Does invasion science encompass the invaded range? A comparison of the geographies of invasion science versus management in the U.S.

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Research Article

Keywords: Biological invasions, Geographic bias, EDDMapS, iMap Invasives, Invasive plant, Spatial bias, Disturbance

Posted Date: July 8th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1739354/v1

Version of Record: A version of this preprint was published at Biological Invasions on December 12th, 2023. See the published version at https://doi.org/10.1007/s10530-023-03208-y.

Abstract

Biases in invasion science have led to a taxonomic focus on plants, particularly a subset of well-studied plants, and a geographic focus on invasions in Europe and North America. Geographic biases could also cause invasion science to focus on a subset of the invaded range, potentially leading to an incomplete understanding of the ecology and management of plant invasions. While broader, country-level geographic biases are well known, it is unclear whether these biases extend to a finer scale and thus affect insights within the invaded range. This study assessed whether research sites for ten well-studied invasive plants in the U.S. are geographically biased relative to each species' known invaded range. We compared the distribution, climate, and land uses of research sites for 735 scientific articles to manager records from EDDMapS and iMap Invasives representing the invaded range. We attributed each study to one of five types: impact, invasive trait, mapping, management, and recipient community traits. While the number of research sites was much smaller than the number of manager records, they generally encompassed similar geographies. However, research sites tended to skew towards species' warm range margins. For all but one species, at least one study type encompassed a significantly different climate space from manager records, suggesting that some level of climatic bias is common. Impact and management studies occurred within the same climate space for all species, suggesting that these studies focus on similar areas – likely those with the greatest impacts and management needs. Manager records were more likely to be found near roads, which are both habitats and vectors for invasive plants, and on public land. Research sites were more likely to be found near a college or university. Overall, we did not find evidence for substantial geographic biases in research studies of these well-studied species, suggesting that researchers are generally doing a good job of exploring the impacts, traits, and management implications of invasions across the extents of the invaded range. However, the consistent climatic biases and spatial clustering of specific study types suggests that researchers and managers should use caution when developing inference for understudied geographic areas.

Introduction

It is well known that spatial and taxonomic biases exist in invasive plant literature (Pyšek et al. 2008; Hulme et al. 2013). Geographic regions such as the U.S. and invasive plants like *Phragmites australis* have an oversized footprint in invasion ecology research (Laginhas and Bradley in press; Hulme et al. 2013). Geographic biases are a problem because they lead to an incomplete view of which species are potentially invasive, their likely impacts, and the efficacy of management options. Even well-studied species in well-studied regions like the U.S. could be biased in terms of the type and location of scientific analyses. For example, if treatment methods are only tested at a species' cool margin, managers in warmer regions could waste resources on methods that are ineffective for their environment. Thus, an important next step in understanding biases in invasion ecology involves delving deeper into potential biases associated with particular types of studies.

Studies on taxonomic biases in invasion literature show that plants make up a significant majority of studies on invasive species, among which grasses, forbs, and herbs are overrepresented (Pyšek et al. 2006, 2008; Jeschke et al. 2012; Hulme et al. 2013; Lowry et al. 2013; Stricker et al. 2015; Tekiela and Barney

2017). Of these, a select few species are exceptionally well studied. Hulme et al. (2013) found that a third of all impact studies focus on only nine species, including *Bromus tectorum* and *P. australis*. Large-scale geographic biases have also led to an overrepresentation of Europe and North America and the underrepresentation of Asia, Africa, and South and Central America (Pyšek et al. 2008, Hulme et al. 2013, Bellard and Jeschke 2016). These biases indicate that plants that are invasive in Europe and North America are the most well-studied invasive species and have, in turn, played an important role in the development of central invasion hypotheses (Colautti and Barrett 2013).

