Ecosystem Services 43 (2020) 101092

Contents lists available at ScienceDirect

Ecosystem Services

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

Valuing earthworm contribution to ecosystem services delivery

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ARTICLE INFO

Keywords:
Earthworms
Ecosystem services
Economic valuation
Regulating services
Provisioning services

ABSTRACT

The contribution of earthworms to soil quality and the provision of ecosystem services is widely recognised, however, few studies have tried to quantify the value of their contribution. In this study, we use variables measured in a mesocosm study to value the contribution of earthworms to provisioning and regulating services under both sheep grazed and dairy grazed systems using monetary valuation techniques where possible. The contribution of earthworms to ecosystem services were determined using the relative value differences between two earthworm treatments. Earthworms contributed to a number of ecosystem services. The greatest contribution of earthworms in these pastoral systems was through the provision of food quantity (NZD $356–1,001/ha). While we recognise the subjectivity and limitations of economic valuation of ecosystem services, we encourage further studies to bridge the gap between soil ecology, farm system analysis and economics, in order to better understand the relative contributions of soil biodiversity to farm systems.

1. Introduction

Soil is a valuable resource that underpins the provision of a great number of ecosystem services. Ecosystem services provided by managed grasslands include provisioning services (e.g., production of food); regulating services (e.g., dung recycling); and cultural services (e.g., such as recreation) (MEA, 2005; Dominati et al., 2010). The services provided by grasslands are influenced by soil properties and their interaction with supporting processes (Dominati et al., 2010) (Fig. 1). Some soil properties can be altered by factors such as land management and natural hazards, affecting the ability of an agro-ecosystem to deliver ecosystem services. Using a framework proposed by Dominati et al. (2010), the value of ecosystem services provided by soils in New Zealand under sheep farming has been reported at NZD $3,717/ha/year, dropping by 65% of this value after an erosion event (Dominati et al., 2014a). Globally soil ecosystem services are estimated to be valued at 11.4 trillion USD dollars, or an average of $867/ha across all landuses and soil types (McBratney et al., 2017).

The contribution of earthworms to soil quality is widely documented in the literature, with these organisms considered ecosystem engineers (Edwards and Bohlen, 1996; Brown et al., 2004). In particular, it is their role in the supporting processes of soil formation and nutrient cycling that have received the most attention (van Groenigen et al., 2014). These processes alter soil properties and therefore also the provision of ecosystem services (Fig. 1). Earthworms also influence other soil processes such as decomposition, formation of aggregates, maintenance of soil porosity (Edwards and Bohlen, 1996; Brown et al., 2004). The role of earthworms in supporting processes have been linked to ecosystem services (Keith and Robinson, 2012; Pulleman et al., 2012; Blouin et al., 2013), but, we are not aware of studies that valued their contribution to more than one ecosystem service. For example, Sandhu et al. (2008) calculated the role of earthworms on soil formation using the market value of topsoil (USD $30/ha). An estimate of the economic value of earthworms (and not their contribution to ecosystem services per se) was made by Stockdill (1982), who calculated that earthworm introduction to a New Zealand sheep and beef system increased stocking rate an extra 2.5 stock units per hectare, which at current market value is worth about NZD $315 a hectare revenue (www.beeflambnz.com). Bailey et al. (1999) also attempted to put an economic valuation on earthworms in context of a cultivation compared to a minimum tillage system and the role of earthworms in providing soil structure. In the estimate made by Dominati et al. (2014a) for the value of ecosystem services provided by soils, the specific contribution of soil fauna was not included.

