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# Effects of stock type, irrigation and effluent dispersal on earthworm species composition, densities and biomasses in New Zealand pastures

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### ABSTRACT

We investigated the effects of grazing stock, irrigation and effluent dispersal on earthworm species compositions, densities and biomasses in 615 locations across 41 farms in the Waitaki Basin, New Zealand, between April and September 2012. No native megascolecid earthworms were found, but four introduced European species were encountered. Among earthworms collected, *Aporrectodea caliginosa* accounted for 70% of the total, 23% were *Lumbricus rubellus* and 4% *Aporrectodea longa*. When compared with untreated locations, total earthworm density was higher by 42% in effluent only locations and 72% in irrigated only locations. Maximum densities and biomasses occurred where both effluent and irrigation were applied. *L. rubellus* density was 32% higher in effluent only locations, 123% higher in irrigated only locations and 180% higher in effluent and irrigated locations than untreated locations. *A. longa* occurred in 24% of the sampled locations and appeared to be suppressed in irrigated locations. When equivalent treatments were applied, earthworm densities were 15.4% to 36.6% higher on sheep farms than on dairy farms; earthworm biomasses differed by –3.3% to 55.8% between these two kinds of stock animal farms. Treatment effects on earthworms were evident only in the upper 10 cm soil layer. Effluent and water application may have reduced the risk of desiccation and increased the availability of resources for earthworms. However, local absence of the deep burrowing species (e.g. *A. longa*) raises concerns about ecosystem functioning. This is a topic that should be explored further.

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## 1. Introduction

Agricultural intensification aimed at expanding New Zealand's export economy has been on-going for over 150 years (Brooking et al., 2011). This intensification has increased in the last 40 years (MacLeod and Moller, 2006; Moller et al., 2008). Associated intensification through increased conversion to dairy farming and irrigation has been particularly marked in the South Island of New Zealand. The dairy herd in South Island increased by 212% between 1994 and 2002 (Statistics New Zealand, 2002). Sheep flocks increased markedly in the 1960s and 1970s, then decreased considerably over subsequent years, while dairy cow numbers increased gradually between 1960 and 1990, and more rapidly thereafter (MacLeod and Moller 2006). Large quantities of effluent

(generated material containing cow excreta and urine deposited in milking sheds and diluted with wash down water) are distributed to small parts of dairy farms as a means of returning nutrients to land. For example in one study, in New Zealand pastures, one cubic metre of effluent contained 7400 g of total solids, 2247 g of total carbon, 246 g of total nitrogen and 55 g of total phosphorus (Di et al., 2002). On the other hand, sheep naturally distribute their dung and urine over the whole farm while grazing.

As ecosystem engineers, earthworms are able to improve soil physical, chemical and biological properties (Jones et al., 1994; Jouquet et al., 2006). Earthworms can enhance the soil's ability to provide many ecosystem functions, such as plant nutrient supply (Gallagher and Wollenhaupt, 1997; Tan et al., 1998), thereby increasing plant productivity (Eisenhauer and Scheu, 2008). Many studies have focused on earthworm responses to factors such as tillage, chemical additions, temperature, and land use change or as soil quality indicators and drivers of ecosystem processes (Callahan et al., 2006; Briones et al., 2009; Malmström et al., 2009; Rossi et al., 2010). Studies of earthworm populations under normal farm paddock conditions in New Zealand are scarce (Schon et al., 2008; Schon et al., 2011a; Fraser et al., 2012; Manono, 2014), and only two have investigated the effects of effluent dispersal

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(Yeates, 1976; Degens et al., 2000). None have investigated the effects of converting sheep farms to dairy, or separated the effects of adding irrigation water to pastoral soils in combination with dairy effluent.

Irrigation and effluent application practices play significant roles in regulating earthworm communities through the provision of moisture, thereby enhancing their reproduction and survival of cocoons and adults (Keplin and Broll, 2010). Farm conversion, effluent dispersal, and wetting and drying cycles are therefore very likely to influence earthworm species identity, density and biomass. In the Waitaki Basin, watering cycles usually extend over 1–2 days followed by a 15 day “drying” period. Drying periods may be protracted during rainy periods, especially in spring or autumn, but the average wetting frequency is 17 days.

