Citizen science and land use data provide insight into the invasive riparian plant composition of the Hudson River Valley watershed

Author for correspondence:
Alexis Garretson, 3197 Route 44 55, Gardiner, NY 12525.
(Email: alexis.garretson@tufts.edu)

Alexis Garretson[1] , Samantha Mohney[2] , Morgan Cahill[3] , Laurel Griffin[4] ,
Rachel Silarszka[3] , Stream Watch Citizen Scientists Mohonk Preserve[5],
Natalie Feldsine[6] , Megan N. Napoli[7] and Elizabeth C. Long[8]

[1]Graduate Research Fellow, Department of Biology, George Mason University, Fairfax, VA, USA; Mohonk-Loewy Data Curation Fellow, Daniel Smiley Research Center, Mohonk Preserve, New Paltz, NY, USA; current: Graduate Research Fellow, Graduate School of Biomedical Science, Tufts University, Boston, MA, USA; [2]Graduate Researcher, Department of Environmental Science and Policy, George Mason University, Fairfax, VA, USA; [3]Undergraduate Researcher, Department of Environmental Science and Policy, George Mason University, Fairfax, VA, USA; [4]Undergraduate Researcher, Schar School of Policy and Government, George Mason University, George Mason University, Fairfax, VA, USA; [5]Citizen Scientists, Daniel Smiley Research Center, Mohonk Preserve, New Paltz, NY, USA; [6]Research Collection and Citizen Science Coordinator, Daniel Smiley Research Center, Mohonk Preserve, New Paltz, NY, USA; [7]Research Ecologist, Daniel Smiley Research Center, Mohonk Preserve, New Paltz, NY, USA and [8]Director of Conservation Science, Daniel Smiley Research Center, Mohonk Preserve, New Paltz, NY, USA

Abstract

Invasive plants in the riparian zone can negatively affect the characteristics and quality of a watershed. To support the development of a watershed management plan and foster public appreciation of the value of the riparian zone, Mohonk Preserve established a volunteer monitoring program surveying sites for invasive species. Between 2017 and 2019, citizen scientists repeatedly surveyed 20 sites in the Hudson River Valley in New York for 10 invasive plant species: purple loosestrife (*Lythrum salicaria* L.), common reed [*Phragmites australis* (Cav.) Trin. ex Steud], multiflora rose (*Rosa multiflora* Thunb.), garlic mustard [*Alliaria petiolata* (M. Bieb.) Cavara & Grande], dame's rocket (*Hesperis matronalis* L.), Japanese knotweed (*Polygonum cuspidatum* Siebold & Zucc.), wineberry (*Rubus phoenicolasius* Maxim.), barberry (*Berberis* spp.), Japanese stiltgrass [*Microstegium vimineum* (Trin.) A. Camus], and Asiatic bittersweet (oriental bittersweet, *Celastrus orbiculatus* Thunb.). We found that the number of target species detected was higher on sites closer to paved roads and with increasing drainage area size, while lower with higher percentages of forested land in the basin. Our analysis results highlight variation in the presence of target invasive species across the Hudson River Valley region, highlighting sites and areas to monitor for future introductions and take action to prevent species' invasions. Our results highlight differences in the most relevant abiotic factors for hydrophytes and non-hydrophyte species, underscoring the importance of considering species' life-history traits before the development of management plans for invasive plant species in the riparian zone. Our case study of community-collected data in the Hudson River Valley region using a relatively simple monitoring protocol can provide a road map for other regions fostering volunteer engagement with invasive plants.

Introduction

Riparian plant species are essential components of the riparian zone, contributing to the flow of water, nutrients, and sediments within watersheds (Gregory et al. 1991; Hood and Naiman 2000; Nilsson and Svedmark 2002; Peterjohn and Correll 1984). Riparian vegetation communities serve as a critical boundary between terrestrial and aquatic ecosystems, provide a variety of ecological services, and facilitate key ecosystem processes (Cummins et al. 1989; Gregory et al. 1991; Groffman et al. 2003; Naiman et al. 1993; Sabo et al. 2005; Tickner et al. 2001). However, the same factors that make riparian zones key components of ecosystems can also facilitate the introduction of exotic species (Hood and Naiman 2000; Naiman et al. 1993; Richardson et al. 2007). Streams provide a corridor for the rapid transportation of invasive species to novel and often uninvaded areas—an indication that riparian restoration activities must be ongoing and must occur across large swaths of a watershed to maintain control over the establishment and spread of invasive plants (Bradford et al. 2007; Kauffman et al. 1997; Lecerf et al. 2007; Richardson et al. 2007; Shafroth and Briggs 2008; Tickner et al. 2001). Riparian zones in urbanized, disturbed, and human-altered

Management Implications

Plants in the riparian zone are an essential component of ecosystem health, providing key services, including erosion control and filtration of surface runoff. However, waterways often serve as a source of species' introductions, making riparian communities important areas for targeted invasive species control. Additionally, roadside introductions of invasive species are quite common, with roads serving as corridors for introductions and facilitators for invasive species spread. Using a citizen science project with many volunteer monitors, we surveyed the riparian invasive community compositions of 10 common nonnative riparian species in the upper Hudson River Valley watershed: *Alliaria petiolata* (garlic mustard), *Lythrum salicaria* (purple loosestrife), *Phragmites australis* (common reed), *Polygonum cuspidatum* (Japanese knotweed), *Rosa multiflora* (multiflora rose), *Hesperis matronalis* (dame's rocket), *Celastrus orbiculatus* (Asiatic bittersweet, oriental bittersweet), *Rubus phoenicolasius* (wineberry), *Microstegium vimineum* (Japanese stiltgrass), and *Berberis* spp. (barberry species). Our citizen science project yielded information on the distribution of target species within our landscape and the associations with land use variation, including increased numbers of target species in sites closer to roads and lower numbers of species in sites with a highly forested basin. These citizen science data were used to draft a watershed management plan and after being made publicly available, have been used in multiple synthesis projects evaluating invasive plants. This work highlights the utility of targeted, trained volunteer monitors in understanding local variability in riparian invasive plants and fostering public engagement in invasive species planning.

coverage for regions that are overlooked in intensive federal and expert-led large-scale invasive plant monitoring programs (Kallimanis et al. 2017; Stohlgren 2006). These data can support local management plans, particularly because mitigation efforts can be disrupted and thwarted by lack of complete data on regional distribution of invasive plant species (Jarnevich et al. 2006). Despite concerns about data quality (Hochmair et al. 2020; Lukyanenko et al. 2016), citizen science can often provide high-quality, cost-effective estimates when paired with training or expert oversight mechanisms (Theobald et al. 2015; Tulloch et al. 2013).