One of the biggest threats to soil biological activity as grasslands intensify is the physical degradation of soil which can make it a difficult habitat for the soil biology to function and contribute to ecosystem services (Greenwood and McKenzie, 2001; Schon et al., 2012). Indeed, Bender et al. (2016) acknowledged the need to maintain or enhance soil biodiversity to enable proper ecosystem functioning. Economic data to

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https://doi.org/10.1016/j.ecoser.2020.101092
Received 5 April 2019; Received in revised form 18 December 2019; Accepted 19 March 2020

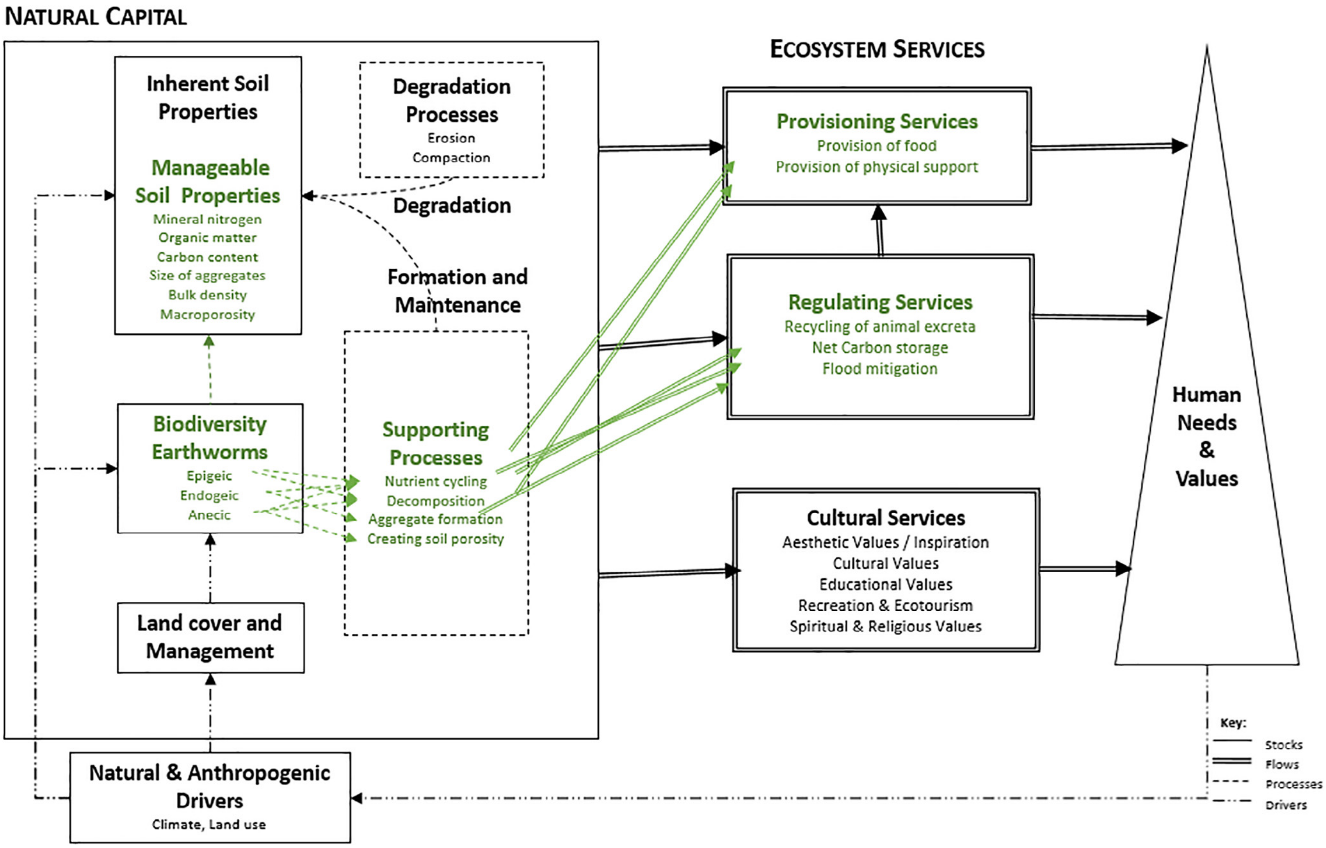

Fig. 1. Contribution of earthworms to soil properties, soil processes and ecosystem services.