The objective of this study was to assess the impacts of land-use intensification on earthworms by determining the extent to which grazing stock, irrigation and effluent dispersal affect their density and biomass under pastoral land use. We hypothesised that both irrigation and effluent dispersal would have positive impacts on earthworms, i.e., enhance their density and biomass (Hypothesis 1). New Zealand dairy farming is much more intensive than sheep farming (Carey et al., 2010; Norton et al., 2010) and is often associated with higher stocking rates (Houlbrooke et al., 2008). Because the stocking rates and trampling pressures of bovids (cows exert greater pressures (160–192 kPa) than sheep (83 kPa); Willatt and Pullar, 1984) are elevated, we hypothesised that bovids reduce earthworm numbers and biomass, even when water is added (Hypothesis 2). Finally we hypothesised that earthworm density and biomass would be highest when land remains under sheep production and irrigation water is applied (Hypothesis 3; applicable when Hypotheses 1 and 2 are confirmed).

## 2. Materials and methods

### 2.1. Study area and irrigation systems

Earthworm data were collected from 41 farms within the Waimate District (44°38′–44°54′S and 170°59′–171°08′E) of the South Canterbury region, New Zealand. The district borders the Waitaki River in the south, the Pareora River in the north and the Hakataramea Valley to the west. The area supports a productive pastoral farming typical of the New Zealand agro-ecosystem landscape. There is irrigation on the flat areas of the Waitaki Basin and a small number of sheep farms with irrigation on the flanking hills. The mean annual rainfall is 500–600 mm (Tait et al., 2006), with frequent droughts in the summer months. Soils are formed

from silty loess deposits with slow permeability, limited rooting depth and a medium to high bulk density. These soils are susceptible to erosion because of high potential for slaking and dispersion. In the New Zealand Soil Classification (Hewitt, 1998), they are classified as mottled fragic pallic soils, while in the USDA Soil Taxonomy (Soil Survey Staff, 1998), the soils are udic Haplustept.

Three irrigation systems are used in the study area, spray, K-line (lateral) and border dyke. Spray irrigators operate either a rotary or fixed boom with sprinklers placed along the full length of the boom with a capacity to deliver up to 90 mm water to 6 ha in one run (24 h). K-line systems consist of underground main lines with a series of sprinklers on sleds connected to the hydrants by flexible non-kink laterals. There is one sprinkler per 0.6 ha that can apply between 25 and 40 mm water in 12 h. Lastly in border dyke systems, water is conveyed onto paddocks (individual farm fields) under gravity by constructing slightly sloping bays separated by low borders that direct the flow.

### 2.2. Selection of study farms, study paddocks and ‘Earthworm Sampling Locations’ (ESLs)

We sampled earthworms from 41 farms; 27 dairy farms that had recently been converted from sheep to dairy farming and five sheep farms intermingled among the irrigated dairy farms to infer the likely effects of conversion to dairy on earthworms. We also selected a further nine unirrigated dairy farms from the nearby Waimate Catchment for baseline comparison with earthworm habitat that most likely prevailed before the conversion in the Waitaki Basin. All selected dairy farms applied effluent onto part of the farms.

In consultation with each individual farmer, study paddocks typical of the farm’s management treatments were selected. These included two different managements in sheep-grazed pastures (irrigated and unirrigated – sheep farms do not collect and disperse animal excrement) and four different managements in dairy grazed pastures (Table 1). Dairy and sheep stocking effects were compared only within equivalent irrigated and unirrigated management treatments. Sheep farm paddocks had been grazed by sheep for  $\geq 10$  years. None of our selected paddocks had been subjected to any form of tillage within the last 5 years of sampling. Although a number of factors are known to affect earthworm communities, this study placed emphasis on irrigation, effluent dispersal and farm conversion.

Three random ‘Earthworm Sampling Locations’ (ESLs) were positioned within each focal paddock using a table of random

**Table 1**  
Numbers of earthworm sampling Locations (ESLs) for each soil management treatment level. The footnotes show the total number of sampled locations for each management level.

Farm type	Irrigated dairy farms				Unirrigated dairy farms		Sheep farms	
	Untreated <sup>a</sup>	Effluent only <sup>b</sup>	Irrigation only <sup>c</sup>	Effluent and irrigation <sup>d</sup>	Untreated <sup>a</sup>	Effluent only <sup>b</sup>	Irrigated sheep <sup>e</sup>	Unirrigated sheep <sup>f</sup>
Number of farms	24				12		5	
Total selected paddocks	113				72		20	
Number of treated paddocks	15	10	44	44	36	36	10	10
Total ESLs sampled	45	30	132	132	108	108	30	30

<sup>a</sup> Dairy grazed paddocks that receive neither irrigation water nor effluent (total number of sampled locations = 153).