In this study, we evaluate the occurrence of target invasive species in the riparian zone of 20 stream sites in the Hudson River Valley region of New York State. We hypothesized that citizen scientists, with training, could collect reliable occurrence data for common invasive plant species and facilitate watershed monitoring in our region. We also hypothesized that the number of target invasive plant species found at each site would be related to the drainage area and distance to nearby roads, because a larger drainage source area and greater vehicle traffic can facilitate species' introductions. We further hypothesized that there would be a relationship between drainage land use and the number of invasive species and that, in particular, a higher amount of forested land in the basin and lower amount of developed land in the basin would be associated with fewer target species. Finally, we hypothesized relationships among species occurrence, the site canopy cover, elevation, and mean annual runoff. We used the results of citizen science monitoring to inform our local site management, facilitate citizen scientist engagement in invasive species management, and supplement current water-quality sampling in local watersheds.

Materials and Methods

Study Area

Our 20 study sites were in the vicinity of Mohonk Preserve (Figure 1A), located 135 km north of New York City, in the Hudson River Valley. Four sites were selected based on nearby recreation/land use (Split Rock, Humpo Marsh, Lenape Lane, Pine Road), but others were selected based on access points and to cover the primary streams onsite at Mohonk Preserve (Sky Lake, Rosendale Larsen, Old Clove, Mossy Brook, Oakwood, Duck Pond, Van Leuven, Trapps). Mohonk Preserve is a nature preserve and land trust that protects more than 3,340 ha of the Shawangunk Mountains, a northern section of the Appalachian Mountains in Ulster County, New York (Garretson et al. 2020). The Shawangunk Mountain bedrock is made up of sedimentary and low-grade metamorphic rock with a silica-cemented combination of sandstone and white quartz pebble, as well as a few occurrences of gneiss and granite (Abrams and Sands 2010; Feldman et al. 2012).

The region comprises approximately 15,380 ha of oak (*Quercus* L. spp.) forest, with about 1,400 ha of chestnut oak (*Quercus montana* Willd.) and red oak (*Quercus rubra* L.) forests in the Mohonk Preserve (Abrams and Sands 2010). Much of the land was never developed, although some was used as agricultural farmland before being placed into trust and regrowth being allowed to occur. The preserve lies approximately 380 m above sea level on a ridge above the Hudson River Valley, far from any urban heat island or large water bodies. The areas around the Shawangunks include multiple agricultural land use areas and

landscapes are particularly vulnerable to invasive species colonization (Hood and Naiman 2000; Maskell et al. 2006; Parendes and Jones 2000; Pyšek and Prach 1993).

The risks of invasive plant species colonization in riparian zones can be increased by human alterations, including dams (Jansson et al. 2000; Nilsson and Svedmark 2002); land use change (Hancock et al. 1996; Patten 1998); and impervious surfaces, particularly roads (Mortensen et al. 2009; Parendes and Jones 2000). These features modify the hydrologic regime in a watershed by increasing the water temperature, altering nutrient and salinity profiles, and impacting the duration and frequency for both flooding and low-flow events (Auble et al. 1994; Fitch et al. 2008; Kelly et al. 2012; Paul and Meyer 2001; Rood and Heinze-Milne 2011; Walsh et al. 2005).

Microhabitats in the riparian zone are caused by variability in hydrologic regimes, stream bank erosion, forest integrity, and elevation (Casanova and Brock 2000; Naiman and Décamps 1997; Pauchard and Alaback 2004; Yang et al. 2011). These microhabitats allow for variability in community composition and the coexistence of riparian plant species with different germination abilities, as well as contrasting light availability, temperature, and soil requirements. These biological and physiological characteristics of riparian invaders can lead to divergent responses to management actions taken to restore riparian zones and prevent species colonization, particularly forest restoration.

Citizen science is an increasingly popular tool for the surveillance, identification, and mitigation of invasive species threats (César de Sá et al. 2019; Crall et al. 2011, 2013, 2015; Gallo and Waitt 2011). Further, volunteer monitors can provide data
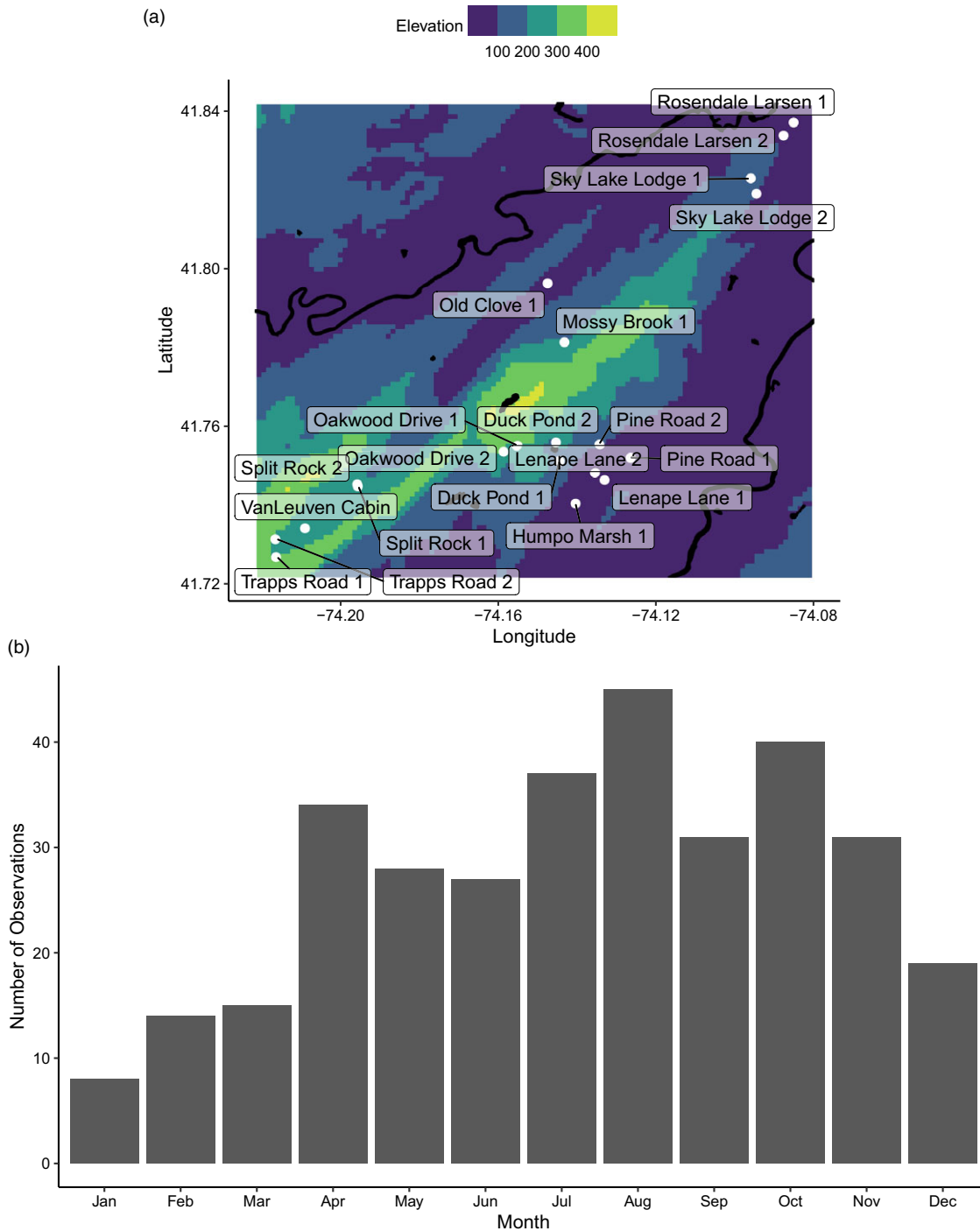
Figure 1. (A) Map of study sites (white) labeled with their names, including the major rivers and lakes (black) and the regional elevations (m). (B) The distribution of sampling events over the months of the year.