On a finer scale, geographic biases could correspond to the accessibility of sites, notably sites near roads and research institutions (e.g. herbaria, universities) (Graham et al. 2004; Boakes et al. 2010; Stolar and Nielsen 2015; Daru et al. 2018). A bias in ecological sampling towards roads could be problematic because invasive plants are often linked to landscape-scale disturbances associated with road corridors (Vilà and Ibáñez 2011; Menuz and Kettenring 2013; Bhattarai and Cronin 2014). Roadsides can be considered as distinct micro-environments, with distinct soil and climate conditions (Kadmon et al. 2004; Rotholz and Mandelik 2013), that are both habitats and vectors for invasive plants (Jodoin et al. 2008; Christen and Matlack 2009) and oversampling them could inflate the reported impacts of invasive plants (MacDougall and Turkington 2005). Sampling may also be biased towards protected or public lands, which may be of higher ecological significance (e.g. biodiversity hotspots) (Martin et al. 2012). Additionally, plant specimen and samples are often found near research institutions, where they are kept and analyzed (Daru et al. 2018). However, research institutions are not evenly distributed throughout the U.S. Coastal and Great Lake states are home to a higher density of these institutions than the rest of the country (Oak Ridge National Laboratory Geographic Information Sciences and Technology Group 2010), which could be the source of a spatial bias towards certain parts of the country. A third potential source of regional bias could result from species being prioritized through state-level noxious weed lists. These lists are mainly used to prevent the sale and import of invasive plants; however, they can also be used to set management priorities (Skinner et al. 2000; Quinn et al. 2013). The identity of state-listed species varies considerably between states (Buerger et al. 2016; Lakoba et al. 2020; Beaury & Fusco et al. 2021) and could create biases in research and management priorities. Collectively, landscape-scale geographic biases could produce a false portrait of the impacts of and vulnerability to plant invasions.

Larger-scale spatial biases in invasion ecology studies could also lead to an overrepresentation of a portion of the climatic range. A bias in sampling towards one margin of the range could produce imprecise or ineffective recommendations for management or understanding of impacts. For example, herbicide efficacy has been found to vary at different temperatures; higher temperatures can notably reduce their effect through a reduction of herbicide uptake because of fewer stomatal openings, dilution within the plant because of higher metabolism rates, and herbicide volatilization (Bailey 2004; Matzrafi et al. 2016; Ziska 2016). Mechanical removal can also be affected by temperature; for example, *Eichhornia* spp., an aquatic invasive, is currently managed in Northern states by pulling, however this treatment method does not work in regions that do not experience winter freezing (Hellmann et al. 2008; U.S. EPA 2008). Invasive plant traits, notably their phenology, also likely vary across climatic conditions (Hou et al. 2014). For example, *Lythrum salicaria* plants from different North American populations flowered at different times and had different growth rates when grown under a single climatic regime (Colautti and Barrett 2013). Thus, spatial biases towards one climatic range margin could lead to an inaccurate understanding of invasive plant competitiveness throughout its range.

Given the extensive documentation of spatial biases in invasion ecology globally (Pyšek et al. 2008; Hulme et al. 2013; Lowry et al. 2013) combined with the need to use relevant science to guide management and policy actions, it is important to understand how well scientific studies encompass the invaded range. Here, we analyze ten widespread and commonly studied invasive plants in the conterminous U.S. We compare the spatial distributions of invasive species documented by managers to the locations of invasive species reported by scientific studies to determine 1) whether researchers study these plants in the same range in which managers record them, and 2) whether ecological studies are biased with regards to land use or climate compared to where they are recorded by managers. By measuring landscape- and regional-scale biases in the literature, this study highlights areas that might be overlooked by researchers, which can affect our understanding of these plants' biology and, in turn, influence management and policy priorities.