<sup>b</sup> Dairy grazed paddocks that receive effluent but not irrigation water (total number of sampled locations = 138).

<sup>c</sup> Dairy grazed paddocks that receive irrigation water but not effluent (total number of sampled locations = 132).

<sup>d</sup> Dairy grazed paddocks that receive both irrigation water and effluent (total number of sampled locations = 132).

<sup>e</sup> Sheep grazed paddocks not receiving irrigation water (total number of sampled locations = 30).

<sup>f</sup> Sheep grazed paddocks receiving irrigation water (total number of sampled locations = 30).

**Table 2**

Number of earthworms collected per species, proportional representations in total earthworms found and the occurrence of each species in all earthworm sampling locations (ESLs).

Species	Individuals	Percentage of total earthworms (%)	Occurrence (% of all ESLs)
<i>Aporrectodea caliginosa</i> , (Savigny, 1826)	4927	70	98
<i>Lumbricus rubellus</i> (Hoffmeister, 1843)	1631	23	80
<i>Aporrectodea longa</i> (Ude, 1885)	268	4	24
<i>Octolasion cyaneum</i> (Savigny, 1826)	156	2	6
Unidentified	88	1	11

numbers to select grid co-ordinates, all of which met the following criteria:  $\geq 30$  m from nearest neighbor coordinates, trees, fences, gateways and water troughs. These restrictions sought to minimize variance between samples and avoid areas where stock congregate.

### 2.3. Earthworm sampling

Earthworm data were collected between April and September 2012 from 615 ESLs across 6 treatments (Table 1). Earthworms were extracted from the 'Upper' 10 cm and 'Lower' 10–20 cm layers of a 20 cm  $\times$  20 cm  $\times$  20 cm deep soil sample cut using a spade; thus, results were expressed as worm density (individuals  $m^{-2}$ ) and biomass ( $g m^{-2}$ ). We divided the samples in half to test for changes in the vertical distribution. Earthworms were searched by sorting and crumbling the soil matrix by hand (Edwards and Lofty, 1977), followed by separation of the collections and determination of species identities.

Separate pooled samples from each layer were weighed using an electronic balance (accurate to 0.1 g). Samples from irrigated and unirrigated farms were collected on alternate days so that changes in earthworms would be less likely to confound treatment effects. Sampling on sheep farms was interspersed between dairy farms for the same reason.

### 2.4. Statistical analysis

Differences in earthworm density, biomass and species distribution between treatment types were analysed using GenStat™ for Windows (release 16) statistical software. The Restricted Maximum Likelihood (REML) routine was considered most appropriate because of the unbalanced nature of the design (not all study farms had similar treatments, Table 1). Building stable predictive models with well distributed residuals proved impossible in the case of *Aporrectodea longa* (Ude, 1885) because there were a large number of zero counts (absences). We therefore followed the approach recommended by Fletcher et al., (2005) by splitting the modelling (still using REML) into (i) a binary regression step (predicting the probability of *A. longa* presence in a given ESL for each treatment), followed by (ii) an ordinary regression analysis in which we predicted the densities and biomasses in treatments using only those ESLs in which  $\geq 1$  *A. longa* individual was found. The first step used the logistic probability model and second step used the normal probability model.

Treatment, layer and earthworm measurements were designated fixed effects, and interactions between them were incorporated when comparing the interaction effects. To account for the lack of independence and the hierarchical nature of the sampling, random effects were always nested as Farm/Paddock/ESL within the REML models. Preliminary models were constructed and residuals inspected to check for heteroscedasticity and to ensure

that the residuals were distributed evenly around the predicted means. The significances of predictor variables were assessed by Wald's tests. When the response variables were proportion based counts (for example, percentages), we used an underlying binomial probability function within Genstat's Generalised Linear Mixed Model (GLMM) routines. This allowed us to match the blocking structure with that in the REMLs. Since earthworm biomass measures are continuous rather than discrete counts (not normally distributed), we used arcsine transformations (Sokal and Rohlf, 1981) to normalise variances within REML models by incorporating the usual blocking structure. Predicted arcsine means and confidence intervals were back-transformed, but the *p*-values reflect the tests performed with arcsine transformed data. Results are presented as means  $\pm 2 \times$  SE (standard error of differences).

