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Short communication

The action of an anecic earthworm (*Aporrectodea longa*) on vertical soil carbon distribution in New Zealand pastures several decades after their introduction

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ABSTRACT

Anecic earthworms have the ability to incorporate carbon (C) from the surface to depth in the soil. This study aimed to quantify the rate of spread of *Aporrectodea longa*, and their influence on the amount of C stored, in two contrasting soils where this earthworm was introduced in the 1980s. The rate of spread of *A. longa* at both sites (5.3–12.5 m/y) is similar to endogeic species. Over several decades there was a decrease in soil C in the presence of *A. longa* in the Pallic soil (78 912 vs. 85 796 kg C/ha for 0–300 mm) while soil C tended to increase in the Allophanic soil (141 845 vs. 111 076 kg C/ha at 0–300 mm). In the Pallic soil, bulk density tended to be lower in the presence of anecic earthworms at 150–300 mm depths and may have encouraged the decomposition of more stable C. Further, the interaction with higher abundances of endogeic earthworms and lower organic matter inputs in the Pallic soil than the Allophanic soil may help explain the lower soil C in the Pallic soil. The conflicting results in the two soils highlight the influence of the earthworm community and soil properties on C dynamics.
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1. Introduction

The soil contains an important reservoir of carbon (C) and any significant change in soil C will impact on soil function and represents a greenhouse gas mitigation issue. Soil C loss has been recorded from some pastoral soils in New Zealand and the UK [1,2]. In pastoral systems, C is deposited onto the soil surface through plant senescence and dung return, as well as root senescence providing a source of C directly into the soil [3]. One of the primary roles that earthworms play in decomposition is the incorporation of the surface C into the soil profile [4], otherwise it remains vulnerable to mineralisation and loss to the atmosphere [5].

Several functional groups of earthworms are recognised [6]. Both epigeic and anecic earthworms feed on the C at the soil surface, with the smaller, surface active epigeic earthworms processing about 20 g dung annually, and the larger, anecic earthworms processing about 40 g dung annually [4]. Some 80% of this intake is excreted in casts and returned both onto the soil surface and within the soil profile [7]. It is the anecic earthworms, by moving C to greater depths in the soil where it may be less susceptible to being lost, that may be particularly beneficial to C storage [8]. While earthworms may stimulate incorporation of organic matter, several studies have also reported that the presence of earthworms increases CO_2 emissions from the soil [9–11], and hence their influence on the net C stored in the soil over long time periods is still not fully quantified.

New Zealand pastures contain a mix of exotic earthworms which arrived accidentally with the first European settlers, improving pasture production [12]. Schon et al. [13] estimated that up to 6.5 million ha of pastures lacked anecic earthworms. As earthworms spread slowly across the landscape, the opportunity exists to investigate the rate of spread of anecic *Aporrectodea longa* as well as their influence on soil C storage more than two decades after their deliberate introduction. We hypothesise that soil C will be greater with depth in the presence of anecic earthworms leading to a potential mitigation option for increasing soil C where this earthworm group is absent.

2. Methods

2.1. Field sites

Anecic *A. longa* were introduced to permanent pasture in two hill country sheep stations in the 1980s. One site was located at

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Rangitoto Station near the coast, east of Waipukurau, New Zealand (40°11'S, 176°44'E). The station is located 100 m above sea level with mean annual rainfall of 1050 mm and a mean annual temperature of 12.2 °C. The soil is classified as an Atua silt loam (Pallic soil) with dominant smectitic clay mineralogy and a depth of approximately 100 cm. Single superphosphate was applied annually at rates of 100–300 kg/ha. Stocking rates since the 1980s have increased from approximately 8 SU/ha to 10 SU/ha, where a stock unit consumes 550 kg DM/ha/y. At the time of introduction in 1981, resident earthworm populations consisted of *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Aporrectodea trapezoides*, *Lumbricus rubellus* and earthworms of the *Octolasion* genus.

The second site was located at Mounganui Station, near Taihape, New Zealand (39°30'S, 175°49'E). Surveys conducted in the early 1980s on the recently converted pasture from tussock found only earthworms of the *Octolasion* family as well as some native earthworms. At this time the species *A. caliginosa* was successfully introduced to combat the problem of pasture thatch accumulation [14]. Subsequently, in 1989 *A. longa* was introduced. The station is located 1000 m above sea level with mean annual rainfall of 1175 mm and a mean annual temperature of 10.2 °C. The soil is classified as an Ohakune sandy loam (Allophanic soil) and has a depth of approximately 90 cm. The farm received annual applications of 250 kg/ha single superphosphate. Stocking rates since the 1980s have increased on the property from approximately 9 SU/ha to 12 SU/ha.

2.2. Data collection

In November 2009 Mounganui Station was revisited to determine the rate of spread of *A. longa* in the Allophanic soil. Soil cores (15 cm diameter, 20 cm deep) or soil monoliths (20 cm width × 20 cm length × 30 cm deep) were taken up to a distance of 500 m from the point of introduction [14]. In August 2011 soil monoliths were collected in the Pallic soil up to 250 m from the point of introduction.

