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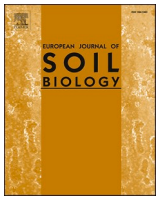

Original article

Testing the impacts of invasive jumping worms at their northern range limit

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ABSTRACT

Earthworms can act as ecosystem engineers by altering soil structure, which impacts other organisms and ecosystem functioning. Jumping worms (family Megascolecidae) originating in Asia have been spreading in North America, extending their northern range limits to Ontario, Canada in the last decade and to New Brunswick in 2021. At the northern limits of their current range, little research has been done to examine the effects of jumping worms in these new habitats since their recent establishment. Our objectives were to evaluate: (1) how jumping worms impact soil nitrogen and soil carbon; (2) how their presence impacts the abundance of non-native European earthworms (family Lumbricidae); and (3) whether two sampling methods (i.e., mustard solution and wooden discs) are equally effective at detecting jumping worms. We sampled a residential property in Oromocto, New Brunswick, which was the first location where jumping worms were found in the province. Jumping worms did not have significant impacts on the abundance and biomass of European earthworms or soil carbon content in the top 5 cm of the soil, but they did significantly affect soil nitrogen levels. Both sampling methods were equally effective at detecting the presence of jumping worms. Further research is needed in managed landscapes, urban areas, and forests to determine the ecosystem impacts and invasion dynamics of jumping worms in Canada as this invasion progresses.

1. Introduction

As the climate warms and human activities increase, many non-native species are expanding northward [1]. Non-native species that are ecosystem engineers and alter their new habitats by creating microenvironments can have especially large impacts [2]. In soil, non-native ecosystem engineers such as earthworms can change soil chemical and physical characteristics, influencing both aboveground and belowground organisms [3]. Thus, it is critical to understand and track these invasions at early stages, given the potential for cascading changes over time.

Native earthworms were almost entirely removed from soils in the northern United States and Canada during the last glaciation (i.e., the Wisconsin glaciation), nearly 12,000 years ago [4,5]. Therefore, most contemporary soils in this region developed in the absence of earthworms. However, the arrival of European settlers to North America, approximately 400 years ago, introduced non-native earthworms [4]. Since their introduction, European earthworms have spread across the continent, with their range expansion being facilitated by recreational and industrial human activities (e.g., fishing, vehicles, agriculture) [6,7]. These non-native earthworms have caused substantial impacts on forest ecosystems in North America, including shifts in soil chemical properties [8] and changes in plant and animal communities (e.g., Refs. [3,9,10]).

Recently, a "second wave" of earthworm invasions has begun in North America. This is due to the spread of pheretimoid or "jumping worms'' which are a group of earthworms within the family Megascolecidae originating from eastern and southeastern Asia (i.e., Japan, Korea, and China) [11]. Their common name "jumping worms" originates from the thrashing behaviour that they make [14]. These species are believed to have been introduced to the United States through horticultural practices that involve the transport of soils [12,13] and now appear to be concentrated around human establishments, with most reported sightings from urban parks, residential yards,

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greenhouses, and compost piles [14]. A total of sixteen species have now been identified in North America [15], of which *Amynthas agrestis* (Goto and Hatai, 1899), *Amynthas tokioensis* (Beddard, 1892), and *Metaphire hilgendorfi* (Michaelsen 1892) appear to be the most invasive in forested ecosystems [14]. In the United States, jumping worms have successfully established in 38 states ranging from the Northeast to Midwest [15]. In Canada, jumping worms were first found in 2014 near Windsor, Ontario [16], and five species have now been recorded across Ontario, Nova Scotia, and New Brunswick [17–19], although there has been little investigation of distributions thus far in Canada.