Rondout Creek, a critical waterway for water supply in New York City. Management for the invasive species has involved hand-pulling Japanese knotweed species (*Polygonum cuspidatum* Siebold & Zucc., *Polygonum sachalinense* F. Schmidt ex Maxim., and *Polygonum × bohemica*) once per year over the past 2 yr at the Coxing Kill site. Presently, the Mohonk Preserve does not have an official Invasive Species Management Plan, although there is continual monitoring of the invasive plants onsite through multiple field surveys and citizen science projects.

Data Collection

Citizen scientists were recruited from the local community through the network of current volunteers, but also through social media, public presentations, and tabling events in the surrounding local communities. All volunteers were trained by staff members at their assigned sites; this included specific training in using pertinent field equipment, including a densitometer. Data were periodically reviewed by Conservation Science staff, and outlier observations were flagged for follow-up, which included discussion with citizen

Table 1. Invasive species in the Hudson River Valley watershed surveyed in this study.[a]

Scientific name	Common name	Duration	Growth habitat	Wetland	Hydrophyte designation
Lythrum salicaria	Purple loosestrife	Perennial	Forb/herb subshrub	Obligate	
Phragmites australis	Common reed	Perennial	Graminoid shrub subshrub	Facultative wetland	Hydrophyte
Microstegium vimineum	Japanese stiltgrass	Annual	Graminoid shrub subshrub	Facultative	Hydrophyte
Alliaria petiolata	Garlic mustard	Annual/biennial	Forb/herb	Facultative upland	Non-hydrophyte
Hesperis matronalis	Dame's rocket	Biennial/perennial	Forb/herb	Facultative upland	Non-hydrophyte
Rosa multiflora	Multiflora rose	Perennial	Subshrub vine	Facultative upland	Non-hydrophyte
Polygonum cuspidatum	Japanese knotweed	Perennial	Forb/herb subshrub	Facultative upland	Non-hydrophyte
Rubus phoenicolasius	Wineberry	Perennial	Subshrub	Facultative upland	Non-hydrophyte
Berberis thunbergii	Japanese barberry	Perennial	Shrub	Facultative upland	Non-hydrophyte
Berberis vulgaris	Common barberry	Perennial	Shrub	Facultative upland	Non-hydrophyte
Celastrus orbiculatus	Asiatic bittersweet	Perennial	Vine	Upland	Non-hydrophyte

[a]Duration and growth habitat from USDA-NRCS (2020); wetland and hydrophyte designations from Lichvar et al. (2014).

scientists about site conditions during their sampling events to ensure accuracy and, where necessary, additional confirmatory sampling by volunteers.

The full sampling protocol (including macroinvertebrate and stream condition observations) is available with the data package (Mohonk Preserve et al. 2020), but the invasive plant portions of the sampling protocol are summarized here: Citizen scientists observed the habitat directly adjacent to the sampling site and performed an invasive species assessment. The invasive species surveyed were Japanese knotweed (*Polygonum cuspidatum* Siebold & Zucc.), common reed [*Phragmites australis* (Cav.) Trin. ex Steud], purple loosestrife (*Lythrum salicaria* L.), multiflora rose (*Rosa multiflora* Thunb.), garlic mustard [*Alliaria petiolata* (M. Bieb.) Cavara & Grande], dame's rocket (*Hesperis matronalis* L.), Asiatic bittersweet (*Celastrus orbiculatus* Thunb.), wineberry (*Rubus phoenicolasius* Maxim.), Japanese stiltgrass [*Microstegium vimineum* (Trin.) A. Camus], and barberry (*Berberis thunbergii* DC. and *Berberis vulgaris* L.); for the purposes of this study, citizen scientists were not asked to differentiate between *B. thunbergii* and *B. vulgaris*) (Table 1). Additionally, observers looked for an invasive algae, didymo [*Didymosphenia germinata* (Lyngb.) C. Agardh], but it was not found at any sites during the sampling period, although surveillance is ongoing.

During each sampling event, volunteers visited the site and determined the abundance of the target invasive species within eyesight of the flagged location. Abundance was qualitatively assessed as "none" (no individuals of the target species were observed), "sparse" (10 or fewer individuals of the target species were observed), "some" (more than 10 individuals were observed but did not cover most of the ground), or "dense" (target species were covering the majority of the ground observed within eyesight of the flagged location and few other species were present). Because sampling frequency varied, in addition to assessing each of the observations independently, we used all sampling events for each site to produce a site-specific checklist of the number of target invasive plants observed there.

The citizen scientists also assessed the canopy cover of each sampling site using a densitometer. Volunteers assessed whether canopy cover was present in the target zone of the densitometer at 21 points along a streambank. Zero was the starting point at which they regularly sampled other parameters and then 10 m upstream and 10 m downstream with canopy cover measured every meter. If there was canopy cover present in the densitometer, a 1 was recorded, and then the total number of points where canopy cover was recorded was divided by the number of sampling points (10) to produce a percent cover.

In addition to these citizen science data, watershed boundaries were delineated for each study site using StreamStats (http://water.usgs.gov/osw/streamstats; Ries et al. 2008), allowing us to aggregate hydrologic, geomorphological, and land use data specific to each sampling site. We then used the delineated boundaries to query the National Land Cover Database 2011 map (https://www.mrlc.gov/data/nlcd-2011-land-cover-conus; Homer et al. 2015) and calculate the percentage of forested land use in the basin area. NLCD 2011 uses a 16-class land cover classification with a spatial resolution of 30 m^2 (size of one pixel). We also extracted the total drainage area to the sampling point using StreamStats. For each site, we also determined the distance to the nearest road, using the Natural Earth North America Roads and Highways dataset, accessed through the UCLA geoportal (https://apps.gis.ucla.edu/geodata/dataset/north-america-roads-and-highways).