In the winter (Allophanic in June and Pallic in August) of 2011 the sites of *A. longa* introduction were sampled to explore the influence of *A. longa* on soil C. At each site two 50 m transects were sampled within the same paddock, one where *A. longa* had successfully established (anecic), and another where *A. longa* had not yet colonised (no anecic). The Pallic transects were located approximately 160 m above sea level, had a slope of 5° with a north aspect. The Allophanic transects were located approximately 1000 m above sea level, had a slope of 5° with a southwest aspect. Six soil monoliths (20 cm width × 20 cm length × 30 cm deep), one extracted every 10 m along the transect were analysed for earthworms. Earthworms were hand-sorted and identified to species where possible. Adjacent to each soil monolith, soil cores (3 cores of 2.5 cm diameter bulked together) were collected for soil C. Samples were collected to a depth of 30 cm, the depth of greatest earthworm activity, and separated into four depths (0–75, 75–150, 150–225, 225–300 mm) and analysed using an elemental analyser (Elementar Vario-Max CN analyser, Elementar GmbH, Hanau, Germany). The vertical distribution of carbon was modelled (using an exponential function) to integrate the C density in the soils from the surface to deepest depth sampled [15,16]. A further set of soil cores (5 cores of 2.5 cm diameter bulked together) were collected adjacent to the centre and two end monoliths for measurement of root mass. Roots were hand washed and sieved from the soil, dried at 60 °C for 24 h and weighed. Bulk density samples (10 cm diameter, 10 cm deep) were collected from the side of a soil pit, dried at 105 °C for 48 h and weighed. Soil moisture (0–100 mm depth) was recorded in the field at the time of sampling using a TDR 300 Soil Moisture Probe, (Spectrum Technologies Inc., USA). One composite sample at each transect was analysed for soil pH and Olsen P.

2.3. Statistical analysis

The effect of site, treatment (anecic vs. no anecic), depth and their interactions on the data was investigated. The data was analysed using an analysis of variance and adjusted for multiple comparisons by Tukey's method (Minitab v.15), except for the earthworm data which was analysed using a generalised linear model, assuming group-specific negative binomial distributions through log link function (SAS version 9.1).

3. Results

After twenty years *A. longa* was found up to 250 m from the initial site of introduction in the Allophanic soil, equivalent to a rate of spread of 12.5 m/y. In the Pallic soil *A. longa* was found up to 160 m away from the point of introduction uphill and up to 200 m down slope after thirty years, equivalent to 5.3–6.7 m/y.

At both sites the abundance of *A. longa* in the anecic transects was approximately 350 ind/m^2 (Table 1). In the non-anecic transect significant differences in endogeic species abundance were observed between the two sites, with significantly lower abundances of *A. caliginosa* in the Allophanic soil. Overall the Pallic soil had significantly higher bulk density and lower root mass and soil C content than the Allophanic soil (Fig. 1). Soil pH (5.7 and 5.8) and Olsen P (26 and 20 μg/ml) were similar for both the Pallic and Allophanic soils.

Table 1
Mean earthworm abundance (ind./m^2, 0–150 mm soil depth) and total biomass (g wet wt/m^2) in sheep-grazed pastures at two sites where the anecic *A. longa* had been introduced three decades (Pallic) and two decades (Allophanic) previously. Within each site transect type indicates where the anecicearthworm, *A. longa*, has and has not yet colonised. Values in parenthesis indicate standard error of mean.

Species	Pallic		Allophanic		Between site P-value	
	Anecic	No anecic	Anecic	No anecic	Anecic	No anecic
Aporrectodea longa (Ude, 1885)	**371** (64)	**0**	**327** (77)	**0**	0.613	1.000
Aporrectodeacaliginosa (Savigny, 1826)	883 (95)	1484 (51)	**274** (180)	**44** (21)	0.108	**<0.001**
Aporrectodea rosea (Savigny, 1826)	170 (17)	80 (30)	0	0	**<0.001**	**<0.001**
Aporrectodea trapezoides (Dugès, 1828)	88 (49)	239 (51)	0	0	**<0.001**	**<0.001**
Octolasion cyaneum (Savigny, 1826)	0	0	9 (9)	0	0.321	1.000
Native 1	0	0	18 (18)	9 (9)	0.206	0.338
Native 2	0	0	9 (9)	0	0.321	1.000
Native 3	0	0	0	9 (9)	1.000	0.321
Total earthworms	1513 (159)	1802 (90)	**637** (188)	**62** (25)	0.061	**<0.001**
Earthworm biomass (g wet wt/m^2)	624 (129)	501 (41)	**499** (91)	**40** (23)	0.648	**<0.001**

Bold indicates significant difference at $\alpha = 0.05$ between the *A. longa* transect and the no *A. longa* transect at a given site in a given row. *P*-value given for significant difference between sites within transect type.

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