The effects of jumping worms at their current northern limit in Canada have not yet been examined, but research in the United States indicates jumping worms can have substantial impacts when they invade [14,20,21]. In general, their larger body sizes, faster reproduction, and wider dietary flexibility as compared to some European earthworm species can result in a competitive advantage over these lumbricids and in larger impacts on ecosystems [21]. Indeed, in Tennessee, USA, the presence of the European earthworm *Lumbricus rubellus* had no impact on jumping worms, but the presence of jumping worms negatively affected the ability of *L. rubellus* to consume leaf litter and soil microbes [22]. Jumping worm invasions in North American forest stands have been associated with decreased litter depth, increased soil pH, and changes in carbon (C) and nitrogen (N) availability [20]. Alterations to soil C depend on forest soil type and earthworm density. In sugar maple forests, soil C availability increased with earthworm density, whereas in oak forests, soil C availability decreased with increasing earthworm density [20]. Jumping worms have also been associated with increases in concentrations of both NH_4^+ and NO_3^- and may have greater impacts on soil nitrogen concentrations than lumbricids [21]. Soil N is a key limiting factor for plant growth in many ecosystems such as temperate forests [23–25].

Understanding the spread and distribution of invasive species is necessary to assess the magnitude of their impacts, but this requires large amounts of time intensive sampling and monitoring. Citizen science (when volunteers participate in scientific research; hereafter referred to as community science), can help increase both the spatial scale and sampling effort resulting in increased data acquisition [26,27]. Jumping worms are well suited for study via community science, due to their large body size, easy to identify traits, and thrashing behaviours [28]. Standard methods used for sampling earthworm populations, including hand sampling and liquid extraction with a non-toxic mustard solution [29], are relatively straightforward. However, the mustard solution does require preparation with large amounts of water and its effectiveness may be diminished after large precipitation events, when soil reaches water holding capacity. Thus, finding alternatives to this method could facilitate community science sampling of jumping worms. We propose the use of wooden discs to detect jumping worms because jumping worms migrate towards areas of greater moisture [30] and we have commonly found jumping worms near wooden surfaces. The wooden disc method is faster, requires less material than mustard extraction, and does not require any mixing or measuring of ingredients. The use of wooden discs to detect the presence of jumping worms is also a non-destructive sampling method, which is preferable when sampling urban or protected areas and can allow for repeated observations of jumping worms over time at the same location.

We examined impacts of jumping worms at a recently invaded residential site in Atlantic Canada, which is at the northern limit of their current North American range. Previous research has occurred at slightly lower latitudes and has generally focused on forests rather than residential areas (e.g., Refs. [20,21,31]) and we hope to determine if the effects of their invasions are similar across habitats. Therefore, our objectives were to assess: 1) whether jumping worms impact the biomass and abundance of European earthworms; 2) whether jumping worms impact soil C and N concentrations; and 3) whether the wooden disc method is as effective as mustard solution for detecting jumping worms. We hypothesized that higher abundance and biomass of jumping worms would be associated with lower abundance and biomass of European earthworms and changes in soil carbon and nitrogen content [20,21,32].

2. Material and methods

2.1. Study site

We conducted this study in a residential neighborhood in Oromocto (45.84°N; 66.48°W), New Brunswick, Canada (Fig. 1, inset map). The mean annual temperature for this region is 5.56 °C and mean annual precipitation is 1077.7 mm (for 1981–2010; Environment and Climate Change Canada [33]). Jumping worms were first discovered in the Maritimes in 2021 near a woodpile at the center of the study site [19], which spans three neighbouring properties (Fig. 1a). Jumping worm densities were much higher at the woodpile than other areas in the site, but it is not clear whether this was the original site of introduction as there has been considerable movement of material across the site. The site is mostly covered by a grassy lawn but has been subjected to various degrees of landscaping activities including gardening, altering ground cover, and introducing soils and plants from other locations. In particular, substantial amounts of soil were brought into the site in 2019–2021 and firewood had been brought in earlier from a commercial supplier [19]. This introduction of soils, vegetation and wood may have acted as a vector for jumping worms to the site. It is likely that the introduction occurred relatively recently as the homeowner spends substantial time working in the yard. However, given the high densities observed in 2021 [19], it seems reasonable to assume that the introduction occurred prior to that year.

Soils at the site are human altered (i.e., anthroposols) with a mosaic of textures and depths, and little organic matter [34]. However, anthropogenic soils are not yet recognized in the Canadian soil classification system and thus site soils can best be classified as podzols. Loam soils are found throughout the site ranging from sandy clay loam to clay loam textures. An exception to this is the northern part of the study site (Fig. 1), where poorly drained silt clay soils were present. Changes in vegetation cover were also noted in this northern area, with more moss than grass cover in some areas (see Supplementary Table 1).