Methods

Study species

We chose ten invasive plant species that are well studied in the scientific literature and also widespread within the lower 48 states (Table 1). We identified well-studied species using the Global Plant Invaders database (Laginhas and Bradley in press), which provides an inventory of scientific articles on invasive plants through 2020. We used an early version of this database to identify well-studied species with scientific articles that also included geographic information (coordinates or a map). We also identified widespread species using spatial records contributed by managers and the public and compiled by the Early Detection and Distribution Mapping System (EDDMapS; Bargeron and Moorhead 2007) or iMap Invasives (iMap; NatureServe 2019) (hereafter, manager databases). Although they were slightly less well studied than some other species, we included *Tamarix ramossissima* and *Ailanthus altissima*, a shrub and a tree respectively, to encompass multiple growth forms. Thus, our ten study species are sufficiently reported in the scientific literature and in manager databases to enable a comparison of their spatial overlap.

Table 1
Species analyzed in this study. Species are sorted by the total number of scientific articles with geographic location data published between 1999–2018. Manager records include data from EDDMapS and iMap Invasives. All species except *Lonicera maackii* were among the top 50 most recorded plants in EDDMapS.

Common name	Scientific name	USDA code	Growth Form	Articles (n)	Articles lower 48 (n)	EDDMapS records (n)	iMap Invasives records (n)
Common reed	*Phragmites australis*	PHAU7	Graminoid	247	148	28763	216
Cheatgrass	*Bromus tectorum*	BRTE	Graminoid	170	162	28136	6329
Japanese knotweed	*Fallopia japonica*	POCU6	Forb/herb	93	18	32484	19847
Japanese stiltgrass	*Microstegium vimineum*	MIVI	Graminoid	86	84	29661	4496
Reed canarygrass	*Phalaris arundinacea*	PHAR3	Graminoid	83	69	36082	3337
Garlic mustard	*Alliaria petiolata*	ALPE4	Forb/herb	78	69	51600	13163
Amur honeysuckle*	*Lonicera maackii*	LOMA6	Shrub	74	74	5657	512
Purple loosestrife	*Lythrum salicaria*	LYSA2	Forb/herb	68	46	41200	24042
Tree-of-heaven	*Ailanthus altissima*	AIAL	Tree	56	24	28416	6341
Saltcedar	*Tamarix ramosissima*	TARA	Shrub	47	41	29637	7675

**L. maackii* was less widespread in manager records, ranking #107 in number of occurrences in EDDMapS

Data collection

We extracted spatial data for the target species from all articles identified in the Global Invaders database (Laginhas and Bradley in press) as having geographic information. At the time of our analysis, this database included species from all papers from 1999–2016 returned using the search term "INVASI* PLANT" in Web of Science (Web of Science 2020). We added information for 2016–2018 for our ten target species by conducting a comparable Web of Science search (Web of Science 2020) for "INVASI* PLANT" AND the target genus and species, as well as all reported synonyms (ITIS 2020). By focusing on papers returned in the Global Plant Invaders database, our aim was to evaluate a representative portion of the literature for the target species to discover what sorts of biases might exist in invasion science. To be included, an article needed to have recorded the occurrence of the invasive species at a given location and have geographic coordinates with a minimal precision equivalent to 0.1 decimal degrees (~ 11 km), or include a map, or an aerial photograph of the study locations. For occurrences reported on maps or aerial photographs, we estimated the location based on toponymy or landmarks using Google maps and recorded these locations to a 0.1 decimal degree precision. For maps with many clustered locations, the level of precision that was given or recorded in a map often led to multiple locations being identically recorded, we therefore estimated the centroid of the cluster and reported that location.

To assess whether some subfields of invasion ecology were spatially biased, we classified articles into one of five study types (Table 2). These categories represent research topics that focus on invasion risk factors (invader traits; recipient community traits), ways in which scientists and stakeholders can monitor or respond to plant invasion (management; mapping), or the impact of invasion (impact). A small number of studies, such as reviews, did not fit into any of these categories and were grouped as “other”. We excluded them from comparative analyses as their subfield was ambiguous. Studies that used location data from EDDMapS or iMap were also excluded from our comparative analysis to avoid double counting locations in both databases.

Table 2
Descriptions and examples of the categories used to classify articles.