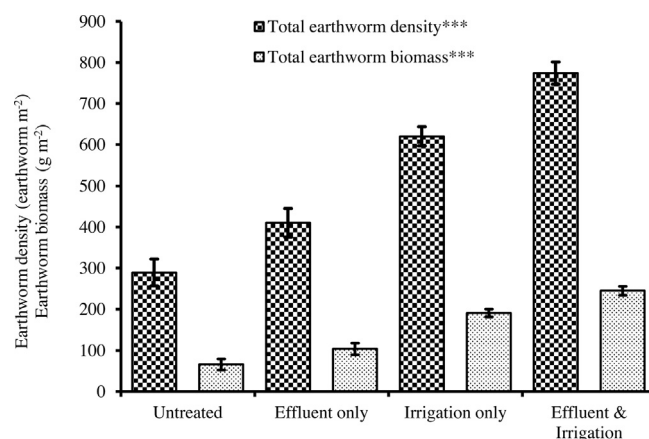
## 3. Results

### 3.1. Earthworm species richness

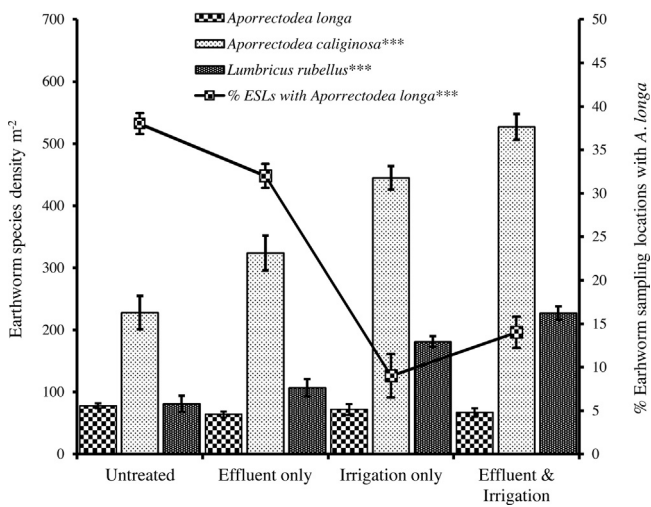
The number of earthworm species was low, with one, two, three and four species present in 10%, 61%, 23% and 6% of all sampled locations respectively. No earthworm species native to New Zealand was sampled (not even the most common, *Octochaetus multiporus* (Beddard, 1885)). Amongst 7070 identifiable worms recovered, *Aporrectodea caliginosa* (Savigny, 1826) was by far the most abundant and widespread (Table 2). In view of their extremely low occurrence (Table 2), specimens of *Octolasion cyaneum* (Savigny, 1826) were not considered further in our analyses.

### 3.2. Did seasonal and irrigation type detection confound tests of treatment effects?

Since earthworm sampling was extended over two seasons, there was concern whether a seasonal detection bias confounded our exploration of earthworm population changes between treatments. Therefore, we tested for the interaction effect between treatment and season in the initial REML models. In all cases, there was no significant interaction effect. This suggests that the unbalanced sampling (between treatment types) and elongated duration of the sampling period was unlikely to have altered the earthworm measurements between treatments. This finding enabled us to drop the Season.Treatment interaction term from our analysis, thereby creating a more parsimonious model to test



**Fig. 1.** Earthworm density and biomass measurements for dairy management treatments. Significant differences between treatments: \*\*\*,  $p < 0.001$ . Values are means  $\pm (2 \times$  standard error of differences). Number of sampled locations for each management type is: untreated,  $n = 153$ ; effluent only,  $n = 138$ ; irrigation only,  $n = 132$  and effluent and irrigation,  $n = 132$ ).