Four transects were laid out using the woodpile, thought to be the initial introduction location, as the centre point (Fig. 1b). These transects ran at 90-degree angles from one another facing in the four cardinal directions. Each transect spanned the greatest distance possible given the size of the yards with the longest being the south-facing transect that spanned 120 m and the shortest being the east-facing transect that spanned 40 m. On each of the four transects, the first sampling point was located at the edge of the woodpile, and the remaining points were located every 10 m. The 10 m distance was selected due to the average yearly spread of earthworm populations being estimated at 5–10 m [35]. In June 2022, a wooden disc was placed at each sampling point ($n = 28$). The discs were made either from birch or spruce wood, with a diameter of 25 cm and height of 10 cm. The south-facing transect contained twelve discs, the east-facing transect contained four discs, the north-facing transect had seven discs and the west-facing transect had five discs. Once the discs were placed along the transects, they were not disturbed until the sampling period in August 2022.

2.2. Field sampling

Field sampling took place from 23 to 25 August 2022. At each sampling point, a single 50 cm × 50 cm quadrat was placed 30 cm to the right of the disc. A 2 cm diameter and 5 cm depth soil core was taken in each of the corners and center of the quadrat, resulting in five soil cores per quadrat. The five soil cores were homogenized and placed in a cooler to keep samples cold while in the field. Following this, the wooden disc was overturned, and all visible earthworms were collected from under the disc. Next, in the quadrat, we used a mustard extraction method (80

Fig. 1. The study site (A) and the woodpile (B). (A) The study site with sampling points (black dots) along the four transects. The yellow polygons represent the three neighbouring houses present at the study site and the brown polygon represents an area of significant disturbance resulting from land management practices. The inset map in the lower right corner delineates the provincial boundaries of New Brunswick. (B) The woodpile at the centre of the study site, where jumping worms were first discovered at the site.

g of mustard powder combined with 8 L of water). Half of this solution was poured in the quadrat and all emerging earthworms found within the quadrat boundaries were collected over a 10-min period. After this, the remaining 4 L of mustard solution was added to the quadrat and emerging earthworms were collected over a 20-min period. Two additional quadrats were added to the west-facing transect beyond the last wooden disc, as ongoing yard work taking place in the spring did not originally allow for discs to be placed in this area. All earthworms were preserved in 70% ethanol for later classification based on morphological characteristics and genetic analyses.

2.3. Soil analyses

Soil samples were air-dried for 96 h. Once dried, we sieved the soil samples through a 2 mm sieve. The concentrations of C and N in each sample were measured using an Elemental Analyzer Perkin Elmer CHN, 2400 Series II. As well, soil pH was measured in 0.01 M $CaCl_2$ using a pH meter (OrionStar A215). For this process, 10 g of soil was placed in a beaker alongside 20 mL of 0.01 M $CaCl_2$. The solution was mixed for 10 s and left to stand for 30 min while stirring occasionally. The samples then settled for a 1-h period after which the pH measurements were taken.

2.4. Earthworm identification and measurement

European earthworms were identified to the species level using taxonomic keys from Sherlock (2018). Earthworms belonging to the Megascolecidae family were identified to the family level using the key of Chang et al. [15]. We also extracted DNA from 14 jumping worms collected from the 14 quadrats where they were detected (one randomly selected individual per quadrat), using an E.Z.N.A Tissue DNA Kit from Omega Bio-tek. A ~660 bp fragment of the mitochondrial cytochrome *c* oxidase I gene was amplified using the universal primers LCO 1490 (5′-GGTCAACAAATCATAAAGATATTGG- 3′) and HCO2198 (5′-TAAACTTCAGGGTGACCAAAAAATCA-3′) [36]. We amplified this fragment using a PCR program of 4 min at 94 °C, followed by 35 cycles of 50 s at 94 °C, 30 s at 50 °C and 60 s at 72 °C, and a final step of 3 min at 72 °C. Products were PCR purified using a Thermo Scientific GeneJET PCR purification kit, quantified by measuring the absorbance at 260 nm with a Molecular Devices SpectraMax M3 Spectrophotometer and SpectraDrop™ Micro-Volume Microplate. Sanger sequencing was performed at the Centre for Applied Genomics in Toronto, Ontario. We measured body lengths and used allometric equations for Lumbricidae spp. and Megascolecidae spp. to calculate ash-free dry mass [37].