Study type	Article Focus	Examples
Impact	Impact of the invasive plant on the abiotic environment or biotic communities	Impact of invasion on hydrology (Martinez 2017), native plants (McGlynn 2009) or native fauna (Wiesenborn 2005)
Invasive Trait	Traits of the invasive plant	Germination (McCaughey and Stephenson 2000); population differences (Shi et al. 2018); genetics (Pyšek et al. 2018); allelopathy (Gómez-Aparicio and Canham 2008); plant growth (Collins et al. 2010); seed dispersal (Kaproth and McGraw 2008)
Management	Management strategies for the invasive plant.	Efficacy of herbicides (Adams and Galatowitsch 2006) or biocontrol agents (Craine et al. 2016); effect of treatments on native species (Hovick and Carson 2015)
Mapping	Occurrence of the invasive plant and/or its spread	Remote sensing (Narumalani et al. 2009); predictive modelling (occurrence data only; Jarnevich et al. 2014); historical reconstruction of invasion (Lavoie et al. 2005)
Recipient Community Traits	Traits of the invaded ecosystem prior to invasion or ecosystem traits that facilitate plant invasion.	Abiotic properties of invaded areas (Uddin and Robinson 2018); disturbance (Hager 2004); invaded plant communities (Peter and Burdick 2010); effects of soil fungi (Shearin et al. 2018); effect of herbivory (Williams and Sahli 2016)

We compiled occurrence data reported in the EDDMapS (Bargeron and Moorhead 2007) and iMap databases (NatureServe 2019), which predominantly contain data from invasive species managers. EDDMapS is the most used database to record and track invasive species; managers and citizens can record sightings of an invasive species along with their GPS location. Following a quality control, their presence is then included in the database. However, some states use iMap as their primary repository for invasive species occurrences, in which data is processed in a similar way as EDDMapS. Therefore, we also compiled iMap data from Arizona, Kentucky, Maine, New York, Oregon, and Pennsylvania. Data were downloaded from EDDMapS on March 2, 2020 and from iMap on October 2, 2019. We removed duplicate points from the combined manager database to avoid double-counting sites that were visited multiple times or were reported in both datasets. We focused on confirmed occurrences of each species rather than their projected range to avoid overestimating the distribution of each species. We also chose to focus on these two databases because they are used by managers and thus have a strong influence on decision-making and plant management. These databases also have strong quality control measures which should lead to higher accuracy of reported sightings.

Data Analysis

Because the majority of EDDMapS and iMap records are in the lower 48 states, we focused our spatial comparison on this region. Records located outside of these states were excluded. Articles sometimes provided measurements at the same plot recorded over time or gave a single latitude and longitude or map location to represent multiple nearby plots with differing occurrence or abundance values. We extracted all abundance or occurrence data for these plots. However, including replicates of the same location could bias our analysis of the spatial characteristics of invasion ecology studies. Thus, we retained only one data point for each individual location, defined by their reported latitude and longitude, in each article. We retained spatial information at the level of precision that each author gave, if only one set of coordinates was given in an article, we reported only one location, but if multiple coordinates were given, we reported each one individually.

In order to visualize the distribution of the two datasets, we created a grid of equal area hexagons with a 50 km cell size height (1623.8 km^2) encompassing the lower 48. Within each hexagon, we recorded the presence of an occurrence from the literature, from a manager record, or both. To assess data clustering, we measured spatial autocorrelation using Moran's I of the number of literature or manager records within each hexagon for each species. To determine whether studies on these species focused on any particular aspect of invasions, we calculated the proportion of papers for a given species that was associated with each study type. We also assessed the number of distinct locations reported within each study type to identify study types or species with more spatial data.