Finally, we used the PLANTS database from the USDA and the National Wetland Plant List: 2014 wetland ratings to determine the regional wetland indicator status for each of the surveyed plant species (Lichvar et al. 2014; USDA-NRCS 2020; Table 1). These designations describe the tendency of a plant species to occur in a wetland or upland habitat and include obligate, facultative wetland, facultative, facultative upland, and upland species.

Statistical Analysis

We performed all analyses in R v. 4.0.2 (R Core Team 2016). To evaluate the relationships between the number of target species, we built a site-level model, with the number of detected target species as a function of the drainage area size, the distance to the closest road, the percent of the basin that is forested, the elevation of the site, and the mean basin slope. We used stepwise model selection, both backward and forward, to determine the best-fit model for the total number of target species, the total number of hydrophyte target species, and the total number of non-hydrophyte target species. To check for multicollinearity, we calculated the variance inflation factor (VIF) using the cars package (cars v. 3.0-10; Fox and Weisberg 2019) for each retained variable in the best-fitting models and excluded variables with a VIF greater than 4.

Results and Discussion

Citizen and Community Scientists Can Provide Reliable Insight into Targeted Species

The twenty sites were sampled 329 times by citizen scientists between April 2017 and November 2019. In total, there were 45
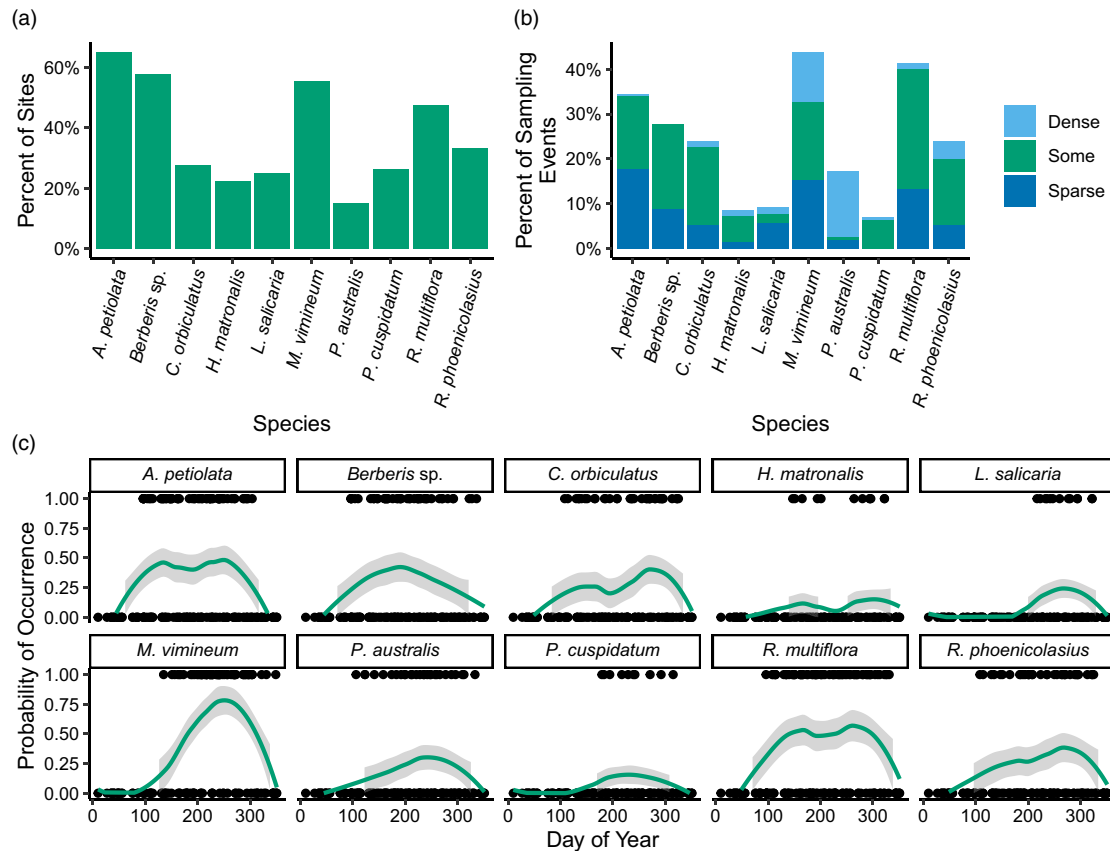
Figure 2. Bar graphs showing the percentage of (A) sites at which each invasive plant species was present and (B) sampling events for which each invasive plant was present. (C) Line graph showing the distribution of presence (1) and absence (0) dates for each species across the year, with fitted locally weighted scatterplot smoothing curves to visualize how probability of occurrence across all study sites for each species varied across the year; shaded gray regions indicate 95% confidence intervals.

citizen scientists who participated in an average of 12 ± 2.4 (minimum 1, maximum 72) sampling dates. Sampling intensity varied over the year (Figure 1B), with the highest number of sampling dates in August and the lowest in January. The most common invasive plant species across all sites was *A. petiolata* and the least frequently occurring species was *P. australis*, which only occurred at 15.0% of sites (Figure 2A). Across all sampling events, the most commonly found species were *M. vimineum* (43.8%) and *R. multiflora* (41.3%), and the least commonly found were *R. phoenicolasius* (6.9%), *H. matronalis* (8.6%), and *L. salicaria* (9.1%) (Figure 2B).

Phragmites australis was the target species most commonly marked as "dense" and was recorded as such on 24 distinct sampling dates, followed by *M. vimineum* (16 dates) (Figure 2B). No invasive plants were detected on 72 sampling dates; however, across the whole of the study period, all sites except Sky Lake Lodge 2 had at least one invasive plant species. In addition to the explicitly monitored species, three other invasive plant species were recorded while sampling: bedstraw (*Galium* sp.) (*n* = 3), bull thistle [*Cirsium vulgare* (Savi) Ten.] (*n* = 1), and bush honeysuckles (*Lonicera* spp.) (*n* = 1). Because these species were not systematically assessed and citizen scientists were not provided with identification guides for these species, they were omitted from further analysis. However, we did add a species to the total site richness if any of the three non-target species were recorded. An average of 3.9 ± 3.0 target invasive plant species was found at each site, with a minimum of zero species found at Sky Lake Lodge 2 and

a maximum of nine species found at Lenape Lane 2 and Pine Road 1.