2.5. Statistical analysis

Statistical analyses were conducted with R 4.2.2 [38] using the 'lme4' package for generalized linear mixed-effect models [39] as well as 'lmerTEST' package for p-values and degrees of freedom [40] and the DHARMa package for model checking for every model [41]. Although pH values were collected with the intent of including the data as a covariate, they were excluded from models due to the complexity of the models and the small sample size given the random effect framework.

Four linear mixed effect models were created to determine the effects of jumping worms on European earthworm communities. Jumping worm abundance and biomass were used as the predictor variables to determine their effects on both European earthworm species' abundance and biomass. The response variables (abundance and biomass of

Fig. 1. (*continued*).

European earthworms) were square root transformed as the data was skewed. The quadrat's distance from center was included in models as a covariate, with transect direction (i.e., N, S, E, W) included as a random effect variable.

To determine the effects of jumping worms on soil properties, four linear mixed effects models were created using total C and N content as the response variables and jumping worm abundance and biomass as the predictor variables. Due to the potential for non-linearity, polynomial terms were added to the jumping worm abundance and biomass predictor variables. However, they were removed if the model was not significantly different from a model without the polynomial term (P-value > 0.05). For jumping worm biomass impacts on soil C, the natural logarithm of C was used, due to fitting issues following removal of the polynomial term. In the other three models, the response was not transformed. As before, quadrat distance from center was used as a covariate and transect direction was used as a random effect variable in all four models.

A generalized linear mixed effect model was used to compare the effectiveness of the wooden disc and mustard solution sampling methods. In this model, presence-absence of jumping worms was the response variable and sampling method was the predictor variable. The model also included the transect direction as a random effect variable and used a binomial error distribution.

All model outputs are included in Supplementary Materials 2.

3. Results

European earthworms were found at a total of 26 out of the 28 sampling points, and 18 sampling points were also occupied by jumping worms. Six European earthworm species were identified at the site, with *Dendrobaena octaedra* and *Lumbricus rubellus* being present in the highest abundance (Table 1). All of the jumping worms sequenced were identified as *Amynthas tokioensis* (GenBank accession nos. OR355660–OR355673). Mean total carbon across the site was 2.56% (ranging from 0.57% to 5.8%). Mean nitrogen across the site was 0.20% (range = 0.04%–0.37%). The mean soil pH across the site was 5.27 (S.E. = 0.712), with the highest pH values (of 7.24 and 7.27; Supplementary Table 2) recorded at quadrats where clay-rich soils were brought in by landowners.

3.1. Impacts on European earthworms

European earthworm abundance (Estimate = 0.04, S.E. = 0.04, t-value = 0.95, df = 22.93, P-value = 0.35) and biomass (Estimate = 0.002, S.E. = 0.01, t-value = 0.35, df = 23.09, P-value = 0.73) were not significantly affected by the abundance of jumping worms in our sampling sites. Similarly, European earthworm abundance (Estimate = 0.22, S.E. = 0.33, t-value = 0.65, df = 22.88, P-value = 0.52) and biomass (Estimate = 0.02, S.E. = 0.04, t-value = 0.43, df = 23.11 P-value = 0.67) were also not significantly affected by jumping worm biomass (Supplementary Table 3).