To test for differences in climate space between literature and manager records, we compared spatial occurrences to 30-year (1981–2010) average annual precipitation and temperature created by the PRISM climate group (PRISM Climate Group 2004). To avoid skewing the comparison with locations that have been studied or sampled multiple times, we performed this analysis using a 4 x 4 km grid size, matching the resolution of the PRISM data. Thus, only one point within each grid cell was retained for analysis. We used a Student t-test to compare the manager data to the literature data as a whole. To determine if any differences exist between the different study types and manager records, we used a Kruskal-Wallis and Dunn post-hoc tests to compare the mean climate conditions.

To assess whether either dataset is biased towards more disturbed areas, we calculated the proximity of each independent location, within a given article, to a road using US census data for road locations (U.S. Census Bureau 2016). We used these data to create and compare proportional histograms for the literature and manager datasets. We also compared these results to a random set of points created within the equal area hexagons for each species (section 2.3). The same approach was used to compare the distances to colleges and universities (Oak Ridge National Laboratory 2010), which could influence the sampling strategies of studies reported in the literature. Lastly, we compared the proportion of literature vs. manager records found on private vs. public land (USGS Gap Analysis Project 2018) as well as within vs. outside states where the species was regulated (i.e. prohibited from sales or planting; Beaury & Fusco et al. 2021). We also compared the proportion of sites on public vs private land to determine if either dataset was more strongly skewed to either one, which might give us insight into whether protected areas on public lands are overrepresented in the literature.

Results

Distribution of literature and manager records

The distribution of literature records and manager records is presented in Fig. 1. Manager records occur in more grid cells than literature records for all species, which is consistent with the larger number of manager records for all species (Table 1). The mean number of grid cells for manager records across all species is 749 +/- 192 (95% CI), whereas the mean number of grid cells for literature records is 200 +/- 143 (95% CI). Moran's I analyses revealed that all of the records for each species are clustered across the lower 48 ($p < 0.01$). As a whole, there do not appear to be any strong spatial biases in the literature, compared to manager records.

Almost all species have at least one spatially explicit study in each of the five study type categories (Fig. 2), except for *F. japonica*, which had no spatial studies on management techniques in the lower 48. On average, impact studies are the most common (29% overall). However, study types vary between species. For example, impact studies represent 45%, 39% and 35% of studies on *L. maackii, F. japonica*, and *M. vimineum*, respectively, but less than 15% of studies on *A. altissima* (Fig. 2A). In contrast, when comparing numbers of individual study locations, invasive trait studies are the most common (46% overall). This pattern is driven by studies focusing on comparing genetics or plant traits from different populations, which tend to collect samples from a large number of locations (Fig. 2B).

Climate comparisons

For most species, we found that mean temperature and mean precipitation differ significantly ($p < 0.05$) between the manager and literature datasets (Table S1). Differences in absolute mean temperature average 1.0° C +/- 0.8° C (95% CI; median 0.6° C), with *P. arundinacea* and *P. australis* showing the largest difference. For all but two species (*A. altissima* and *T. ramosissima*), the literature records are skewed towards warmer climate conditions. Precipitation ranges are more variable between the two datasets: six species have less than 50 mm difference between mean annual precipitation, while four (*B. tectorum, F. japonica, L. maackii*, and *P. australis*) have precipitation differences as high as 180 mm (mean absolute precipitation difference: 53.0 mm +/- 45.1 mm (95% CI; median 41 mm)). Literature records for six species tend towards drier conditions, while records for the remaining four species (*B. tectorum, F. japonica, L. salicaria*, and *T. ramosissima*) tend towards wetter conditions.

At least one study type has a significantly different average climate (precipitation or temperature) from manager records (Fig. 3) for most species. One species, *A. altissima* has no significant climatic differences between study types and manager records; however, this species also had low sample sizes. Impact studies are the most likely to occur in a significantly different climate space than manager records (35%; 7 out of 20 possible differences). These differences are significant for both temperature and precipitation in the cases of *L. salicaria* and *P. australis*. Management studies were most climatically similar to manager records (22% significantly different; 4 out of 18 possible cases due to a lack of spatial management studies for *F. japonica*). The other three categories have a significantly different climate for 6 out of 20 possible values (30%). There is no consistent directionality (hotter vs. colder or wetter vs. drier) for the differences between study types and manager records.