assess the contribution of soil fauna such as earthworms to the provision of multiple ecosystem services can provide evidence to help with behaviour change towards soil conservation and soil biodiversity protection (MEA, 2005). In this study, we use the framework of Dominati et al. (2010) to quantify the relative contribution of earthworms to ecosystem service provision in managed grasslands. Changes in soil properties under different treatments measured in a controlled outdoor (mesocosm) study (Schon et al., 2014) were used to define proxies for each ecosystem service. The relative value of earthworms to ecosystem services was determined using monetary valuation methods following Dominati et al. (2014a) and Dominati et al. (2014b) where possible.

2. Methods

To determine the influence of earthworms on soil properties and their subsequent influence on ecosystem services under a pastoral use, we utilised the results from a ryegrass-based mesocosm study by Schon et al. (2014). Values from two earthworm treatments were used for these purposes, a ‘low abundance and functionally limited treatment’ which had predominately epigeic earthworms, and a ‘high earthworm abundance and functionally diverse treatment’ which had all earthworm functional groups present (epigeic, endogeic, anecic). Epigeic earthworms live and feed predominantly near the soil surface; endogeic earthworms burrow extensively through the topsoil; anecic earthworms form large vertical burrows which open up at the soil surface where they feed on organic matter (Paoletti, 1999).These treatments received a single application of cattle dung (5 t DM/ha), unless otherwise specified. A range of soil and pasture properties were assessed during a period of 444 days (Table 1). The mesocosms (30 cm diameter) were filled with an Ultisoil (USDA) and received equivalent to 20 kg P/ha/yr and 150 kg N/ha/yr. Data collected during the experiment are used here as proxies to quantify the ecosystem services provided by earthworms.

Table 1
Soil and pasture properties assessed during the mesocosm study (Schon et al., 2014) used as a proxy for the corresponding ecosystem service (adapted from Dominati et al. 2014).

Ecosystem service	Proxy to quantify the services	Low	Diverse
Provisioning			
Food Quantity	Pasture production (kg DM/ha)	26 400	29 200
Support for Animals[1]	Soil moisture (%)	54.2	45.6
Support for Infrastructures	Bulk density (Mg/m^3)	0.9	0.9
Regulating			
Flood mitigation	Total leachate volume (L/m^2)	505	533
Filtering of Nitrogen[1]	Nitrogen in leachate (kg N/ha/yr)	48	48
Recycling of excreta	Dung decomposed (% of DM)	79	96
C storage	Net change in C stock (kg C/ha)	3544	8500
Greenhouse gas regulation[1]	Measured N_2O emissions (kg N_2O/ha)	1.0	1.0

[1] Interpolated from treatments receiving multiple dung applications in the same mesocosm study.

Based on the outputs of the mesocosms, proxies for the provisioning service of food quantity and support for animals and the regulating services of flood mitigation, recycling of dung and C storage, filtering of nitrogen and greenhouse gas regulation were assessed in this study. Their relative value changes between the two scenarios were then determined using monetary valuation techniques using costs and benefits specific for each of the two land uses considered (Dominati et al., 2014a; Dominati et al., 2014b). Although there are a number of other ecosystem services, including food quality, methane (CH_4) oxidation, regulation of pest and disease populations, filtering of phosphorus, and filtering of contaminants, proxies for these services were not measured during the mesocosm study and so cannot be adequately addressed in this study. Cultural services such as spiritual values weren’t considered in this study either because their quantification and economic valuation requires very different techniques including surveying people's values and willingness to pay for the services (TEEB, 2010).