**Fig. 2.** Earthworm species density measurements for dairy management treatments. *A. longa* density is from only earthworm sampling locations with at least one *A. longa*. Significant differences between treatments: \*\*\*,  $p < 0.001$ . Values are means  $\pm 2 \times$  standard error of differences. Number of sampled locations for each management type is: (untreated,  $n = 153$ ; effluent only,  $n = 138$ ; irrigation only,  $n = 132$  and effluent and irrigation,  $n = 132$ ). For *A. longa*, (untreated  $n = 58$ ; effluent only  $n = 44$ ; irrigation only  $n = 12$  and irrigation and effluent  $n = 19$ ).

treatment effects. However, we retained season as a random blocking effect to increase the power to detect treatment effects which were the primary focus of our study.

Three irrigation systems are used by the Waimate District farmers (border-dyke, K-line and spray). We first checked whether the three systems have any differential effects on earthworms. There was no evidence for differences in worm densities and their biomasses when irrigation method was considered as a main effect. Overall there were insufficient farms with the same irrigation method to reliably and separately replicate tests of each irrigation method. Accordingly, we combined all irrigation methods as a single treatment comparison ('irrigated' vs. 'unirrigated').

**3.3. Variation in earthworm density and biomass between treatments**

Untreated paddocks had the lowest density and biomass of earthworms, i.e., less than half the numbers on average where

effluent and water were both added (Fig. 1). Addition of water had about double the effect of adding effluent alone (Fig. 1). These changes were mainly attributable to large increases in *A. caliginosa* and *Lumbricus rubellus* (Hoffmeister, 1843), especially in irrigation treatments (Fig. 2). Although the occurrence of *A. longa* was considerably reduced in irrigated paddocks, there was no evidence of reduced densities when considering only ESLs in which *A. longa* persisted (Fig. 2).

**3.4. Vertical distribution of earthworms**

Treatment effects occurred in the 0–10 cm depth layer of the soil: the numbers of earthworms and their biomass in the 10–20 cm layer were remarkably similar between treatments (Fig. 3).

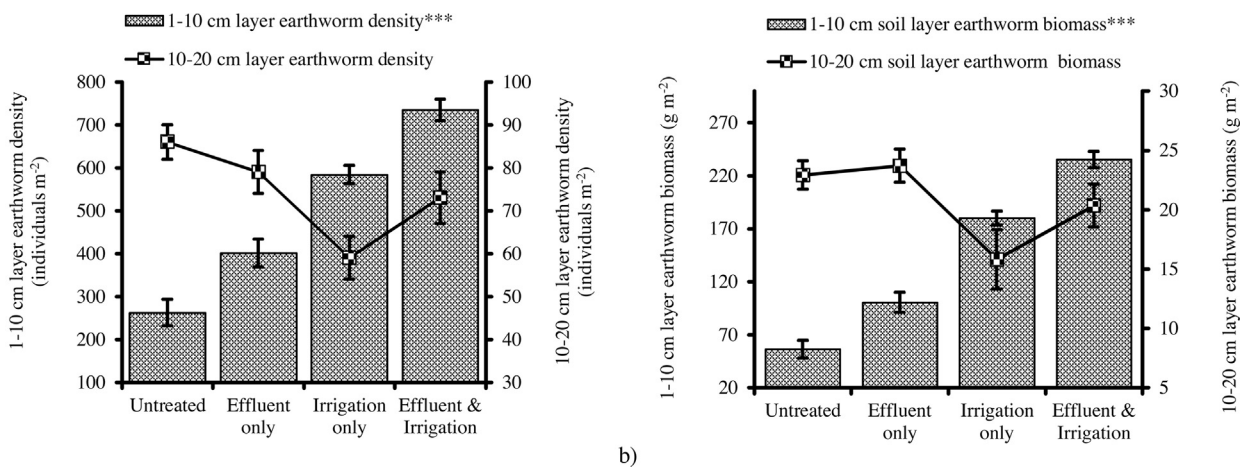
**3.5. Effect of grazing stock on earthworms**

There were many statistically significant differences in earthworm communities between irrigated and unirrigated soils (Table 3). Similar irrigation treatment effects were evident on sheep farms to those observed in dairy farms (Table 4). However, we were especially interested in the interaction between land treatment (irrigated/unirrigated) and stock type (sheep/dairy); instances of statistical interaction differences between these two factors were detected (Fig. 4). So, the interaction effect of stock and irrigation was larger in dairy farms than in sheep farms. For example, earthworm density increased by 82% for dairy compared to 54% in sheep farms between unirrigated and irrigated sampled locations. The respective shift in earthworm biomass due to the irrigation treatment was even more pronounced: earthworm biomass increased by 175% in dairy compared to 47% in sheep farms (Fig. 4).