The detection probability of each species varied across the year (Figure 2C), in patterns approximately following the species phenology. This suggests that the citizen scientists observing the riparian sites may have relied on characteristics related to observable reproductive structures and estimates of presence or absence may not have been as accurate during reproductively dormant periods. However, a large number of citizen science studies have suggested that observer errors can be reduced by averaging across multiple observers, focusing on presence values, or having a larger number of observers involved in a project (Feldman et al. 2018; Fuccillo et al. 2015; Kallimanis et al. 2017; Young et al. 2021). With this in mind, we focused on the presence of targeted species across all observers in the study to further evaluate the relationships between target species occurrence and abiotic site features.

Using a linear model, we assessed the relationship between the presence of individual observers and variation in the canopy cover estimates. We found that only 5 of the total 45 citizen scientists (11%) had a statistically significant impact on canopy cover estimations, and all were associated with a lower-than-expected value for canopy cover. Removing dates where any of these five individuals were present yielded a model of canopy cover that was only dependent on the sampling day of year and the site identity. This suggests that training in using a densitometer can support volunteers' ability to collect reliable canopy cover information.
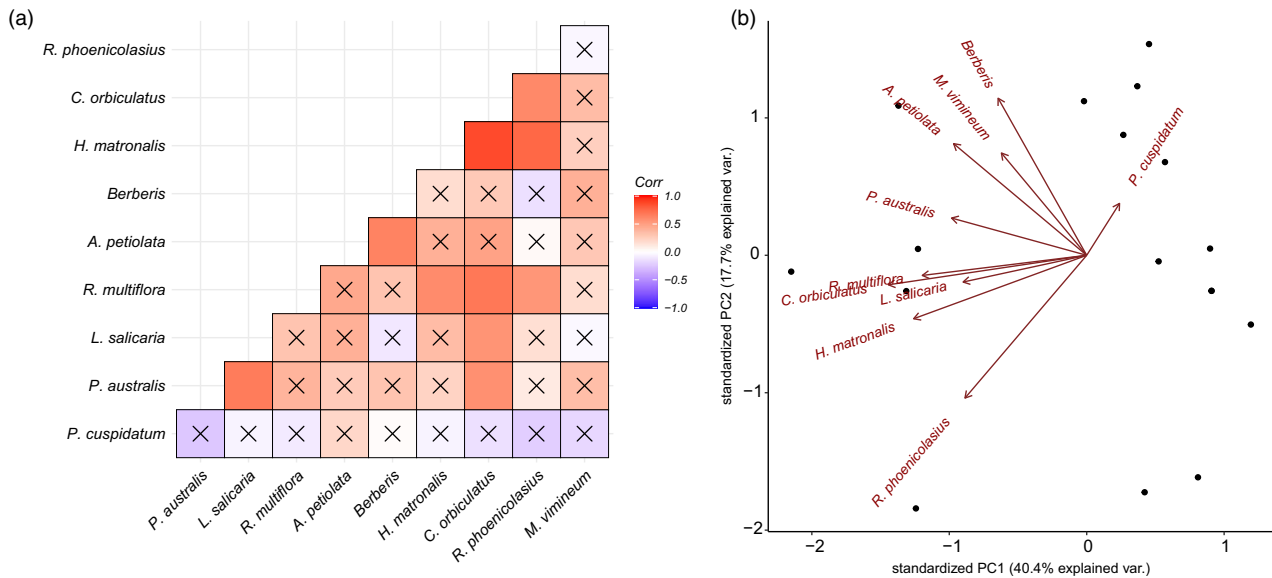
Figure 3. Composition of invasive species community at each site. (A) A correlation plot shows how likely two species are to occur together, with darker blue indicating greater likelihood of co-occurrence and darker red indicating lower likelihood of co-occurrence. An "X" indicates an insignificant (P > 0.05) correlation coefficient. (B) A biplot of the two principal components (PC) of occurrence covariation for each site. Principal component analysis loadings for each species are plotted in red.

The data collected by citizen scientists in our region were used to inform a watershed management plan to identify relevant needs for riparian buffers, to document changes in nearby agricultural practices (some of which directly affect portions of the watershed), to support management actions against invasive species, and to uncover any additional solutions to problems these watersheds may be afflicted by presently or in the future. Volunteer involvement in this stream and riparian area monitoring process encouraged the concept of stewardship among visitors and members of the public who participated in the monitoring activities. Further, results from these monitoring activities have been included in educational activities to inform individuals about the conservation needs of the local environment (Bennett and Chronister 2017; Kathe and Feldsine 2017; Reed 2017). To date, data collected from this citizen science program have been used in seven journal articles, including synthesis research focused on invasive species, due to the data being made publicly available through the Global Biodiversity Information Facilities (Daru et al. 2021; Häkkinen et al. 2022; Kendig et al. 2022; Klimeš et al. 2022; Schneider et al. 2021; Seebens and Kaplan 2022; Zhao et al. 2022).

Target Species Presence Was Correlated across Sites

The results from the correlation analyses indicated that there was on average a weak positive correlation between the occurrence of any given species, with a mean correlation coefficient of 0.26 ± 0.28. The two species most likely to occur together were *H. matronalis* and *C. orbiculatus*, which had a correlation coefficient of 0.85 (P < 0.0001). Further, *C. orbiculatus* had the highest average correlation across all target species (0.47) and was significantly correlated with the presence of *R. multiflora* (0.68, P = 0.002), *L. salicaria* (0.55, P = 0.002), *R. phoenicolasius* (0.60, P = 0.01), and *P. australis* (0.56, P = 0.02). The occurrence of *P. cuspidatum* and *M. vimineum* were not significantly correlated with other target species, with *P. cuspidatum* showing the least variability and lowest likelihood of occurrence with other invasive plant species (Figure 3A and B).

Variation in Site Characteristics Was Associated with Variations in the Number of Target Invasive Species

In all three models of the number of target invasive plant species present, the size of the drainage area was retained as a predictor that improved model fit. Additionally, all variables had VIF scores below 3. In both the model of total target species and the number of hydrophyte species, there was a significant, positive relationship between the size of the basin and the number of species (Table 2). This result conforms with prior research demonstrating that larger drainage areas lead to a higher probability of species' introductions, particularly in large drainage areas containing roads (Barney 2006; Christen and Matlack 2009; Parendes and Jones 2000). No models retained the mean basin slope as a predictor, in contrast to our hypothesis. This finding may be due to conflicting individual species' relationships with bank steepness, as for some species, seed deposition can be decreased with increasing bank steepness (Leeuwen et al. 2014; Naiman et al. 1993; Soomers et al. 2010), while other species may facilitate reduced steepness by stabilizing banks (Bunn et al. 1998; Jones et al. 1997; Zedler and Kercher 2004).