Most species also show at least one significant difference in mean climate between study types. For 14 of 20 possible species and climate variable combinations, there is at least one significant study type difference. Impact and management studies are the only study types with no significant differences in mean climate across all species. We found three instances of differences between recipient community trait and impact studies (*L. salicaria, P. australis*, and *T. ramosissima*) and three instances of differences between recipient community trait and management studies (*B. tectorum, P. australis*, and *T. ramosissima*). As a whole, ecological studies on plant invasions (impact, management, and recipient community trait studies) tend to occur in similar climate spaces.

Disturbances and other biases

Both literature and manager datasets tend to be located close to roads, with manager records more likely to be near roads. 54% of manager records are found within 100 m of a road versus 45% of literature records and 27% of randomly distributed points (Fig. 4; Figure S1). These values vary between species. Over 70% of *F. japonica* records are found within 100 m of a road (74% manager and 71% literature), whereas less than 25% of *T. ramosissima* records are next to roads (22% manager and 13% literature). The pattern of manager records located closer to roads is consistent across all species (Figure S1).

For both datasets, most records, regardless of species, are found within 50 km of a college or university, although records for western species (*B. tectorum* and *T. ramosissima*) tend to be farther away. As a whole, 70% of literature records are found within a 25 km radius of a college or university versus 60% of manager records and 53% of randomly distributed points. The proportion of records found within this radius varies between species. *T. ramosissima* represents the low end of records near higher education institutions (25% literature and 16% manager records) whereas *L. maackii* represents the high end (94% literature and 83% manager records) (Figure S2). Literature records are consistently closer to a college or university than manager records.

A majority of manager records are on public land (67%), whereas only half of literature records are on public land (50%). The proportions of points on public land varied between species. *F. japonica* is least commonly recorded on public land (38% literature and 37% manager records) whereas *T. ramosissima* is mostly recorded on public land (72% literature and 89% manager records) (Table S2). Only two species, *F. japonica* and *L. salicaria*, had a slightly higher proportion of literature records on public land compared to manager records (< 2% difference between datasets). All other species had a higher proportion of manager records on public land than literature records.

Finally, the presence of a species listing does not relate to increased reporting in the literature or by managers. An average of 34% of literature and 30% of manager records are found in states where that species is listed as a noxious weed. *L. maackii* is listed in four states (2% land area in the lower 48) and a low proportion of records are in states with a listing (0.5% literature and 8% manager records). On the other hand, *L. salicaria* is listed in 34 states (70.2% land area in the lower 48) and most of the records are found in states with a listing (90% literature and 92% manager records) (Table S2). Species that are listed in a larger number of states and over a larger area have more records in areas with a listing.

Discussion

Geographic biases in invasion science are common (Pyšek et al. 2008, Hulme et al. 2013, Lowry et al. 2013, Bellard and Jeschke 2016) and have the potential to skew our understanding of invasive plant impacts, efficacy of management, and native community susceptibility if these studies focus on a portion of the invaded range. Our results suggest that there is often a significant geographic bias in one or more study type, though it is more common for scientific studies to match manager records. The distribution of scientific studies is not as extensive as the distribution of manager records, but the geographies are similar (Fig. 1). Overall, though biases exist for individual species and study types, we do not find strong evidence of consistent or systemic geographic or climatic biases in scientific studies (Fig. 1, Fig. 3), suggesting that, as a whole, scientific studies tend to encompass the invaded range.