3.2. Impacts on soil C and N

The mean C content in quadrats with jumping worms was slightly lower (2.39%, S.E. = 1.26), than in quadrats without jumping worms (2.87%, S.E. = 0.77), but total C content was not significantly affected by jumping worm abundance (Estimate = −3.09, S.E. = 1.55, t-value = −2.0, df = 15.04, P-value = 0.06) or biomass (Estimate = −0.03, S.E. = 0.11, t-value = −0.24, df = 22.84, P-value = 0.81). In quadrats where jumping worms were present, mean N content was slightly lower (0.19%, S.E. = 0.09) than in quadrats without jumping worms (0.21%,

Table 1
Earthworm species present at the site, including their mean abundance and biomass in grams per m^2, standard error, maximum and minimum number of individuals per m^2 as well as the number of quadrats where they were present. We multiplied the abundance and biomass in each quadrat by 4 (as each quadrat was 0.25 m^2) to express them as values per m^2.

Species	Abundance per m^2				Biomass (g) per m^2				Percent of points where present (%)
	Min.	Max.	Mean	S.E.	Min.	Max.	Mean	S.E.	
Dendrobaena octaedra	0	52	7.59	12.44	0	0.48	0.08	0.03	57
Lumbricus rubellus	0	24	3.86	6.17	0	0.72	0.16	0.04	50
Aporrectodea rosea	0	4	0.14	0.73	0	0.08	1.72	2.27	3.6
Lumbricus terrestris	0	8	0.28	1.46	0	0.08	0.008	0.01	11
Octolasion tyrtaeum	0	24	1.10	4.57	0	0.016	0.004	0.1	7.1
Aporrectodea tuberculata	0	12	0.55	2.28	0	0.88	0.04	0.02	11
Megascolecidae spp.	0	164	16.55	32.17	0	40.8	7.52	4.24	50

S.E. = 0.04). As with C content, N content was not significantly affected by jumping worm biomass (Estimate = −0.18, S.E. = 0.10, t-value = −1.79, df = 9.79, *P*-value = 0.10). However, jumping worm abundance did have a significant effect on N content. The model revealed a positive non-linear relationship between total N and jumping worm abundance. This non-linear relationship showed an increase in the number of jumping worms is associated with an increase in N content (Fig. 2; Estimate = −0.23, S.E. = 0.10, t-value = −2.36, df = 15.24, *P*-value = 0.03). But, once a certain threshold is met, higher jumping worm abundance could lead to decreased soil N. However, this non-linear relationship was only driven by a single quadrat. This quadrat, closest to the woodpile, had the greatest jumping worm abundance and lower nitrogen concentrations compared to other sampled quadrats. When the single quadrat with high abundance was removed from the analysis, a near significant positive slope remained (dashed line Fig. 2; Estimate: 0.009, S.E = 0.005, df = 14.02, t-value = 2.05, *P*-value = 0.06) (Supplementary Table 4).

3.3. Sampling methods comparison

Combining results from the two sampling methods revealed that jumping worms were present at a total of 18 of the 28 sampling points (Fig. 3). Mustard solution had a detection rate of 78%, with jumping worms present at 14 quadrats of the 18 sampling points (Fig. 3). Wooden discs detected the presence of jumping worms at 13 discs of the 18 sampling points (Fig. 3), resulting in a detection rate of 72%. The jumping worm detection rate did not differ significantly between the two sampling methods (Estimate = −0.16, S.E. = 0.57, Z-value = −0.28, P = 0.78) (Supplementary Table 5).

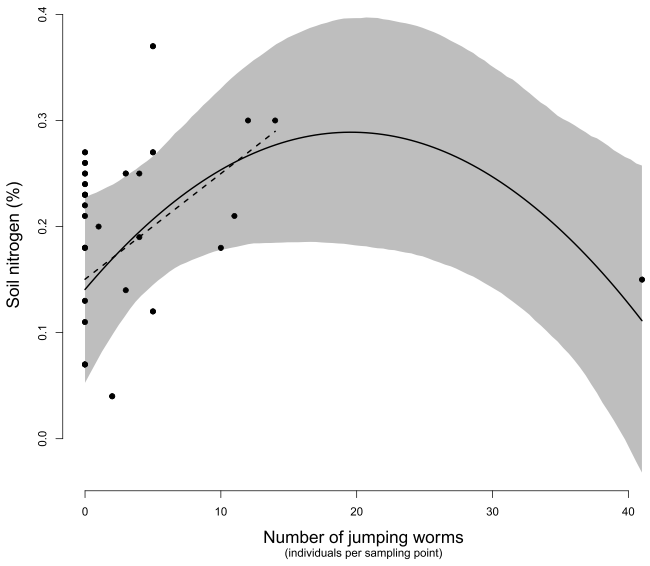

Fig. 2. Total soil nitrogen content in relation to jumping worm abundance. Each black point represents a quadrat (n = 28). The grey shading represents the 95% confidence interval of the black prediction line.