The relationship with the distance to the closest paved road may provide further insight into this pattern, as sites closer to paved roads were found to have a higher number of total target species and a higher number of non-hydrophyte species (Table 2). The spread of invasive species can be facilitated by roads that serve as corridors for movement through a landscape and as a route for novel introductions (Christen and Matlack 2006, 2009; Mortensen et al. 2009). Additionally, roads are the sites of major disturbances during both their construction and subsequent road maintenance (Rentch et al. 2005). Our finding that hydrophyte species numbers did not retain the distance to the closest road as a predictor may also indicate that these species may be less affected by road-related introductions and may instead be introduced in this region through other means.

Invasive plant species are less likely to occur in forest interiors compared with developed or roadside regions (Hansen and Clevenger 2005). In concordance with this expectation, our

Table 2. Best-fit models for the number of target invasive species found at each of the surveyed sites ($n = 20$).[a]

	Range	Total target species	Hydrophyte target species	Non-hydrophyte target species
Adjusted R-squared		0.489	0.468	0.491
P-value		0.003	0.002	0.003
Intercept		8.23 ± 2.06**	1.44 ± 0.33***	7.69 ± 1.89***
Drainage area (km^2)	0.091–21.42 km^2	0.22 ± 0.09*	0.08 ± 0.03*	0.15 ± 0.09†
Distance to closest paved road (per 100 m)	2.41–1468.70 m	0.35 ± 0.14*	—	0.37 ± 0.13*
Percent of basin forested	21.4%–100%	−0.07 ± 0.02**	—	−0.08 ± 0.02**
Elevation (m)	56.08–315.15 m	—	−0.005 ± 0.002**	—
Mean basin slope	284–1680 m m^{-1}	—	—	—

[a]Species data presented as coefficients ± SE, with dagger/asterisks indicating significance levels: †P=0.1; *P=0.05; ** P=0.01; *** P=0.001. See Table 1 for hydrophyte and non-hydrophyte designations of target species.

results show lower numbers of target invasive plant species, both total and non-hydrophytes, as the percent of the basin that is forested increases (Table 2). There are variations among the target species in their shade tolerance and light availability requirements. For example, *M. vimineum* is highly shade tolerant (Barden 1987; Horton and Neufeld 1998), while *L. salicaria* exhibits more modest shade tolerance (Jorgensen et al. 2020; Ture et al. 2004; Weihe and Neely 1997), and *P. australis* requires high light availability (Chambers et al. 1999; Hickman 2012; Jacobson et al. 1991). Therefore, there may be both biological constraints and development-related invasibility differences in the number of target species in relation to the percentage of forested land.

Elevation was retained as a significant predictor of only the number of hydrophyte species, showing a decreasing number of target species as elevation increased. In the eastern United States, as in most temperate ecosystems, the vast majority of invasive plant species' introductions occur in lower-elevation, highly disturbed areas (Hobbs 2000; Pauchard et al. 2009; Pauchard and Alaback 2004). However, elevation is also an important contributor to microclimate variations (Forcella and Harvey 1983; Wilson et al. 1992), which may further contribute to physiological limits on invasive plant species' establishment and proliferation in the riparian zones. Interestingly, the number of target hydrophyte species model retained only the drainage area size and the elevation of the site, and the total target species and non-hydrophyte species models did not retain elevation as a predictor. While our sample size precludes eliminating elevation as a contributor to the variability of these species, this may suggest that elevation limits on establishment may be particularly salient for hydrophyte species in this region.

This study serves as a case study of the utility of community-led citizen science efforts in supporting watershed management plan development and invasive plant species monitoring. We found that the number of target species detected was associated with increasing drainage area size, sites closer to paved roads, and decreasing percent of a basin being forested. These findings highlight site-level variability in the region, which can support our efforts to prioritize sites and streams in the Hudson River Valley to monitor for future introductions and preventative action to counter invasions. Additionally, our results showed differences in the most salient site-level features for hydrophyte and non-hydrophyte species, which highlights the importance of considering species' life-history traits in stream ecosystems before the development of mitigation and/or prevention strategies for invasive plant species in the riparian zone.

References

Abrams MD, Sands BA (2010) Oak forest composition on contrasting soil types at the Mohonk Preserve, Eastern New York. North J Appl For 27:105–109

Auble GT, Friedman JM, Scott ML (1994) Relating riparian vegetation to present and future streamflows. Ecol Appl 4:544–554

Barden LS (1987) Invasion of *Microstegium vimineum* (Poaceae), an exotic, annual, shade-tolerant, C_4 grass, into a North Carolina floodplain. Am Midl Nat 118:40–45

Barney JN (2006) North American history of two invasive plant species: phytogeographic distribution, dispersal vectors, and multiple introductions. Biol Invasions 8:703–717

Bennett A, Chronister N (2017) Water resources of the Catskills. Page 192 *in* The Catskills: A Sense of Place. Arkville, New York: Catskill Center for Conservation and Development

Bradford MA, Schumacher HB, Catovsky S, Eggers T, Newingtion JE, Tordoff GM (2007) Impacts of invasive plant species on riparian plant assemblages: interactions with elevated atmospheric carbon dioxide and nitrogen deposition. Oecologia 152:791–803

Bunn SE, Davies PM, Kellaway DM, Prosser IP (1998) Influence of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian shading. Freshw Biol 39:171–178

Casanova MT, Brock MA (2000) How do depth, duration and frequency of flooding influence the establishment of wetland plant communities? Plant Ecol 147:237–250

César de Sá N, Marchante H, Marchante E, Cabral JA, Honrado JP, Vicente JR (2019) Can citizen science data guide the surveillance of invasive plants? A model-based test with Acacia trees in Portugal. Biol Invasions 21:2127–2141

Chambers RM, Meyerson LA, Saltonstall K (1999) Expansion of *Phragmites australis* into tidal wetlands of North America. Aquat Bot 64:261–273

Christen D, Matlack G (2006) The role of roadsides in plant invasions: a demographic approach. Conserv Biol 20:385–391

Christen DC, Matlack GR (2009) The habitat and conduit functions of roads in the spread of three invasive plant species. Biol Invasions 11:453–465

Crall AW, Jarnevich CS, Young NE, Panke BJ, Renz M, Stohlgren TJ (2015) Citizen science contributes to our knowledge of invasive plant species distributions. Biol Invasions 17:2415–2427

Crall AW, Jordan R, Holfelder K, Newman GJ, Graham J, Waller DM (2013) The impacts of an invasive species citizen science training program on participant attitudes, behavior, and science literacy. Public Underst Sci 22:745–764

Crall AW, Newman GJ, Stohlgren TJ, Holfelder KA, Graham J, Waller DM (2011) Assessing citizen science data quality: an invasive species case study. Conserv Lett 4:433–442