The contribution of earthworms to ecosystem services provision was determined using the relative differences between the two earthworm treatments, rather than considering the absolute values of services. Using this approach we are able to specifically isolate the contribution of earthworms to each service and determine where earthworms had the most impacts on agro-ecosystems. The abundance of earthworms in the low treatment was less than $300/m^2$, and was likely too low to contribute significantly to pasture production (van Groenigen et al., 2014) and potentially other ecosystem services. The abundance of earthworms under the high treatment was over $1000/m^2$ which is high for permanent grasslands, although earthworms are known to aggregate under dung pats (Martin and Charles, 1979; Curry, 1994).

Proxies were used in this study to determine the economic value of ecosystem services in the context of actual farm systems. It is important to note that the economic value attributed to the same ecosystem service will depend on land use, because land use specific costs are used to determine the economic value of a service. Hence, to estimate the contribution of earthworms to the provision of ecosystem services under specific pastoral systems, the data collected from the mesocosm study were placed in the context of two typical New Zealand farm systems. The farm systems included a dairy system where 225 ha were grazed by 3.3 milking cows/ha, producing 900 kg of milk solids (MS) per hectare per year (Dominati et al., 2014b), and a sheep system where 410 ha were grazed by sheep only, at a stocking rate of 10 SU/ha and 130% lambing percentage (Dominati et al., 2014a). On-farm management options which can be used to provide the same ecosystem service were utilised, and the cost of these management options was used to estimate the economic value of the services provided naturally by the soil/plant system. The management options considered would not necessarily be adopted on farm unless a specific service failed significantly. Valuation of each ecosystem service individually may result in some 'double counting' if the sum of their values are used and hence the value of each individual service is important (Dominati et al., 2014b). It was assumed that the quantification of ecosystem services provided by the mesocosms was applicable at paddock scale for both the two pastoral systems.

2.1. Provision of food quantity

In a grazed pasture the provision of food is essentially represented by pasture production converted to meat or milk. To quantify the amount of pasture grown, the contribution of soil natural capital stocks must be distinguished from added capital inputs. In the system studied here, the contribution of fertiliser (12 kgDM/kgN) (Gillingham et al., 2007) was subtracted from total pasture production measured on the mesocosms to calculate the contribution from the soil natural capital stocks, which is the service. For dairy systems, the pasture yield measured from the mesocosms minus fertiliser contributions (kg DM/ha/year) was converted to milk solids using a conversion factor (15 kg DM/kg MS, www.dairynz.co.nz) and then valued using the price of milk solids (Table 2). For sheep systems, the pasture yield measured from the mesocosms minus fertiliser contributions was converted to potential stock units carried, where a standard stock unit consumes 550 kg DM/year (Parker, 1998). The service was then valued using the revenue per stock unit (Table 2).

2.2. Provision of support for animals

Support for grazing animals is based on the resilience to treading pressure, which is influenced by soil moisture content. A proxy to measure the service was defined here as the number of days during the wet period (May to October), when soil water filled pore space was greater than 50% following Houlbrooke et al. (2009). The Agricultural Production Systems sIMulator (APSIM; v.7.7; www.apsim.info) was used to simulate water filled pore space (I. Vogeler unpublished) for the two mesocosms treatments. The provision of support to dairy animals was valued using the construction and maintenance costs of a standoff pad, with the price of a concrete pad being \$500/cow and a freestall barn costing up to \$3000/cow (Askin and Askin, 2012). These costs do not include supplementary feed. A proxy to measure the support for animals under sheep grazed systems was calculated using the differences in daily lamb survival rates (Stevens et al., 2015) when the soil water content was above 50% water filled pore space (Lambing July-October). Lamb mortality was greater when soil moisture was higher (D. R. Stevens pers. Comm.) and the cost of this was calculated using lost revenue per stock unit (Table 2).

2.3. Flood mitigation

This service refers to the ability of the soil to buffer excessive rainfall events, reduce flood risk and increase groundwater recharge, and reduce surface runoff (Brauman et al., 2007). The flood mitigation potential depends on how much water can move through the soil before runoff occurs. Runoff was not measured in our mesocosms and we assumed runoff was negligible on the flat surface, with both mesoscosms receiving the same amount of rainfall (1460 mm). Leachate quantity was used as a proxy for the amount of water that can move through the soil before flooding occurred. To value this service, if the soil–plant system was not buffering rainfall, another option at the farm scale would be to use a dam to retain excessive rainfall. Annualised construction costs of an on farm dam were used to value this service (Table 2).

