Ready, Set, Go: Community Science Field Campaign Reveals Habitat Preferences of Nonnative Asian Earthworms in an Urban Landscape

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Asian pheretimoid earthworms of the genera Amynthas and Metaphire (jumping worms) are leading a new wave of coinvasion into Northeastern and Midwestern states, with potential consequences for native organisms and ecosystem processes. However, little is known about their distribution, abundance, and habitat preferences in urban landscapes—areas that will likely influence their range expansion via human-driven spread. We led a participatory field campaign to assess jumping worm distribution and abundance in Madison, Wisconsin, in the United States. By compressing 250 person-hours of sampling effort into a single day, we quantified the presence and abundance of three jumping worm species across different land-cover types (forest, grassland, open space, and residential lawns and gardens), finding that urban green spaces differed in invasibility. We show that community science can be powerful for researching invasive species while engaging the public in conservation. This approach was particularly effective in the present study, where broad spatial sampling was required within a short temporal window.

Keywords: citizen science, invasive species, Amynthas, earthworms, urban ecosystems

Invasive earthworms are associated with biodiversity loss and profound effects on native organisms and ecosystem processes (Hendrix and Bohlen 2002, Hendrix et al. 2008). The effects of European earthworms (Lumbricidae) on plants, soils, litter, and nutrient dynamics of temperate forests in North America are well documented (e.g., Bohlen et al. 2004, Hale et al. 2005, 2006, McCay and Scull 2019). However, Asian pheretimoid earthworms (Megascolecidae) of the genera *Amynthas* and *Metaphire* are leading a new wave of coinvasion into New England and Midwestern US states (Chang et al. 2018). The ecological consequences of these species remain unclear, even as they spread northward toward southern Ontario, Canada (Moore et al. 2018). Collectively referred to as *jumping worms* for their characteristic rapid snake-like movement when touched, three key species—*Amynthas tokioensis* (Beddard, 1892), *Amynthas agrestis* (Goto and Hatai, 1899), and *Metaphire hilgendorfi* (Michaelsen, 1892; formerly reported as *Amynthas hilgendorfi*)—share life history traits and functional dynamics that differ from their European counterparts (Greiner et al. 2012, Chang et al. 2016a, Ziter and Turner 2019). Recent studies report jumping worm presence and activity in forests, but relatively little is known about their distribution, abundance, and habitat preferences in urban landscapes—areas that may influence range expansion given their likely spread via human activity.

The three species of jumping worm share several traits that enhance their invasiveness and may give them a competitive advantage over other soil organisms. *Amynthas agrestis, A. tokioensis,* and *M. hilgendorfi* have an annual life cycle—unlike most well-known European earthworm species in North America—and reproduce through parthenogenesis. Juveniles hatch from cocoons when soils warm in late spring then grow rapidly, with individuals reaching reproductive maturity between 77 and 93 days (Görres et al. 2016). Adults die at the end of the growing season but produce frost-hardy cocoons that ensure overwinter persistence of the population (Görres et al. 2016, Nouri-Aiin and Görres 2019) and allow populations to expand in northern climates. These cocoons are small and cryptic (figure 1), which facilitates inadvertent spread throughout the landscape in soils, mulch, horticultural plants, or on footwear (figure 1). These species are epiendogeic (i.e., they dwell in litter and surface soils) but are larger than many epigeic species of European origin (Greiner et al. 2010). Jumping worms are also dietary generalists, feeding on both leaf litter and soil (Zhang et al. 2010,

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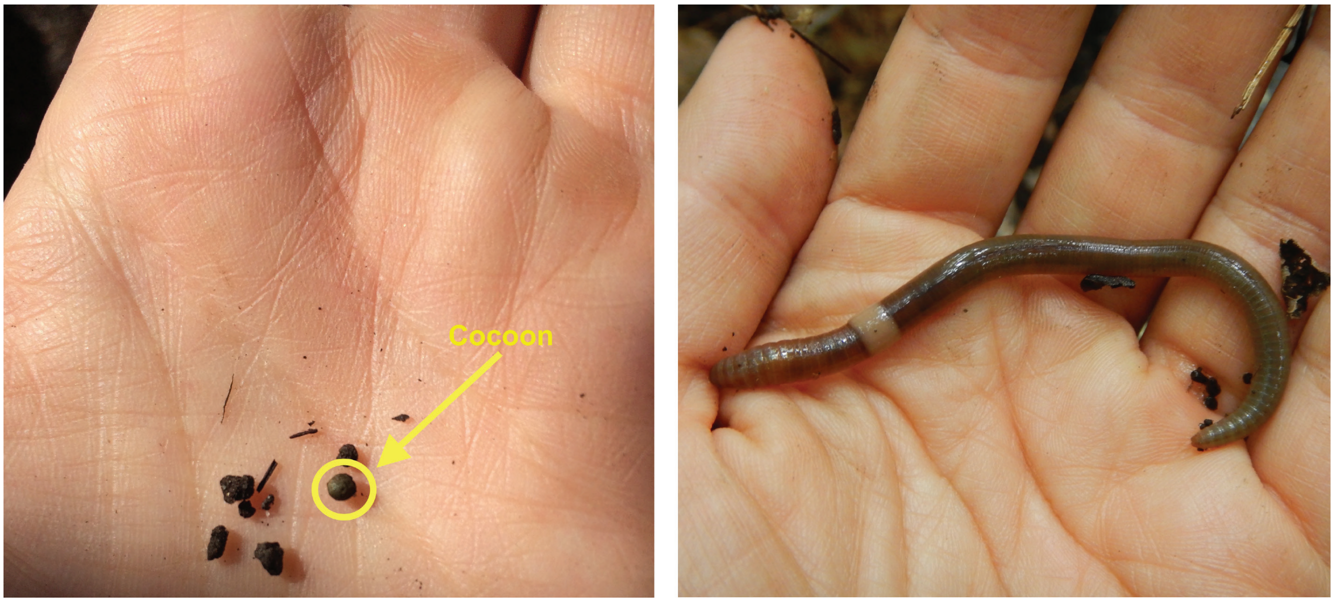

Figure 1. A. tokioensis cocoon surrounded by soil aggregates (left), and adult (right). Photographs: Carly Ziter

Snyder et al. 2013). The three species coexist, and the trio is considered an expanding multispecies assemblage (Chang et al. 2018).