4. Discussion

4.1. Effects on European earthworm species

We hypothesized that greater abundance and biomass of jumping worms would lead to a decrease in the abundance and biomass of European earthworms, due to competition. However, jumping worm abundance and biomass had no significant effects on European earthworm abundance or biomass. Prior research indicates that the presence of jumping worms at a site can reduce European earthworms' consumption rates of leaf litter and soil microbes [22]. This limits available resources, ultimately impacting the abundance and biomass of European earthworm species [22]. Our study site varies from those examined in past research in that there was no tree cover, and thus an absence of leaf litter, which suggests that the earthworms present must use soil microbes and soil organic matter as their primary food sources. If this is the case, our work suggests that the effects of jumping worms on European earthworms may be reduced in populations that do not primarily consume leaf litter. It is also possible that jumping worm density at the site was too low to deplete food resources and thus outcompete European earthworm species. Jumping worm populations can reach densities greater than 200 individuals per m^2 [28], but density at our study site ranged from four to 160 jumping worms per m^2 (between 1 and 41 individuals in a quadrat). Research conducted in 2021 at our study site suggested that jumping worms had been introduced only recently [19], so it is also possible that the effects of this invasive species may only become apparent as their density and time since invasion increases.

4.2. Effects on soil properties

We found no significant effects of jumping worm abundance and biomass on soil C or jumping worm biomass on soil N; however, jumping worm abundance was positively related to N concentrations, such that an increase in jumping worm abundance was associated with an increase in N when jumping worms were present at lower to medium densities. In contrast, in the quadrat with the highest density of jumping worms, soil N concentration decreased. Thus, the relationship may be non-linear, but this non-linearity was driven by only one quadrat, and is discussed further below.

Prior studies found that jumping worms typically have significant impacts on soil C (but see Ref. [31]), but there is little consensus on whether they increase or decrease soil C [20,21,32]. Therefore, we hypothesized that jumping worms would have significant impacts on total C but did not have *a priori* predictions for the direction of change. However, we found no significant effect of jumping worms on soil C content, similar to a recent study in Wisconsin [31]. These contrasting results may be related to the fact that: (1) jumping worms were not present at our site in very high densities, and (2) the effects of jumping worms on C may be dependent on habitat type (e.g., grassland versus