2.4. Recycling of animal excreta (waste)

Soil fauna helps decompose and recycle the nutrients contained in animal excreta deposited on pasture. A proxy for this service was defined as the total amount of dung decomposed annually, which in the mesocosm study was the total amount of dung deposited, minus the residues still observed at the end of the study. An alternate solution to the dung recycling activity of soil biota in a dairy system is to use an effluent treatment pond to degrade excreta. The annualised set-up and maintenance costs of such infrastructure were used as a proxy for the value of the service (Table 2). In a sheep system an equivalent would be manually cleaning excreta out the races and woolshed, calculated on a weight basis.

2.5. Carbon (C) storage

Net C storage helps regulate climate. A proxy for this service is net C storage by the soil pasture system, not the C stocks themselves. A proxy was defined as the annual net C storage for the mesocosms (0–150 mm depth). To quantify the value of the difference in C storage between the two treatments the market value of C was used (Table 2).

2.6. Other ecosystems services

In the mesocosm study, the proxies measured for the ecosystem services provision of support for infrastructure, and the regulating services of filtering of nitrogen and greenhouse gas regulation (Table 1) were not different between the two treatments so it was assumed that the extra contribution of earthworms to these services was NZD \$0/ha/yr.

3. Results

Using the data collected in the mesocosms (Table 1) and a range of economic valuation methods (Table 2) we were able to quantify and value some of the ecosystem services provided in the two pastoral

Table 2
Costs used for the valuation of ecosystem services.

Ecosystem Service	Valuation used	Average (NZD $)	Low (NZD $)	High (NZD $)	Reference
Provisioning					
Food Quantity	Price of milk solids ($/kg MS)[1]	6.1	4.1	8.47	www.dairynz.co.nz
	Revenue per stock unit – wool and sheep ($/SU)[1]	85.4	54.6	126.1	www.beeflambnz.com
Support for Animals	Standoff pad ($/cow)	500	100	3000	Askin and Askin (2012)
	Standoff pad maintenance ($/cow/day)	0.5	0.01	2	Dominati (2011)
Regulating					
Flood mitigation	Dam construction cost ($/m^3)	10	5	15	Pangborn (2010)TRC (2006)
Recycling of excreta	Effluent treatment ($/m^3)	10	4	16	Askin and Askin (2012)Dominati (2011)
	Cleaning woolshed ($/t)	90	80	100	Pers. Comm Scotty's Contracting
Carbon storage	Carbon cost ($/t CO_2)	14[2]	2[2]	25[3]	Clarke et al. (2014)World Bank, 2014)

[1] Over 10 years.
[2] Carbon market cost over 5 years.
[3] Mitigation cost.

Table 3
The value of earthworms as listed for a number of provisioning and regulating ecosystem services. The proxies measured for the ecosystem services of support for infrastructures, greenhouse gas regulation and the filtering of nitrogen were not different between the two treatments, so the relative value difference between the two treatments is considered to be $0.

Ecosystem service	Measure	Relative value difference between the two treatments (NZD $/ha/yr)					
		Dairy Average	Low	High	Sheep Average	Low	High
Provisioning							
Food Quantity	Pasture production (kg DM/ha)	1001	612	1265	356	222	513
Support for Animals	Days above 50% water filled pore space	8	0	33	0	0	0
Regulating							
Flood mitigation	Effective rainfall L/m2)	329	164	493	329	164	493
Recycling of excreta	Dung decomposed (%)	293	117	469	28	25	31
C storage	Net change in C stock (kg C/ha)	43	6	78	43	6	78
Total value		*1674*	*900*	*2338*	*756*	*418*	*1115*

systems considered (Table 3). The economic valuation results presented here are the relative value differences between the two earthworm treatments, not the absolute value of each service in NZD $/ha/yr.