Cummins KW, Wilzbach MA, Gates DM, Perry JB, Taliaferro WB (1989) Shredders and riparian vegetation: leaf litter that falls into streams influences communities of stream invertebrates. BioScience 39:24–30

Daru BH, Davies TJ, Willis CG, Meineke EK, Ronk A, Zobel M, Pärtel M, Antonelli A, Davis CC (2021) Widespread homogenization of plant communities in the Anthropocene. Nat Commun 12:6983

Feldman HR, Smoliga JA, Feldman BA (2012) Notes on the geology of the Shawangunk Ridge on the Mohonk Preserve and environs. Northeast Nat 19:3–12

Feldman RE, Žemaitė I, Miller-Rushing AJ (2018) How training citizen scientists affects the accuracy and precision of phenological data. Int J Biometeorol 62:1421–1435

Fitch GM, Craver VO, Smith JA (2008) Recycling of Salt-Contaminated Stormwater Runoff for Brine Production at Virginia Department of Transportation Road-Salt Storage Facilities. Charlottesville: Virginia Transportation Research Council. 26 p

Forcella F, Harvey SJ (1983) Eurasian weed infestation in western Montana in relation to vegetation and disturbance. Madroño 30:102–109

Fox J, Weisberg S (2019) An R Companion to Applied Regression. 3rd ed. Thousand Oaks, CA: Sage. 608 p

Fuccillo KK, Crimmins TM, de Rivera CE, Elder TS (2015) Assessing accuracy in citizen science-based plant phenology monitoring. Int J Biometeorol 59:917–926

Gallo T, Waitt D (2011) Creating a successful citizen science model to detect and report invasive species. BioScience 61:459–465

Garretson A, Napoli M, Feldsine N, Adler-Colvin P, Long E (2020) Vernal pool amphibian breeding ecology monitoring from 1931 to present: a armonized historical and ongoing observational ecology dataset. Biodivers Data J 8:e50121

Gregory SV, Swanson FJ, McKee WA, Cummins KW (1991) An ecosystem perspective of riparian zones. BioScience 41:540–551

Groffman PM, Bain DJ, Band LE, Belt KT, Brush GS, Grove JM, Pouyat RV, Yesilonis IC, Zipperer WC (2003) Down by the riverside: urban riparian ecology. Front Ecol Environ 1:315–321

Häkkinen H, Hodgson D, Early R (2022) Plant naturalizations are constrained by temperature but released by precipitation. Glob Ecol Biogeogr 31:501–514

Hancock CN, Ladd PG, Froend RH (1996) Biodiversity and management of riparian vegetation in Western Australia. For Ecol Manag 85:239–250

Hansen MJ, Clevenger AP (2005) The influence of disturbance and habitat on the presence of non-native plant species along transport corridors. Biol Conserv 125:249–259

Hickman JC (2012) The Jepson Manual: Higher Plants of California. 2nd Printing edition. Berkeley: University of California Press. 1424 p

Hobbs RJ (2000) Invasive Species in a Changing World. Washington, DC: Island Press. 480 p

Hochmair HH, Scheffrahn RH, Basille M, Boone M (2020) Evaluating the data quality of iNaturalist termite records. PloS ONE 15:e0226534

Homer C, Dewitz J, Yang L, Jin S, Danielson P, Xian G, Coulston J, Herold N, Wickham J, Megown K (2015) Completion of the 2011 National Land Cover Database for the conterminous United States–representing a decade of land cover change information. Photogramm Eng Remote Sens 81:345–354

Hood WG, Naiman RJ (2000) Vulnerability of riparian zones to invasion by exotic vascular plants. Plant Ecol 148:105–114

Horton JL, Neufeld HS (1998) Photosynthetic responses of *Microstegium vimineum* (Trin.) A. Camus, a shade-tolerant, C_4 grass, to variable light environments. Oecologia 114:11–19

Jacobson GL, Almquist-Jacobson H, Chris Winne J (1991) Conservation of rare plant habitat: insights from the recent history of vegetation and fire at Crystal Fen, northern Maine, USA. Biol Conserv 57:287–314

Jansson R, Nilsson C, Dynesius M, Andersson E (2000) Effects of river regulation on river-margin vegetation: a comparison of eight boreal rivers. Ecol Appl 10:203–224

Jarnevich CS, Stohlgren TJ, Barnett D, Kartesz J (2006) Filling in the gaps: modelling native species richness and invasions using spatially incomplete data. Divers Distrib 12:511–520

Jones C, Lawton J, Shachak M (1997) Positive and negative effects of organisms as physical ecosystem engineers. Ecology 78:1946–1957

Jorgensen A, Sorrell BK, Eller F (2020) Carbon assimilation through a vertical light gradient in the canopy of invasive herbs grown under different temperature regimes is determined by leaf and whole-plant architecture. AoB PLANTS 12:plaa031

Kallimanis AS, Panitsa M, Dimopoulos P (2017) Quality of non-expert citizen science data collected for habitat type conservation status assessment in Natura 2000 protected areas. Sci Rep 7:8873

Kathe J, Feldsine N (2017) StreamWatch: A Citizen Science Based Approach to Assessing Stream Water Quality in the Kleine Kill and Coxing Kill Watersheds. Oral Presentation. State University at New Paltz, New Paltz, NY. May 3, 2017

Kauffman JB, Beschta RL, Otting N, Lytjen D (1997) An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22:12–24

Kelly WR, Panno SV, Hackley KC (2012) Impacts of road salt runoff on water quality of the Chicago, Illinois, Region. Environ Eng Geosci 18:65–81

Kendig AE, Canavan S, Anderson PJ, Flory SL, Gettys LA, Gordon DR, Iannone BV III, Kunzer JM, Petri T, Pfingsten IA, Lieurance D (2022) Scanning the horizon for invasive plant threats using a data-driven approach. NeoBiota 74:129–154

Klimeš A, Šímová I, Zizka A, Antonelli A, Herben T (2022) The ecological drivers of growth form evolution in flowering plants. J Ecol 110:1525–1536

Lecerf A, Patfield D, Boiché A, Riipinen MP, Chauvet E, Dobson M (2007) Stream ecosystems respond to riparian invasion by Japanese knotweed (*Fallopia japonica*). Can J Fish Aquat Sci 64:1273–1283

Leeuwen CHA van, Sarneel JM, Paassen J van, Rip WJ, Bakker ES (2014) Hydrology, shore morphology and species traits affect seed dispersal, germination and community assembly in shoreline plant communities. J Ecol 102:998–1007

Lichvar RW, Butterwick M, Melvin NC, Kirchner WN (2014) The National Wetland Plant List: 2014 update of wetland ratings. Phytoneuron 41:1–42

Lukyanenko R, Parsons J, Wiersma YF (2016) Emerging problems of data quality in citizen science. Conserv Biol 30:447–449