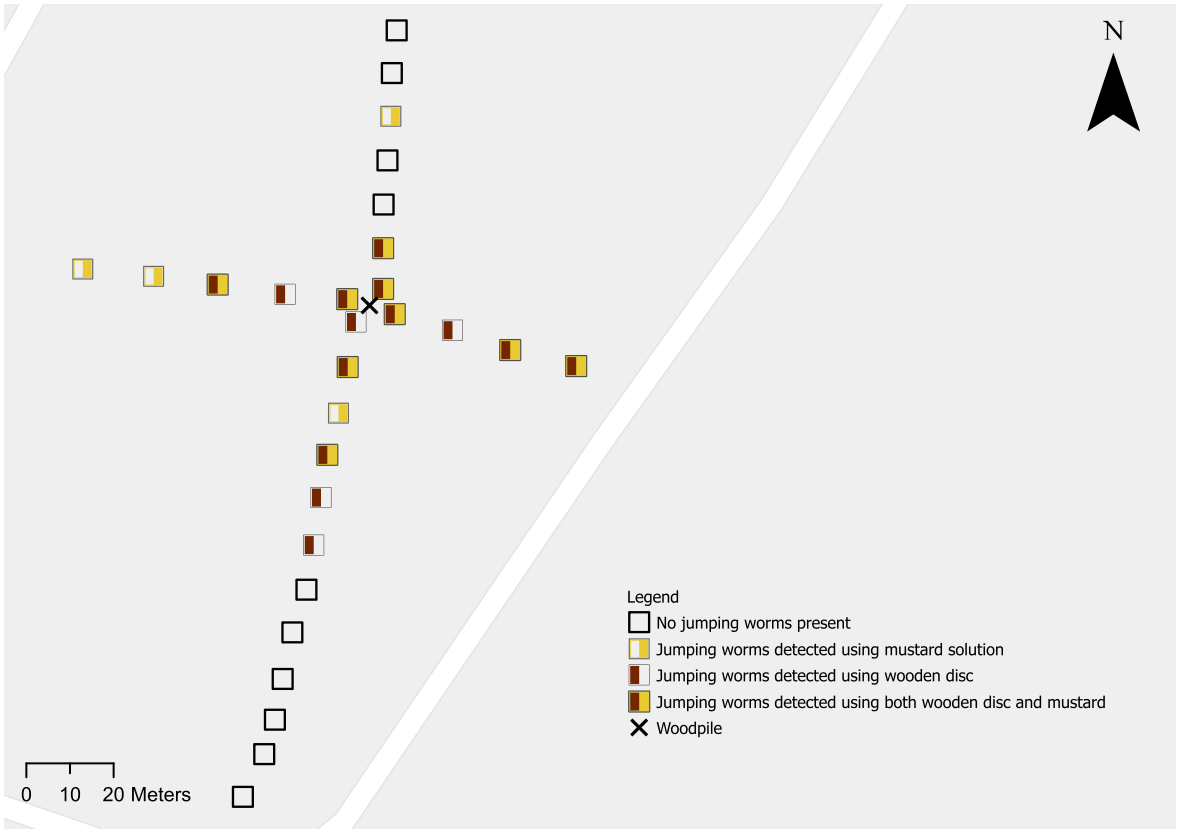

Fig. 3. The detection of jumping worms using two sampling methods (i.e., mustard solution, wooden disc). Sampling points are represented by square symbols. Fully white symbols indicate that no jumping worms were detected using either method. When the right-hand half of the symbol is mustard coloured, jumping worms were detected using mustard solution. When the left-hand half of the symbol is cherry-brown, jumping worms were detected using wooden discs. Fully coloured symbols indicate that both methods detected the presence of jumping worms at the sampling point.

forest). Jumping worm castings and burrowing activities are assumed to increase C mineralization rates, ultimately leading to greater C loss [14]. With greater jumping worm densities, there are greater amounts of earthworm castings and disturbance from burrowing activities, which is expected to result in greater effects on total C. As mentioned earlier, as this invasion is still in the early stages, the impact of soil C may become more apparent as population size grows. Studies suggest that the impact of jumping worms may be influenced by leaf litter quality and quantity, soil pH, soil moisture levels, soil bulk densities, and soil microbial activity [20,32]. Indeed, jumping worms appear to have lesser impacts in prairie ecosystems with less leaf litter, than in forest ecosystems with greater leaf litter [32]. The low quantities of leaf litter present at our site, as well as the urban setting may explain our finding that there was little impact of jumping worms on soil C content. This highlights the need to study invasive species in a variety of settings, including more human-dominated habitats, to determine if, and how, their effects vary.

In our study, an increase in jumping worm abundance was associated with a significant increase in total N content at lower to medium densities of jumping worms. This result is similar to previous research showing total N content was substantially increased in areas invaded by jumping worms [32], although other research has found no significant effect on N [20]. High levels of jumping worm castings have been associated with increases in soil nitrogen content at the soil surface, especially nearing the end of the growing season [42–44]. Earthworm casts contain elevated levels of mineral N, with casts' nitrification rates being dependent on the nitrogen content of the earthworms' food source [45]. Therefore, the positive correlation observed between soil nitrogen content and jumping worm abundance found in our study may be associated with increased amounts of casts as jumping worm abundance increases. However, in our study, the relationship between soil N content and jumping worm abundance appeared to be non-linear, with lower N content occurring in the quadrat with the highest jumping worm density, which was also closest to the central wood pile. It is unclear how robust this non-linear relationship is as it was driven by a single quadrat with a high jumping worm density, so further N measurements at higher densities are needed. It has been suggested that once N reaches high enough concentrations, vegetation may no longer readily uptake the additional N and thus accelerated N leaching may occur [46]. This may explain why higher densities of jumping worm abundance eventually led to a decrease in N content. The mechanisms driving shifting soil N dynamics are still poorly understood but may be dependent on worm density and forest type [20], similarly to soil C concentration [32]. These contrasting study results, as well as the lack of understanding of the mechanisms driving changes in soil properties, highlight the need for additional studies. In particular, long-term studies are required given our limited knowledge of how earthworm communities change over time in response to jumping worm invasions.