3.1. Provisioning services

A high earthworm abundance and diversity had the largest influence on the provision of food quantity through pasture production. More pasture was grown in the abundant and diverse earthworm treatment (10% more pasture), corresponding to an additional value of $222–1265/ha/yr for this service compared to the low earthworm treatment, with the average value for this being greater under dairy grazed pastures ($1001) compared to sheep grazed pastures ($356).

Earthworms had little influence on the provisioning service of support for animals. Although there was a large variation in soil moisture, this did not equate to perceivable differences in the number of days water filled pore space was above 50% during the critical periods, which would not result in a difference in grazing management. The value of this service ranged from an average of $0/ha/yr in the sheep system to $8/ha/yr in the dairy system.

3.2. Regulating services

Among the regulating services, earthworms had the largest impact on the recycling of excreta. The removal of dung from the soil was enhanced in the abundant and diverse earthworm treatment compared to the low treatment. Again there was large variation in the economic value of this service between dairy and sheep systems, ranging from an average of $28/ha/yr in the sheep system to $293/ha/yr in the dairy system as the costs used to value this services vary greatly between farm system types.

Earthworms also had an obvious benefit on C storage. Earthworms were able to increase net C storage within the soil during the study period. The added value associated with this service for the abundant and diverse earthworm treatment compared to the low was the same for both dairy and sheep systems ranging from $6 to $78/ha/yr.

The presence of earthworms increased drainage and thereby decreased flood risk. Increasing the amount of water that actually travels and is retained through the soil had the same middle range economic value of $329/ha for both dairy and sheep systems.

4. Discussion

4.1. Relative value of earthworms to ecosystem services

Earthworms modified soil properties in the mesocosm utilised (Schon et al., 2014) and therefore also influenced the provision of ecosystem services. The greatest contribution of earthworms to ecosystem services value came from the provision of food quantity, equating to 47% of the overall relative value contribution to a sheep system (NZD $222 to $513) and 60% of the overall relative value contribution to a dairy system (NZD $612 to $1265). The role of earthworms in the production of food quantity in pastoral systems has been extensively studied, with a meta-analysis attributing a 20–30% increase in grass production to earthworms (van Groenigen et al., 2014). The benefit of earthworms to pasture production is attributed largely to improved nutrient cycling, but other processes such as improvement in soil structure may also play a role (Baker et al., 1994; Francis and Fraser, 1998; Six et al., 2004; Amador et al., 2006; Fonte and Six, 2010). These same processes also underpin other provisioning and regulating services.

Earthworms also provided a valuable contribution for flood mitigation, or the ability of the soil to buffer rainfall events. The value of earthworms to flood mitigation was calculated to be NZD $164 to $493/ha/yr. Earthworms increase rates of water infiltration (Lee and Foster, 1991). While greater infiltration rates can increase water available for plant growth, this was reflected in increased leachate volume in the mesocosm study, as an artefact of greater preferential flow when the soils were dry (Schon et al., 2017). Smith (2012) also reported an improvement in macroporosity under an abundant earthworm community increasing water infiltration rates in the winter, with an increased risk of preferential flow during summer. The mesocosm study was conducted throughout the entire year so is likely to reflect the actual contribution of earthworms to this service, future studies need to ensure that they account for annual variations that may occur. While flood events may be a bigger issue during the winter, we did not examine how the value of this service changed during the wetter months, and it may be that in the future extreme climate events will mean that this service is equally important throughout the year.

In this study the provisioning service of support for animals made up less than NZD $33/ha/yr to the total services provided. The soil is better able to support animals when moisture content is lower, particularly important during the winter period when soils are wet and nearing their plastic limit (Hewitt and Shepherd, 1997). In the mesocosm study earthworms decreased soil moisture, Eisenhauer et al. (2012) also reported a reduction in soil moisture by earthworms. Despite these differences this did not equate to quantifiable differences in the provisioning service of animal support during the wetter months.