Combined with the capacity to reach extremely high population densities (over 200 individuals per square meter [m^2]), their large body size and resource consumption rate compounds the effects of jumping worms on ecosystems. For example, jumping worms alter the litter layer and soil structure, affecting nutrient dynamics in forest ecosystems (Snyder et al. 2011, Greiner et al. 2012, Qiu and Turner 2016). Jumping worms can negatively affect other fauna such as native millipedes (Snyder et al. 2013) and salamanders (Ziemba et al. 2016) and may also displace European earthworms (Zhang et al. 2010, Chang et al. 2016b, Laushman et al. 2018)—although longer-term monitoring is needed to better understand these complex species interactions in field conditions. Consequences of jumping worm invasion on native vegetation are less well understood, but recent studies show the potential for altered forest ecosystem dynamics, including species-specific effects on the magnitude and direction of tree growth (Bethke and Midgley 2020). Negative effects have also been hypothesized—and anecdotally observed—in managed ecosystems (e.g., private and public lawns and gardens; Wisconsin Hardy Plant Society 2017).

City managers and residents actively seek information on the distribution and habitat preferences of jumping worms in urban landscapes to implement controls and prevent spread into adjacent areas. Cities offer diverse habitats within relatively close proximity, but the habitat preferences of the three jumping worm species are unknown. Their presence is often linked to horticultural settings (Görres et al. 2012); gardens can serve as reservoirs for earthworms harbored in soils or mulch, and landscaping activities can facilitate spread (Bellitürk et al. 2015). Although jumping worms may reasonably be anticipated to influence urban forest stands and other seminatural areas in similar ways as rural ecosystems, they may alter managed green spaces such as parks and residential gardens in unknown ways.

Changes to urban green space and biodiversity will have implications for the ecosystem services provided by urban ecosystems (Ziter 2016). Urban areas are also hotspots of nonnative and invasive species because of their higher levels of disturbance, greater resource diversity, and lower (interspecific) competition (Gaertner et al. 2017). Therefore, invasive species within cities can act as broader sentinels in invasion ecology, providing an early warning of what is to come in periurban, rural, and natural systems (Gaertner et al. 2017). Given the importance of urban areas as vectors of spread for many invasive species, understanding the distribution and habitat preferences of jumping worms within urban environments is critical to a broader understanding of their regional ecology and effects.

Jumping worms are well suited for study via community science because they are large, easy to identify when they are mature, and very abundant near the soil surface where they are present. Jumping worms also leave a characteristic granular signature on the soil surface (closely resembling coffee grounds) that is easily seen. Community science approaches (e.g., citizen science, participatory mapping; Cooper 2016) are increasingly powerful for mapping and monitoring changes in biodiversity, particularly for invasive species (Crall et al. 2015, Maistrello et al. 2016, Gallo and Waitt 2011). Field campaigns that harness the effort of many volunteers to cover a large spatial extent in a short timeframe can efficiently generate time-sensitive data. Although jumping worms have identifiable markers, they are easily sampled for only a few weeks late in the growing season when they reach peak size and abundance. Therefore, a rapid sampling event is needed to maximize detection and minimize potential for misidentification. Furthermore, detection of earthworms is sensitive to environmental conditions (e.g., rainfall, temperature), so it is critical to census these taxa within a short time period to minimize confounding factors that affect sampling. Interest from the public and a steady increase in queries from local residents (Hansmann and Thornton 2016) made the assessment of distribution and abundance of jumping worms an ideal opportunity for community science. Although earthworms in general are included in several ongoing community science initiatives throughout North America (e.g., via worm-specific platforms Great Lakes Worm Watch and Journey North or general platforms such as iNaturalist and EDDMapS), these larger initiatives are rarely designed to target specific species, or answer specific research questions. In the present article, we (academic scientists and conservation practitioners) collaborated with members of the community to coproduce knowledge both of local importance and broad scientific relevance.

Designing a community science study of invasive earthworms

We led a 1-day, participatory field campaign the afternoon of 10 September 2017 (from 1:00 to 5:00 p.m., with sampling occurring between 2:00 and 5:00 p.m.) to assess the distribution and abundance of jumping worms in Madison, Wisconsin, in the United States. This field campaign was a modified expert bioblitz (Parker et al. 2018), in which a traditional bioblitz approach (i.e., a rapid field survey in which volunteers document all species they observe) was combined with an expert study design and laboratory identification of specimens to ensure that collected data met scientific standards. Because the field campaign occurred during the early phase of an ongoing species invasion, we designed a study that could be repeated in subsequent years. This inaugural field campaign targeted three questions: What is the current distribution of jumping worms (*Amynthas* spp. and *Metaphire* spp.) in the Madison metropolitan area? Do the presence and abundance of jumping worms vary among urban land-cover classes? And how does the presence of jumping worm species relate to the presence of other (nonpheretimoid) earthworm species?

We expected to find an increased presence and abundance of jumping worms in habitats containing abundant leaf litter, disturbed soil, or mulch; similarly, we expected greater abundance of jumping worms in areas characterized by frequent human activity (e.g., forests with recreational trails, residential gardens). Furthermore, we anticipated that the areas inhabited by jumping worms would have reduced abundance of European earthworms.