4.3. *Comparison of methods*

Previous studies have shown that the migration of jumping worms is often moisture dependent, as populations shift towards areas of greater moisture during times of drought [30]. Wooden discs may therefore create a favourable microhabitat for jumping worms. As we hypothesized, jumping worm detection rates were similar between the mustard extraction method and the easier to deploy wooden disc method. These

findings indicate that both methods can be considered when evaluating the presence of jumping worms.

This finding is particularly important for community science projects aiming to detect the presence of jumping worms, as the wooden disc method is simple, safe, and requires relatively low time investment. Through this active participation, individuals can learn more about the spread of invasive species, the scientific method, and help reduce costs of jumping worm distribution research. Considering the potential use of the wooden disk in community science, further research investigating if disk size, thickness, weight, and wood type impacts detection rates would be beneficial.

Land managers, homeowners, and community scientists are generally most concerned to know whether jumping worms are present rather than how abundant they are, and therefore we designed our study to test the effectiveness of wooden discs for determining presence-absence of jumping worm rather abundance. A larger study should be conducted to examine whether similar densities and biomasses of jumping worms are found when using discs versus mustard sampling.

4.4. Limitations

Differences between our findings and previously published results may be partially explained by limitations of our study. In particular, varying degrees of soil compaction across our site may have influenced both European earthworm and jumping worm abundance results. Indeed, at a couple of sampling points on the S-facing transect, elevated soil compaction reduced the infiltration of the mustard solution, resulting in greater runoff; no earthworms were detected at these points. Previous landscaping work importing clay-rich soils along the W-facing transect may have also impacted the results, as this soil was visibly different from those at other quadrats, and more compact. This compaction similarly inhibited the mustard solution's ability to effectively extract earthworms from the soil, potentially explaining the lower densities of earthworms found in these quadrats. The small sample size ($n = 28$) may have also limited the power of the study. However, this was the maximum sample size possible due to the presence of multiple disturbances at the study site (e.g., property boundaries, roads).

4.5. Conclusions

Our results suggest that jumping worms in Oromocto, New Brunswick have not significantly affected their ecosystem, with the exception of their effects on total N content. Results from prior studies suggest that low population densities characteristic of recent invasions as well as the urban setting (e.g., lack of leaf litter, soil compaction) of this study may be behind these limited impacts [20]. This highlights the need to continue studying these sites as the invasion continues. The data collected in this project can act as a baseline data to evaluate jumping worm spread rates, effects on European earthworms at new and old co-invasion sites, and effects on soil characteristics prior to and post jumping worm invasions in Atlantic Canada. Once the implications of jumping worm invasions on different types of Canadian ecosystems are better understood, improved management strategies may be developed to help mitigate potential damage. Although the invasion of jumping worms in New Brunswick was detected early in their invasion process, it will be vital to develop greater understanding of their impacts on these ecosystems and develop strategies limiting their spread into neighbouring environments.

CRediT authorship contribution statement

Samantha Bennett: Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Methodology. **Helen R.P. Phillips:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing, Visualization. **Anne C. Dalziel:** Methodology, Resources, Writing – review & editing. **Lawrence R. Manzer:** Conceptualization, Methodology, Resources, Writing – review & editing. **Erin K. Cameron:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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.

Data availability

Data is available in Appendix A Supplementary data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejsobi.2023.103590.

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