The service of recycling of excreta, a result of the decomposition process, was valued to be greater in dairy pastures compared to sheep pastures (average of NZD $117/ha/yr and $25/ha/yr respectively). It is well recognised that earthworms enhance the decomposition of dung pats (Holter, 1979). Although earthworms have shown differing preferences to dung types (Doube et al., 1997), we observed earthworm abundance to be similar between cattle and sheep dung for the species used in this study (unpublished). Despite their contribution to breaking down dung pats, the influence of earthworms on carbon storage is still debated in the literature (Blouin et al., 2013), and even differences in pasture management can fail to alter soil carbon stocks (Condron et al., 2012; Schipper et al., 2017). Schon et al. (2014) found carbon incorporated into the soil was dependent on the amount of carbon available for incorporation as well as the earthworm community, and reported a positive influence of earthworms on this service. There was evidence that earthworms increased C into smaller size fractions, potentially leading to an increase in the stability of C within the pasture system (Schon et al., 2019). However, the results here may be more likely to reflect what occurs underneath dung and the value of earthworms to this service would likely be diluted at the paddock scale with only 10–20% of the soil surface in grazed pastures is covered by dung. In this study we valued the contribution of earthworms to carbon storage to be NZD $6 to $78/ha/yr. New Zealand soils are also naturally high in carbon and once soils have reached their saturation limit (Beare et al., 2014) the role of earthworms to this service would be reduced.

There were other proxies that were not different between the two treatments and hence, the relative contribution of earthworms to the services of support for infrastructure, filtering of nitrogen and greenhouse gas regulation was assumed to be NZD $0. However, in the literature earthworms are shown to influence N_2O emissions (Rizhiya et al., 2007; Lubbers et al., 2011) as well as nitrogen in the leachate (Edwards et al., 1989; Domınguez et al., 2004). Therefore, it is expected that under different conditions the methodology applied here may show different values of earthworm contribution to these services.

Even though the cultural value placed on ecosystem services was not considered in this study, we recognise that earthworms also play a role in their provision. Globally many indigenous cultures recognise the value of earthworms (Cooper et al., 2012). In New Zealand endemic earthworms were a valuable food source for Maori, with some also used during burial ceremonies (Benham., 1904), they are still also used as a food source for the Amerindian peoples of South America (Paoletti et al., 2003). Earthworms have also been used in alternative medicines such as traditional Chinese medicines (Cooper et al., 2012). Importantly, cultural services provided by earthworms are still relevant today, including their use as a teaching tool for children to learn about decomposition, as well as for their presence in the soil being an indicator of wider soil health. Their market value for use as fishing bait is approximately USD $0.10–0.20 per earthworm (www.unclejimswormfarm.com). Future studies should quantify the cultural ecosystem services provided by earthworms as this value is likely to be significant.

The total added value of ecosystem services provided by abundant and functionally diverse earthworm communities ranged was on average NZD $1674/ha/yr for the dairy system and $756/ha/yr for the sheep system. This represents the relative value of earthworm communities to ecosystem services provision, rather than the absolute value of the ecosystem services provided by those farm systems which was nearly ten times greater for dairy, and nearly five times greater for sheep and beef (Dominati et al., 2014a; Dominati et al., 2014b). Although this is the total value for this service it may involve some ‘double counting’ and it will be more accurate to look at the value of each individual service (Dominati et al., 2014b). The ecosystem services provided by soil biota in managed ecosystems are often undervalued with a reliance on human inputs (Brussard, 1997). Considering the 2012–2013 operating profit was NZD $206/ha in sheep systems and $1830/ha in dairy systems (MPI, 2012; DairyBase, 2015), any compromise in the ability of the soil to provide ecosystem services naturally may well jeopardise these profit margins and suggest the importance of earthworms in the provision of ecosystem services in the farm system.

