter, 75 mm depth cores were sampled from each slice for root