We sampled 123 sites stratified by land-cover class: forest (*n* = 16), grassland (primarily restored prairie, or unmowed meadows; *n* = 16), open space (primarily city parks, *n* = 14), and both lawn and garden habitat within residential parcels (*n* = 38 lawn, 39 garden; one residential location sampled contained only garden with no lawn, accounting for the discrepancy in lawn and garden sites in residential areas; figure 2). Sampling sites included public and private land, and coincided with a previous urban ecology study where possible (see Ziter and Turner 2018) to leverage existing landowner connections and site-specific knowledge. The initial list of sites was supplemented with additional residential properties volunteered by community members, with substantially more sites volunteered than could be accommodated during fieldwork. We purposefully sampled residential parcels at a greater frequency than other land covers because of the large proportion of Madison's green space composed of residential land (approximately 50%; with the remainder composed primarily of forest, grassland, and open space) and because of the anticipated fine-scale differences in residential environments (Ziter and Turner 2018). We did not ask whether homeowners suspected earthworm presence nor did we consider this in our site selection, so as not to bias our results. The sites spanned an area of approximately 200 square kilometer, and sites within each land-cover class were distributed throughout the city of Madison to avoid geographic bias. We obtained landowner permission or appropriate permits to access all sites prior to the event.

Implementing the field campaign

Our field campaign was a combination of a traditional bioblitz and an expert bioblitz (Parker et al. 2018). In the week prior to the sampling day, a dozen individuals who would serve as team leaders were briefed on the sampling protocol and jumping worm identification. These individuals include the authors, academic scientists, and experienced local conservation practitioners. Community participants were recruited via an email invitation sent to the Arboretum volunteer mailing list several weeks prior to the sampling day, outlining the aims of the study and the general field campaign plans. Given that this was the first event of this type, we limited the participant list to existing volunteers familiar with the goals and efforts of the Arboretum to decrease logistical overhead and maintain a reasonable group size. On sampling day, all 40 participants gathered for a short presentation on the incipient jumping worm invasion and study goals, followed by a brief outdoor training session on earthworm collection and identification (figure 3). Importantly, all participants had an opportunity to see and handle jumping worms. We then split the group into preassigned teams of three to four participants, each with one team leader. Each team was provided with a packet including information on their designated sites (maps, directions, and any relevant site notes), a step-by-step instruction sheet outlining a standard protocol, an identification key, and blank data sheets. The participants were free to withdraw their participation at any point, including during the field campaign.

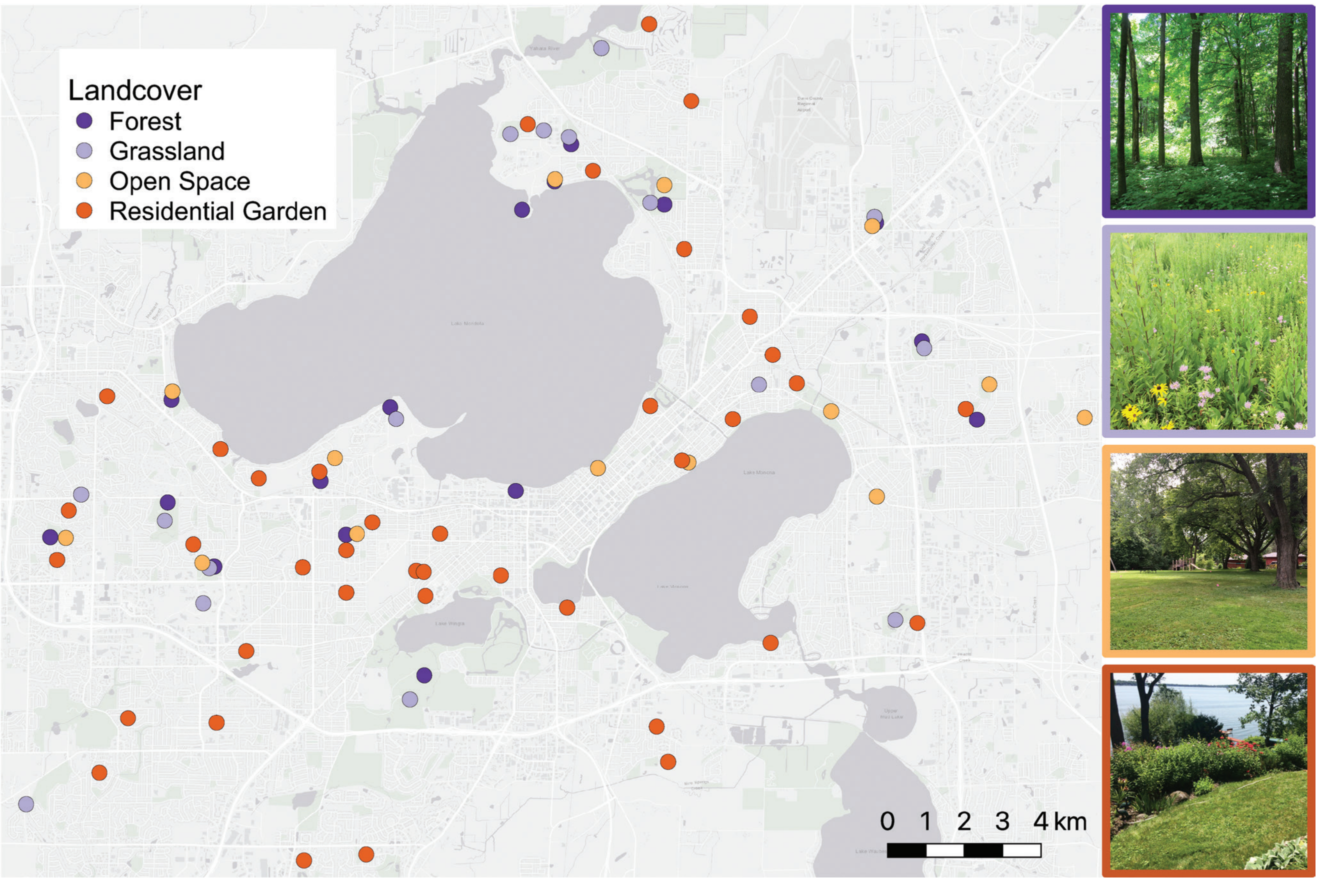

Figure 2. Jumping worm sampling locations throughout the greater Madison area, Wisconsin. Color represents land-cover class. Residential sites include both garden and adjacent lawn habitats.