4.2. Limitations of the ecological valuation

The differences in valuation between the dairy and sheep systems are due to differences in the proxies and valuation methods used for each land use which can dramatically alter the final economic value. The proxies chosen for dairy and sheep systems were different for all ecosystem services, except that of C storage and flood mitigation. In some instances, such as in the provision of food quantity, which is relatively easy to define and measure, differences between the sheep and dairy grazed systems were exacerbated by the fact that dairy systems have been more profitable per hectare in recent years. Therefore, the contributions of earthworms to the value of this service reflects this. However, there are other instances where comparable proxies between the two systems are difficult to define. For example, the recycling of dung through effluent management is the well documented under dairy management, with no comparable method in sheep systems, where the cleaning of the woolshed is the next best alternative. Such differences show the importance of considering the conditions of use of the soil resource for a specific land use and management when trying to quantify and value ecosystem services, as the services that are beneficial as well as valuation techniques used (range of mitigations available) are land use specific.

Some services remain difficult to quantify economically. For example, although there was a big difference in soil moisture between the two earthworm treatments, and while this did reduce the number of days the soil water filled pore space exceeded 50%, this did not equate to quantifiable differences in the provisioning service of animal support during the wetter months. It may be that the proxies used in this study (e.g., standoff pad and lamb mortality) do not adequately represent the provisioning service for animal support. Dominati et al. (2014b) reported the value of this service to be NZD $112/ha/yr in a dairy system, and Dominati et al. (2014a) less than $33/ha/yr in a sheep system. This study uses data from a mesocosm study, hence the increased risk of treading damage by grazing animals during wet periods (Greenwood and McKenzie, 2001) could not be quantified here.

We recognise the differing role each of the earthworm functional groups offer soil processes and subsequent ecosystem services through their different burrowing and feeding behaviour (Paoletti, 1999; Lavelle et al., 2006; Keith and Robinson, 2012). Epigeic earthworms are associated with decomposition processes and the service of recycling animal excreta near the soil surface. Endogeic earthworms burrow extensively through the topsoil and are associated with the process of aggregate formation and soil structure as well as nutrient cycling and therefore many ecosystem services including provisioning services such as food quantity and physical support are linked to these earthworms. Anecic earthworms form large vertical burrows which open up at the soil surface where they feed on organic matter, they are associated with the processes of creation of soil porosity and decomposition, contributing to services such as flood mitigation, carbon storage and recycling of animal excreta. In this study we did not specifically identify the value each of the earthworm functional groups had to ecosystem services. Future studies should quantify this, but as an initial guide it is important to quantify the contribution of earthworms to ecosystem services under a wider range of landuses and environments.

5. Conclusion

This study highlights the value of earthworm contributions to provisioning and regulating services from two pastoral agro-ecosystems. Instead of restricting earthworms to a product with market value or assessing their contribution to separate ecosystem services, this study utilises the status of earthworms as ecosystem engineers, modifying soil properties and contributing to the provision of multiple ecosystem services to value their contribution to two agro-ecosystems. We provide a basis on which to conduct further studies, presenting values for multiple ecosystem services and highlighting that earthworms have the greatest contribution to the provision of food quantity (NZD $222 to 1265/ha) in the two pastoral systems presented here. We acknowledge that these values will depend greatly on the system considered as well as the point in time that ecosystem services are quantified and valued. It is also important to reiterate that the economic values presented here are the relative contribution provided by earthworms to ecosystem services values, rather than the actual values of ecosystem services provided by the systems considered here. We encourage further studies to bridge the gap between soil ecology, farm system analysis and economics in order to better inform the importance of soil biodiversity for a range of agro-ecosystems and their impacts on the environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank I. Vogeler for modelling using APSIM. We are grateful to funding received from NZAGRC and B + LNZ that has made this study possible.

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