Maskell LC, Bullock JM, Smart SM, Thompson K, Hulme PE (2006) The distribution and habitat associations of non-native plant species in urban riparian habitats. J Veg Sci 17:499–508

Mohonk Preserve, Feldsine NA, Garretson AC, Kathe JJ, Long EC, Montoya AJ, Napoli MM, Wander H, Citizen Science Volunteers (2020) Mohonk Preserve Stream Water Quality Invasive Species and Macroinvertebrate Sampling in from 2017-Present. Environmental Data Initiative https://doi.org/10.6073/pasta/a00ff0a44f3305f17c99d87e6a0f29fd. Accessed: December 1, 2021

Mortensen DA, Rauschert ESJ, Nord AN, Jones BP (2009) Forest roads facilitate the spread of invasive plants. Invasive Plant Sci Manag 2:191–199

Naiman RJ, Décamps H (1997) The ecology of interfaces: riparian zones. Annu Rev Ecol Syst 28:621–658

Naiman RJ, Decamps H, Pollock M (1993) The role of riparian corridors in maintaining regional biodiversity. Ecol Appl Publ Ecol Soc Am 3:209–212

Nilsson C, Svedmark M (2002) Basic principles and ecological consequences of changing water regimes: riparian plant communities. Environ Manag 30:468–480

Parendes L, Jones J (2000) Role of light availability and dispersal in exotic plant invasion along roads and streams in the H.J. Andrews Experimental Forest, Oregon. Conserv Biol J Soc Conserv Biol 14:64–75

Patten DT (1998) Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498–512

Pauchard A, Alaback PB (2004) Influence of elevation, land use, and landscape context on patterns of alien plant invasions along roadsides in protected areas of south-central Chile. Conserv Biol 18:238–248

Pauchard A, Kueffer C, Dietz H, Daehler CC, Alexander J, Edwards PJ, Arévalo JR, Cavieres LA, Guisan A, Haider S, Jakobs G, McDougall K, Millar CI, Naylor BJ, Parks CG, et al. (2009) Ain't no mountain high enough: plant invasions reaching new elevations. Front Ecol Environ 7:479–486

Paul MJ, Meyer JL (2001) Streams in the urban landscape. Annu Rev Ecol Syst 32:333–365

Peterjohn WT, Correll DL (1984) Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466–1475

Pyšek P, Prach K (1993) Plant invasions and the role of riparian habitats: a comparison of four species alien to central Europe. J Biogeogr 20:413

R Core Team (2016) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing

Reed G (2017) StreamWatch helps protect Hudson's headwaters. Poughkeepsie Journal, July 14, 2017

Rentch JS, Fortney RH, Stephenson SL, Adams HS, Grafton WN, Anderson JT (2005) Vegetation-site relationships of roadside plant communities in West Virginia, USA. J Appl Ecol 42:129–138

Richardson DM, Holmes PM, Esler KJ, Galatowitsch SM, Stromberg J, Kirkman SP, Pyšek P, Hobbs RJ (2007) Riparian vegetation: degradation, alien plant invasions, and restoration prospects. Divers Distrib 13:126–139

Ries KG III, Guthrie JG, Rea AH, Steeves PA, Stewart DW (2008) StreamStats: A Water Resources Web Application. Fact Sheet 2008-3067. Baltimore, MD: U.S. Geological Survey. 6 p

Rood SB, Heinze-Milne S (2011) Abrupt downstream forest decline following river damming in southern Alberta. Can J Bot 67:1744–1749

Sabo J, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, Jani A, Katz G, Soykan C, Watts J, Welter J (2005) Riparian zones increase regional species richness by harboring different, not more, species. Ecology 86:56–62

Schneider K, Makowski D, Werf W van der (2021) Predicting hotspots for invasive species introduction in Europe. Environ Res Lett 16:114026

Seebens H, Kaplan E (2022) DASCO: a workflow to downscale alien species checklists using occurrence records and to re-allocate species distributions across realms. NeoBiota 74:75–91

Shafroth PB, Briggs MK (2008) Restoration ecology and invasive riparian plants: an introduction to the special section on *Tamarix* spp. In western North America. Restor Ecol 16:94–96

Soomers H, Winkel DN, Du Y, Wassen MJ (2010) The dispersal and deposition of hydrochorous plant seeds in drainage ditches. Freshw Biol 55:2032–2046

Stohlgren TJ (2006) Measuring Plant Diversity: Lessons from the Field. New York: Oxford University Press. 408 p

Theobald EJ, Ettinger AK, Burgess HK, DeBey LB, Schmidt NR, Froehlich HE, Wagner C, HilleRisLambers J, Tewksbury J, Harsch MA, Parrish JK (2015) Global change and local solutions: tapping the unrealized potential of citizen science for biodiversity research. Biol Conserv 181:236–244

Tickner DP, Angold PG, Gurnell AM, Mountford JO (2001) Riparian plant invasions: hydrogeomorphological control and ecological impacts. Prog Phys Geogr Earth Environ 25:22–52

Tulloch AIT, Possingham HP, Joseph LN, Szabo J, Martin TG (2013) Realising the full potential of citizen science monitoring programs. Biol Conserv 165:128–138

Ture C, Bingol NA, Middleton BA (2004) Characterization of the habitat of *Lythrum salicaria* L. in floodplain forests in western Turkey—effects on stem height and seed production. Wetlands 24:711–716

[USDA-NRCS] U.S. Department of Agriculture–Natural Resources Conservation Service (2020) The PLANTS Database. Greensboro, NC: National Plant Data Team

Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, Morgan RP (2005) The urban stream syndrome: current knowledge and the search for a cure. J North Am Benthol Soc 24:706–723

Weihe PE, Neely RK (1997) The effects of shading on competition between purple loosestrife and broad-leaved cattail. Aquat Bot 59:127–138

Wilson JB, Rapson GL, Sykes MT, Watkins AJ, Williams PA (1992) Distributions and climatic correlations of some exotic species along roadsides in South Island, New Zealand. J Biogeogr 19:183–193

Yang J, Dilts TE, Condon LA, Turner PL, Weisberg PJ (2011) Longitudinal- and transverse-scale environmental influences on riparian vegetation across multiple levels of ecological organization. Landsc Ecol 26:381–395

Young AM, van Mantgem EF, Garretson A, Noel C, Morelli TL (2021) Translational science education through citizen science. Front Environ Sci 9:604

Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Crit Rev Plant Sci 23:431–452

Zhao J, Li S, Farnsworth A, Valdes PJ, Reichgelt T, Chen L, Zhou Z, Su T (2022) The Paleogene to Neogene climate evolution and driving factors on the Qinghai-Tibetan Plateau. Sci China Earth Sci 65:1339–1352