Figure 3. Community members participate in training at the UW–Madison Arboretum (left), followed by a 1-day field campaign to determine jumping worm presence and abundance in different urban land-cover classes (right).

At each site, teams visually surveyed the area for signs of jumping worm presence, including live organisms or the characteristic granular soil signature indicative of their activity. For example, in a residential yard, participants would walk through the space for approximately 10 minutes, brushing aside leaf litter and checking underneath planters or landscaping cloth (where the species are anecdotally known to congregate) for live earthworms, and examining garden soil for structural characteristics. Next, earthworms were surveyed at three haphazard locations using a 30 cm × 30 cm quadrat and a standard mustard extraction (Lawrence and Bowers 2002). This simple, fast, and nondestructive procedure involves pouring a mixture of mustard powder and water over a designated area of soil (figure 3). The mustard mixture irritates the earthworms' skin, and they come to the surface, where they can be identified and counted. The cost, ease, and safety of use makes this method particularly appropriate for a community science campaign, particularly for invasive pheretimoid earthworms that live close to the surface (McCay et al. 2020). The participants recorded the presence or absence and abundance of jumping worms within each quadrat and photographed each mustard-pour location. Any suspected jumping worms found were collected and returned to the laboratory for visual identification following the field campaign. We identified jumping worms to species (*A. tokioensis*, *A. agrestis*, *M. hilgendorfi*) when possible (Chang et al. 2016a). The participants also recorded the presence or absence of any additional (nonpheretimoid) earthworm species observed during sampling. Our community science campaign resulted in approximately 250 person-hours of sampling effort.

Analyzing the data: Jumping worm distribution and abundance

To determine the current distribution of jumping worm species across the city of Madison, we mapped their presence and abundance at each sampling site using open source GIS software (QGIS).

To evaluate whether the presence and abundance of jumping worms varied with land cover, we used a generalized linear mixed model approach (using the “glmer” function, in R package “lme4” version 1.1.12). First, we tested for differences in jumping worm presence among land-cover classes. Jumping worms were scored as present at a site if at least one individual was found during the initial site search or in any of the three mustard extractions. Land cover was specified as a fixed effect, and residential parcel was included as a random effect to account for the fact that lawn and garden sites were nested within the same residential parcels. Next, we tested for differences in jumping worm abundance among land-cover classes, considering all sites at which they were present. We excluded sites at which jumping worms were absent because this is an incipient invasion, and we wanted to ensure that the earthworms had been able to reach and establish in the area in question. Land cover was again specified as a fixed effect, and we included a random effect for residential parcel to account for lawn and garden sites that were nested within the same residential parcels. We also included a random effect for site to account for the fact that three samples were collected in each site to assess abundance. Models were fit using maximum likelihood. We analyzed earthworm presence using a binomial distribution, and count data (earthworm abundance) using a Poisson distribution. We excluded grassland sites from our model, because jumping worms were absent from all grassland sites that we sampled.

To determine whether the presence of jumping worms was associated with presence of other earthworm species, we used Fisher's exact test. In the present article, earthworms (for either species group) were scored as present within a given site if at least one individual was found in any of the three mustard extractions, and absent otherwise. First, we tested for an association between the presence or absence of jumping worms and the presence or absence of other earthworm species across all sites combined. Next, we tested for the same relationship across sites within each land-cover class separately.

All analyses were performed using R statistical software (R Development Core Team 2017). We used a statistical significance level of $\alpha = .05$ in all analyses.

Variation in jumping worm presence and abundance across green space types

A total of 263 individual jumping worms were counted in the field, belonging to three different species. Of these, 94% (247 worms) were recovered for expert identification in the laboratory. Although only 103 of the 247 recovered jumping worm individuals were confidently identified to species on the basis of external characteristics described in Chang and colleagues (2016a), all were confirmed of the family Megascolecidae and were therefore of Asian origin. Of these 103 jumping worms, 35% were *A. tokioensis,* 55% were *A. agrestis*, and 10% were *M. hilgendorfi*. The 10 *M. hilgendorfi* individuals identified in our study represent the first recorded finding of *M. hilgendorfi* in the state of Wisconsin. Co-occurrence of multiple species was common, with nine sites confirmed as containing both *A. tokioensis* and *A. agrestis*, and one site confirmed as containing all three species.

There were hotspots for both presence and abundance throughout the city, with both presence and abundance high near the initial detection site (figure 4). Jumping worms were present in all types of green spaces with the exception of grasslands. Within the remaining four categories, jumping worms were more frequently observed in forests and residential gardens compared with turfgrass dominated areas (open space and residential lawns; figure 4). The worms' presence in residential lawns was lower than in other land-cover classes (p = .014), with jumping worms largely restricted to lawns adjacent to invaded garden habitats (figure 4). Only a single residential site contained jumping worms in a lawn but not the adjacent garden (compared with 11 sites