**4. Discussion**

**4.1. Earthworm community composition in the Waitaki Basin: comparisons with other studies**

The absence of native New Zealand megascolecid earthworm species in our collections is consistent with other earthworm studies (Fraser et al., 1996). These earthworms have been normally associated with undisturbed soils and native vegetation (Springett et al., 1998), conditions that may have been absent in the area we



**Fig. 3.** (a) Earthworm density and (b) earthworm biomass in the 0–10 cm and 10–20 cm soil layers for the dairy management treatments. Earthworm densities and biomasses were statistically different between treatments: \*\*\*,  $p < 0.001$  in the 0–10 soil stratum while there was no evidence of differences in the 10–20 soil stratum. Values are means  $\pm 2 \times$  standard error of differences. Number of sampled locations for each management type is: untreated,  $n = 153$ ; effluent only,  $n = 138$ ; irrigation only,  $n = 132$  and effluent and irrigation,  $n = 132$ ).

**Table 3**

Earthworm measurements for the main effect of irrigation (irrigated versus unirrigated). Total ESLs are: dairy unirrigated,  $n = 153$ ; dairy irrigated,  $n = 132$ ; sheep irrigated,  $n = 30$  and sheep unirrigated,  $n = 30$ . Significant differences between treatment as assessed by Wald's tests are: \*\*\*,  $p < 0.001$ . Dairy grazed ESLs where effluent was applied are excluded.

Earthworm measurement	Unirrigated		Irrigated		p-value
	Value	se	Value	se	
Total earthworms (individuals $m^{-2}$ )	375	31	635	25	***
Total biomass ( $g m^{-2}$ )	95.2	9.3	182	7.7	***
<i>Aporrectodea longa</i> density $m^{-2}$	75	7	67	9	
<i>Aporrectodea caliginosa</i> density $m^{-2}$	286	24	459	20	***
<i>Lumbricus rubellus</i> density $m^{-2}$	89	10	165	16	***
0–10 cm soil layer density (individuals $m^{-2}$ )	303	30	550	24	***
0–10 cm soil layer biomass ( $g m^{-2}$ )	72.5	9.0	159.6		***
10–20 cm soil layer density (individuals $m^{-2}$ )	109	9	113	7	
10–20 cm soil layer biomass ( $g m^{-2}$ )	27.2	3.2	23.6	2.9	

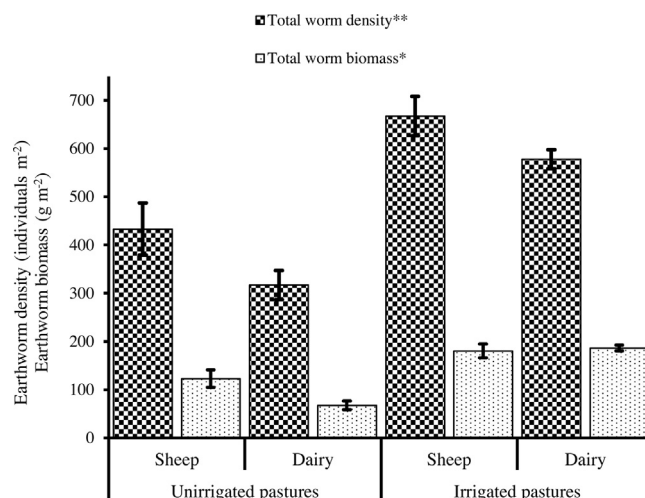
studied. *A. caliginosa* dominance is in agreement with other earthworm studies in New Zealand (Riley et al., 2008; Schon et al., 2011a; Fraser et al., 2012). The low earthworm species richness we encountered may reflect elements of biogeography, especially the long period of geographic isolation of the island ecosystems without ecological disturbance by humans, such as agricultural activities. This observation contrasts with the norm in European farmlands where the encountered earthworms are native and several species flourish together (Muldowney et al., 2003; Neilson and Boag, 2003; Curry et al., 2008). The earthworm species present were introduced between 1949 and 1965 to increase pasture production (Lee, 1959; Stockdill, 1982; Syers and Springett, 1983; Yeates, 1991).