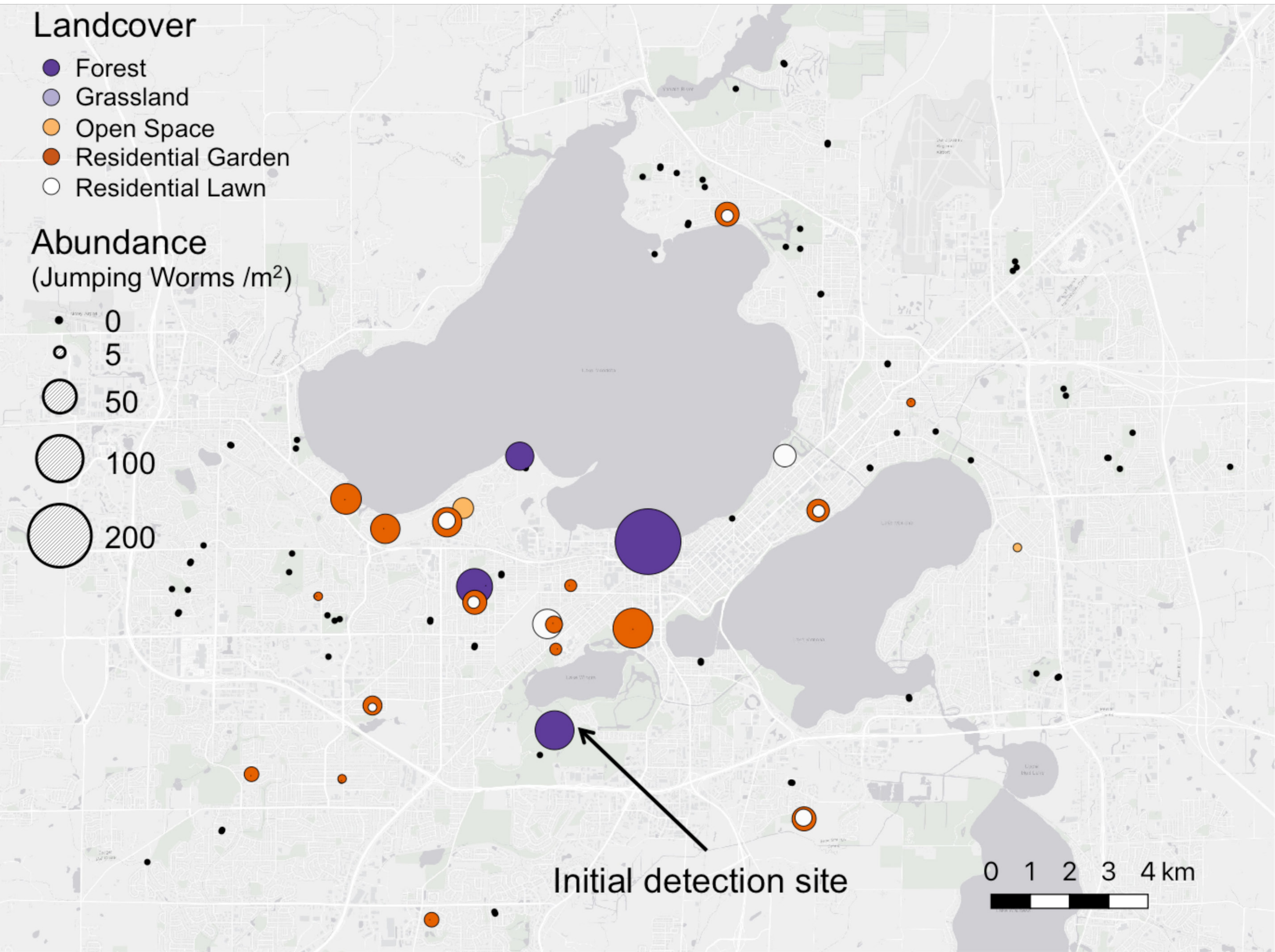

Figure 4. Jumping worm presence and abundance throughout the greater Madison area, Wisconsin, per the community campaign. Small black circles indicate absence of jumping worms; colored circles indicate presence of jumping worms, by land-cover class; circle size indicates earthworm abundance (individuals per m^2). The area of the initial detection site (where Amynthas were first identified in Madison in 2013) is indicated with an arrow.

at which they were found in gardens but not the adjacent lawn). Where they were present, jumping worms occurred at higher densities in forested sites (a mean of 102 individuals per m^2; $p < .0001$) and residential gardens (a mean of 24 individuals per m^2; $p = .0016$; figure 5). At their highest density and in a forested site, jumping worms reached over 220 individuals per m^2 (figures 3, 4). Residential properties that were volunteered by homeowners for the study were similarly likely to contain jumping worms as properties chosen on the basis of past unrelated work (14 of 28 volunteered properties contained jumping worms in either lawn, garden, or both, versus five of 12 past properties). We therefore conclude that methods of site selection were unlikely to introduce significant bias.

Earthworms of European origin (Bajcz et al. 2018) were found in all land-cover classes, including grassland (where jumping worms were absent; figure 6). Except for residential gardens, European earthworms were present in a greater percentage of sites than jumping worms. European earthworms occurred in 38% of forest, 44% of grassland, 71% of open space, and 26% of residential lawn sites, compared with jumping worms present in 25%, 0%, 14%, and 21% of sites, respectively. In residential gardens, European earthworms were present in 39% of sites, compared with jumping worms in 44% (figure 6). Where jumping worms were present, they were most likely found alone rather than co-occurring with other earthworm species; Fisher's exact test confirmed a negative association among the two species groups ($p = .034$), which was most pronounced in garden sites ($p = .024$; figure 6).

Community science yields new ecological insights

This initiative was the first community-wide field campaign to assess jumping worms in the urban environment and

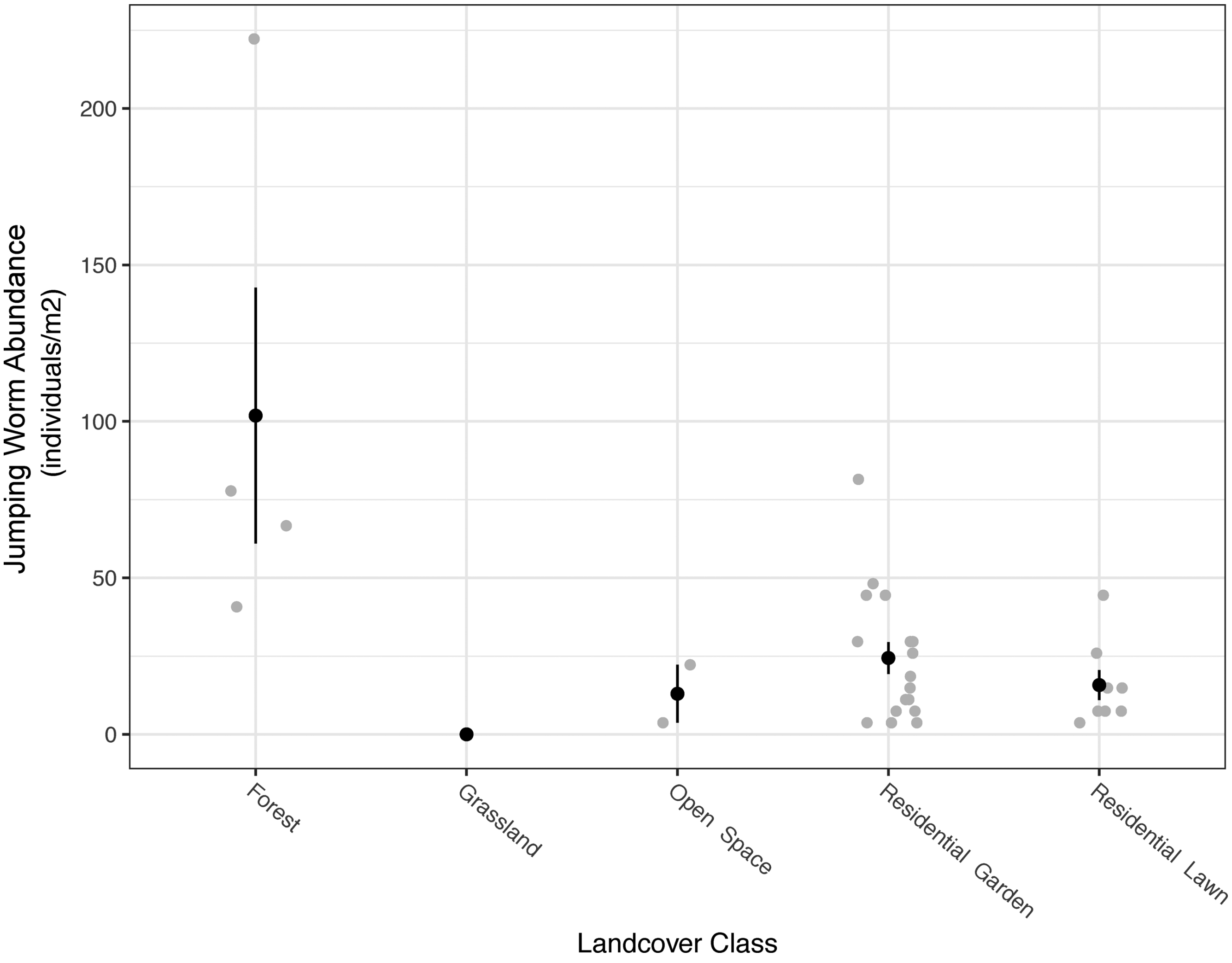

Figure 5. Variation in jumping worm abundance (where they are present) among land-cover classes (forest, grassland, open space, residential gardens, and residential lawns), in Madison, Wisconsin. Black points represent mean jumping worm abundance by land-cover class. Bars represent standard errors. Grey points represent mean jumping worm abundance at each of the sites (of* n *= 3 mustard pours) sampled per land-cover class.

yield insight into their distribution, habitat preferences, and ecology. The collective effort of team leaders and volunteers made it feasible to collect timely data on jumping worm presence and abundance during the early phases of invasion. A single day of sampling revealed that jumping worm abundance varied with land cover and that green spaces differ in their vulnerability to invasion. As hypothesized, jumping worms were found more frequently at sites with more leaf litter or mulch, including deciduous forests and residential gardens and were found less frequently in grassy sites, including turfgrass and restored prairies or meadows. Our study also corroborates frequent co-occurrence of these three species of jumping worm and suggests that they may exclude other earthworm taxa in some habitats. However, as with any single-day study, our results should be interpreted with caution. Relatively dry soil conditions on the sampling day may have led to an underestimation of earthworm abundances using our extraction technique (especially for deeper dwelling endogeic and anecic species), and future studies with increased sampling effort are needed to corroborate our findings; this is particularly important regarding species co-occurrence or displacement of European earthworms, which was a tertiary goal of this work rather than primary.

Consistent with other invaders, the distribution of jumping worms in the urban landscape is likely driven by a variety of abiotic, biotic, and historic variables related to both suitability of the environment and propagule pressure. As with other epigeic soil organisms, human management and transport are also suspected to play a large role in urban jumping worm spread (Cameron et al. 2007). Jumping worms are typically found in locations where some potential point of introduction can be identified. In the present article,