The total absence of *Lumbricus terrestris* (Linnaeus, 1758), a dominating anecic species in many agro-ecosystems (Boag et al., 1997; Curry et al., 2008); the infrequency of *A. longa* species and its low density at locations of occurrence is indicative that the local soil conditions are not suitable for anecic earthworms. As a consequence the fertility and sustainability of the Waitaki soils maybe constrained by lack of anecic species, whose presence in agro ecosystems is important in providing ecosystem services that benefit agriculture (Fraser et al., 1996; Lavelle et al., 2006; Postma-Blaauw et al., 2006). This observation deserves further attention because it contrasts with earlier earthworm studies in the study region where *A. longa* formed the dominant species of the earthworm community (Lee, 1959) and *L. terrestris* was reported to be “common, plentiful and everywhere” (Smith, 1894). However, it is important to note that our sampling protocol for anecic earthworms was inadequate, and that *A. longa* is not widely distributed in New Zealand pastures

**Table 4**

Earthworm measurements for the main effect of stock type (sheep versus dairy). Total ESLs are: dairy unirrigated,  $n = 153$ ; dairy irrigated,  $n = 132$ ; sheep unirrigated,  $n = 30$  and sheep irrigated,  $n = 30$ . Significant differences between stock type as assessed by Wald's tests are: \*\*\*,  $p < 0.001$ , \*\*,  $p < 0.01$ , \*,  $p < 0.05$ . Dairy grazed ESLs where effluent was applied are excluded.

Earthworm measurement	Sheep		Dairy		p-value
	Value	se	Value	se	
Total density (individuals $m^{-2}$ )	550	38	461	19	
Total biomass ( $g m^{-2}$ )	150	11.2	129	5.5	
<i>Aporrectodea longa</i> density $m^{-2}$	86	7	63	6	*
<i>Aporrectodea caliginosa</i> density $m^{-2}$	404	27	341	14	
<i>Lumbricus rubellus</i> density $m^{-2}$	121	9	131	19	
0–10 cm soil layer density (individuals $m^{-2}$ )	429	35	426	16	
0–10 cm soil layer biomass ( $g m^{-2}$ )	118.6	10.3	109.8	5.3	
10–20 cm soil layer density (individuals $m^{-2}$ )	151	11	72	7	***
10–20 cm soil layer biomass ( $g m^{-2}$ )	33.3	4.9	19.4	2.2	*



**Fig. 4.** Effects of the interaction between irrigation and stock type on earthworm density and biomass. Earthworm density and biomass increased when sheep farms are converted to dairy with accompanying irrigation, but reduced when converted without accompanying irrigation. The significances of the interaction term (stock type  $\times$  irrigation) are as follows: \*\*,  $p < 0.01$ , \*,  $p < 0.05$ . Values are means  $\pm$  ( $2 \times$  standard error of differences).

(Springett, 1992; Fraser et al., 1996; Schon et al., 2011b). Nevertheless, this lack of anecic species raises questions whether it matters, and if so, whether another species could replace their functions. If it matters, then there is a potential for their introduction and determination of optimum conditions for maintaining their populations to benefit pasture production. Prior to these introductions, their effects to natural ecosystems should be established because introduced earthworms can have deleterious effects on indigenous ecosystems (Bohlen et al., 2004; Eisenhauer et al., 2007).

The observed mean densities of 620 individuals  $m^{-2}$  in irrigated dairy paddocks we studied and 667 individual  $m^{-2}$  in irrigated sheep farms were comparable to the values of 600 individuals  $m^{-2}$  recorded in an irrigated sheep farm in the Canterbury region of New Zealand (Fraser et al., 2012), 523 individuals  $m^{-2}$  in irrigated pastures in South Australia (Baker et al., 1992), and 904  $m^{-2}$  in the Netherlands (Zorn et al., 2005). Other records of earthworm density in unirrigated New Zealand pastures are very disparate: Fraser et al. (1996) recorded 900 individuals  $m^{-2}$ ; Schon et al., (2011a) recorded 823 individuals  $m^{-2}$ ; while Lee (1985) considered 200–1000 individuals  $m^{-2}$  as a normal range. Therefore, the effect of irrigation in the Waitaki Basin has been to lift average earthworm density to above the New Zealand median found in unirrigated pastures.