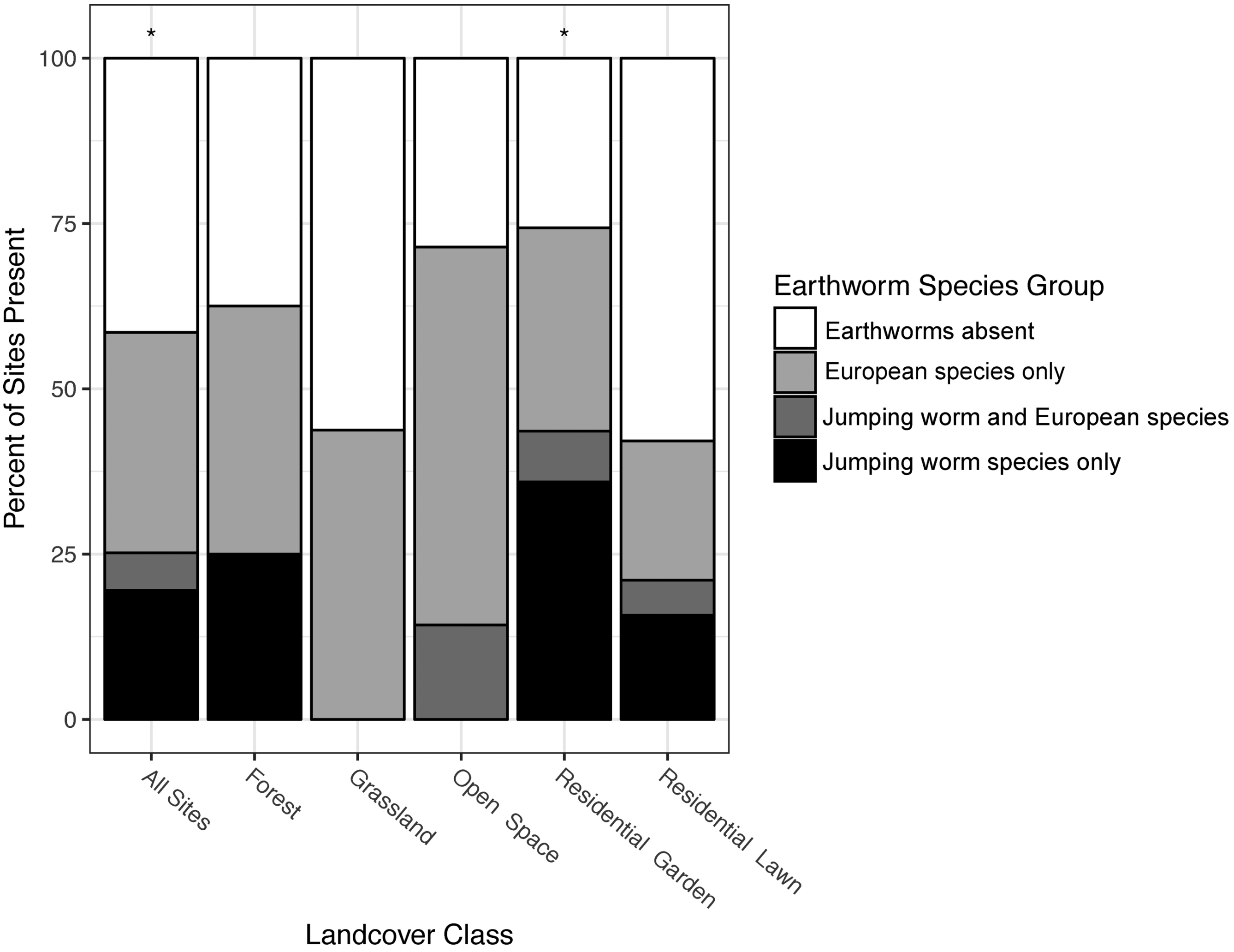

Figure 6. Co-occurrence of jumping worm species and European earthworm species within the same sampling site, averaged across all sites (far left bar), and within each land-cover class (forest, grassland, open space, residential garden, and residential lawn). Asterisks indicate a negative association among the two species groups within a land-cover class (Fisher's exact test,* p *< .05).

we observed increased presence and abundance of jumping worms in close proximity to the University of Wisconsin–Madison Arboretum (figure 4), which recorded the first sighting of *Amynthas* spp. in Wisconsin in 2013. Other areas in Madison with a high abundance of jumping worms included neighborhoods with active gardening communities, as well as areas of campus frequented often for outdoor recreation. Despite the presence of suitable habitat, jumping worms were sparsely distributed across the eastern half of the city (far from the suspected invasion site) and, if found, always of low abundance (figure 4). This localized and patchy pattern is consistent with studies of early invasions of plants (Albright et al. 2009) that show a strong spatial legacy of introduction. Replication of this initial field campaign will allow the rate and pattern of local spread to be tracked.

The proximity of preferred and less-preferred habitats may help explain jumping worm distributions within an urban landscape. We expected jumping worms to occur in sites with abundant leaf litter, disturbed soil, and mulch, but their presence in turfgrass-dominated areas (open spaces, residential lawns; figure 4) was surprising. We hypothesize that turfgrass occurrences may represent spillover from more preferable habitats (Rand et al. 2006; e.g., nearby landscaping, mulched beds, or forest patches), supported by the prevalence of jumping worms in residential lawns that were adjacent to invaded gardens (figure 4). Whether the dietary breadth of these species (Zhang et al. 2010) will allow jumping worms to persist in turfgrass systems remains to be seen. However, jumping worms were absent in grassland sites dominated by native prairies species, despite close proximity to other invaded sites (figure 4). The lack of jumping worms in grassland habitats may be the result of a more challenging soil environment (e.g., dense roots) or the less labile tissues of prairie plants

Box 1. Lessons learned from an event-based community science campaign.

We present five key lessons learned through the process of conducting an event-based community science campaign—ordered approximately chronologically from event preparation to follow-through. These insights draw from both strengths and weaknesses of the current work, and we hope will help inform future efforts.

Start early, and plan for reproducibility. Community science is often framed as a way to gather a large data set quickly. Although the event itself can achieve the goal of high sampling effort in a short temporal window, it is important not to underestimate the total preparation involved in a successful community science effort. Planning a successful event demands a nontrivial time commitment. In addition to developing an ecological study design, consider the time needed to develop handouts and materials, order and organize equipment, and conduct volunteer recruitment, registration, and training; and this is assuming the research team has already built relationships of trust with the local community. This high up-front time commitment is a strong incentive to plan for reproducibility from the outset; in many cases, a key scientific benefit of planning a well-organized community science campaign is the development of a strong protocol that can be repeated in time or space.

Think broadly regarding event logistics. To share a personal anecdote, after considering the biology of our study organism, the schedules of organizers, and the time constraints of participants, we planned a seemingly appropriate time for our event. However, we neglected to cross-reference our date with other area events, and inadvertently scheduled on the day of the local Ironman race. The associated road closures added additional—and avoidable—challenges. This was a reminder to pay close attention not only to within-event logistics (e.g., team makeup, sampling locations, site-level protocols), but also to consider the broader context in which an event will occur (and to plan for the unexpected!).