#### 4.2. Differences in earthworm measurements between treatments and farm types

We hypothesised that irrigation and effluent dispersal would have positive impacts on earthworms by promoting their density and biomass (Hypothesis 1). This hypothesis was supported, largely because of substantial increases in *L. rubellus* and *A. caliginosa* numbers where water and effluent were added. However, the effect was not universal: *A. longa* was missing in many irrigated and effluent treated ESLs. Relatively high earthworm numbers recorded in effluent and irrigation paddocks indicate that animal manure additions increase earthworm numbers.

We also hypothesised that earthworm density and biomass would be higher on sheep farms than on dairy farms (Hypothesis 2), and highest on land under sheep when supplied with irrigation water (Hypothesis 3, when Hypothesis 1 and 2 are supported). Hypothesis 3 was also supported. The effects of adding water and effluent together appeared to be additive, which is an indication that there were no synergistic or multiplicative effects from having both effluent and water added together. The density and biomass effects between treatments were proportional: the two response variables changed by about the same relative amount between treatments.

#### 4.3. What is the mechanism responsible for changes in earthworm measurements between treatments and farm types?

The shift of *L. rubellus* species indicate that the species has marked capacity for increased reproduction in response to irrigation (Zorn et al., 2008). Irrigation water appeared to make conditions suitable for early maturation, and hence reproduction (Tiunov and Scheu, 2004); thus, irrigation appeared to shift the allocation towards reproduction in the fields we studied. Here, we propose several potential additional underlying mechanisms for the treatment effects observed in our study. Elevated numbers of *L. rubellus* in irrigated soils may reflect a species preference for locations with high moisture (Sims and Gerard, 1985), which certainly reduces the likelihood of desiccation (Edwards and Bohlen, 1996). Moving water in irrigation events may also promote the spreading of either living worms or their cocoons. Additions of effluent may have given earthworms an additional source of nutrients (Longhurst et al., 2000; Di et al., 2002). Furthermore, since the effluent was applied as slurry containing considerable amounts of water, effects of the effluent only treatment may mimic those resulting from irrigation. This increase in density and biomass with intensification is consistent with other studies (Muldowney et al., 2003; Fraser et al., 2012).

As cows exert greater hoof pressure than sheep (Willatt and Pullar, 1984), trampling may have reduced earthworm density in dairy ESLs. The generally low occurrence of *A. longa* in irrigated soils is unlikely to result from lack of food since anecic earthworms thrive in pasture soils (Lindahl et al., 2009). The species may not be well adapted to the prevailing soil conditions when irrigation is added to other stress factors. They might drown or their burrows may fracture and lose structural integrity in successive watering events. Continuous irrigation may result in an overall high capillary fringe and saturated soil conditions during most times of the year. This might explain why experimental effects were only evident near the surface; *A. longa* frequency was low in irrigated lands and did not increase under irrigation while populations of other species increased.

#### 4.4. Robustness of the treatment design

Caution is needed when interpreting the results reported in this study, especially those comparing sheep and dairy farms, as

individual farmers made personal decisions on whether to convert or not. Inclusion of the unirrigated set of dairy farms for comparison with irrigated farms might have potentially introduced added variation. Comparison of large sets of converted with unconverted farms should have been able to detect the effect of conversion. Ideally such a comparison would be done across regions. Alternatively, a before-after-control-impact (BACI) experimental design would have fully controlled for these potential disruptions. Unfortunately all the Waitaki study farms had converted between 25 and 30 years before our study and no 'before' data were available. We attempted to minimise these confounding effects by using a hierarchical, nested sampling design within study farms, and blocking the variance within the REML and GLMM models. Strong and consistent differences were detected between treatments within the same farms, so we are confident that the shifts between treatments were real and certainly ecologically important.

## 5. Conclusion

Our study has demonstrated that application of effluent and irrigation water to grazed pasture soils generate preferential advantage to *A. caliginosa* and *L. rubellus* but disadvantaged *A. longa*. Irrigation and effluent addition may have reduced the risk of desiccation and improved resource availability for earthworms by increasing soil microbial biomass. The latter may have particularly increased the density and biomass for the endogeic species *A. caliginosa*. We lack an explanation for the considerable reduction of *A. longa* occurrence in response to irrigation and effluent treatments. Given the significant functional role of this anecic species, further long-term experiments with repeated samplings are necessary to assess the effect of irrigation and effluent dispersal on these species.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.pedobi.2015.09.002>.

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