Acknowledge the participants' strengths while considering their limitations. Our project would never have happened without the curiosity, observation, and excellent questions of community members that precipitated this work. Community participants are valuable collaborators, and should be treated accordingly. However, even participants with extensive natural history knowledge and experience may lack fieldwork-specific knowledge we take for granted as trained ecologists (e.g., following a scientific protocol, correct sample labeling, thorough note taking). It is critical to allocate adequate time and resources to training participants prior to data collection. Although our day-of training was largely effective, in future campaigns we would consider distributing a best practices guide, or perhaps a short training video, in advance to further reinforce new skills.

Team up for effective knowledge transfer. A key aspect of our project success was pairing experienced field samplers with community participants. This team-based strategy ensured consistency in data collection and quality control, which was the major impetus behind this design. However, we also observed increased knowledge transfer between community participants and professional scientists throughout the event. This increased interaction encouraged by the small group, field-based setting led to both a deeper understanding of project goal by participants, and a stronger understanding of participant concerns by scientists, strengthening our work.

Evaluate your efforts. In the present study, we limited our focus to ecological goals. However, in retrospect, collection of social science data (e.g., to assess what participants learned, whether attitudes toward invasive species changed) would have added considerable value to our work. To better assess whether, and how, community science approaches influence participant knowledge, behavior, and management, we suggest an interdisciplinary approach in which participant feedback is assessed alongside ecological outcomes. Although this may seem beyond the scope (or disciplinary expertise) of projects rooted in ecology or conservation biology, it is an excellent opportunity to collaborate with social scientist colleagues to achieve greater impact.

(Bajcz et al. 2018). Jumping worms do inhabit grasslands within their native range in Japan (Masamichi et al. 2011, Ishizuka and Minagoshi 2014), however, so plant community composition may be a key driver of habitat preference. Continued monitoring of restored grasslands near invaded sites is needed to determine whether these plant communities will remain uninvaded.

The frequent presence of jumping worms across a range of human-dominated areas implies a strong likelihood of human-assisted movement and emphasizes the difficulty of invasive species control in management mosaics governed by many land managers (Epanchin-Niell et al. 2010). Given the overlap between hotspots of human activity and earthworm density (e.g., residential gardens, frequently visited urban forests; figures 4 and 5), conservation and education efforts should emphasize best practices for landscaping and gardening, as well as forest-based recreation and management. We advocate adoption of current best management practices as outlined by the Wisconsin Department of Natural Resources: learn identification; reduce transfer of any materials that may serve as vectors of spread; and clean tools, vehicles, and personal gear (Wisconsin DNR 2015).

The knowledge transfer and engagement inherent to community science activities also enhances public understanding of science (Bonney et al. 2016). This study likely aided invasive species management by involving community members and training them to recognize nonnative jumping worms. Following the field campaign, each participant could return to their neighborhoods prepared to answer questions and discuss jumping worm ecology with their immediate community. The results of the field campaign were also shared with all of the study's participants, and we reached the broader community through a series of public seminars and events ranging from small (approximately 20 person) neighborhood events for gardeners, to the annual UW Arboretum Research Symposium, attended by approximately 150 community members.

The prevalence of jumping worms in residential gardens underscored the importance of including private land in urban ecology research along with public land (Dyson et al. 2019). Private land makes up a sizeable percentage of urban green space in most cities (Aronson et al. 2017) and can differ from public green space in ecologically important ways. In the present article, for example, not only were jumping worms more likely to be present in residential gardens than any other habitat type, but residential gardens was the only habitat class in which *Metaphire hilgendorfi* was detected. The confirmed identification of this third species—the first recorded occurrence in Wisconsin—would have been missed had we limited our study to public green spaces. This detection further highlights the value of community science, which can facilitate access to private lands that are often missed in other approaches (Dörler et al. 2018).

In addition to habitat preference, our results contribute to an improved understanding of earthworm species co-occurrence and interaction. The three species of jumping worms identified in Madison are commonly found together at invasion sites (Chang et al. 2018). Similarities in behavior and visual markers among the three species (Chang et al. 2016a) have made it difficult to determine their ecological differences or their potential threat as invasive species. Our results are consistent with those of other studies suggesting competition among earthworm species (Laushman et al. 2018) and suggest the potential for expansion of jumping worms at the expense of European earthworms. This potential displacement should be confirmed by further studies with increased sampling effort and a broader temporal scope. In addition, because our study was designed primarily to assess jumping worm occurrence and distribution, it's possible that our sampling techniques may have underestimated European earthworm occurrences and abundances, because they tend to occur at lower densities relative to jumping worms. We would recommend a higher sampling effort in order to better characterize all earthworm species across the urban landscape. Future research on urban earthworms should also meticulously confirm species (or groups of species) and differentiate among Asian pheretimoid species.

Community science offers an underused but powerful approach when broad spatial sampling is required in a short window of time. Designing a study in advance, giving instruction to team leaders, and training a large group of volunteers worked well because earthworms were easy to recognize and collect. Access to private land was also facilitated via a community-based approach (where in several cases, the participants visited their own local neighborhoods). By combining community science with the structure of an ecological sampling design, we engaged the community, ensured a rigorous collection of scientific data, and transferred knowledge to a wide audience. Our study generated a benchmark of jumping worm distribution and abundance, and repeated sampling in future years can quantify rates, patterns and potential mechanisms of spread of this incipient invasion. The approach described in the present article joins a growing array of planned citizen science campaigns (Cooper 2016; Cavalier et al. 2020) that can be replicated elsewhere. (See box 1.)

Data availability

The data are available through the Environmental Data Initiative Data Portal, accessible through the North Temperate Lakes Long Term Ecological Research data repository: https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-ntl&identifier=387

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