Distribution of records

With an order of magnitude more occurrence records, manager records typically described a larger invaded range than scientific studies (Table 1, Fig. 1). The comparison of literature and manager records reveal three types of patterns between these species which can be related to their total number of articles. The first pattern can be observed for *A. altissima, F. japonica*, and *T. ramosissima*, which have few articles in the lower 48; there are significant gaps in the literature records compared to manager records. The second pattern concerns *A. petiolata, L. maackii, L. salicaria, M. vimineum*, and *P. arundinacea*; literature records essentially encompass the same range as manager records and no large gaps exist between the two. Finally, for *B. tectorum* and *P. australis*, literature records have a larger range than manager records. This broader geography is due to genetic studies seeking to understand the introduction, spread, or hybridization of these species (Meyerson et al. 2016; Arnesen et al. 2017). However, genetic studies likely include locations where the species are naturalized, but not necessarily invasive (spreading or having impact). For example, *B. tectorum* is recorded throughout the lower 48, but is most problematic in western states (Knapp 1996; Bradley et al. 2018), which aligns with manager records. Because EDDMapS and iMap records tend to focus on areas of high priority for monitoring and management, it is likely that manager records provide an effective description of the invaded range.

Although the invaded range is encompassed by scientific studies in general, different study types are not as evenly distributed or pursued. Between each species, the relative proportion of each study type is variable, indicating that the research priorities for these species are not the same. These uneven prioritizations of study types affect the total number of study locations for each species, as certain study types, such as genetic studies (recorded under invasive trait), retrieve data from more sites than others, such as impact studies (Fig. 2B). As a whole, management and mapping studies, which relate to ways in which stakeholders can track and respond to plant invasions, consistently represent a low proportion of the total number of studies (Fig. 2A). Considering their more applied nature, questions related to management and mapping might be more extensively addressed in grey literature instead of scientific literature. However, even if management information is available in the grey literature, it will be harder to locate and therefore less useful for supporting effective management between counties or states. The large differences in research priorities makes it harder to identify comparable information for multiple species that would enable broader insights into prominent processes of invasion.

On average, literature records tend to occur in warmer environments than manager records, although, for most species, the temperature differences between datasets are small (< 1°C). With climate change, temperatures are likely to increase in the near term (Allen et al. 2018). When ecological studies varied climatically from manager records, they tended to occur towards the warm range margin (Fig. 3, Table S1). This focus on the warm range margin suggests that ecological studies could provide an effective illustration of the future ecology of invasions as temperatures increase. However, a focus on the warm range margin could also suggest that invasions are of greatest concern or highest impact in these areas. In this case, climate warming could make plant invasions worse than anticipated (Hellmann et al. 2008; Bradley et al. 2010; Mainka and Howard 2010) as more of the invaded range becomes climatically similar to the more problematic warm range margin. These changes could also produce greater management challenges because treatment strategies, notably herbicides, are not only affected by climate, but can be less efficient in warmer regions (Bailey 2004; Matzrafi et al. 2016; Ziska 2016).

Mean annual precipitation had up to 180 mm difference between literature and manager records but showed inconsistent directionality towards wetter or drier climates. Similarly, for all but one species, at least one study type occurred on a climate range margin, compared to manager records, but there is no consistent trend towards warmer/colder or wetter/drier climates across species (Fig. 3). This suggests that the focus on a more limited climate range is driven by other factors, such as impact, land use, or access, which varies between species. Two study types that never differed significantly in climatic space for any species were impact and management studies. The similarity between studies on management and studies on impact suggests that they focus on areas with the largest impacts that are also the most important to control. Impact studies were also most likely to be found at a climatic range margin (Fig. 3), which suggests that reported invasive plant impacts may not apply to the entire invaded range. The varied biases with respect to precipitation and inconsistent biases by study type show that invasion science often does not encompass the climate of the invaded range. This could lead to higher uncertainty in ecological forecasting of risk from future invasions because we lack information across climatic gradients encompassing the invaded range.

Disturbances and other biases

Invasive species are known to preferentially colonize disturbed areas, especially roadsides, which are both a habitat and a dispersal corridor for invasive plants (Christen and Matlack 2009; Menuz and Kettenring 2013). However, a major question in invasion ecology is whether invasive species are drivers of ecological impacts or passengers taking advantage of disturbance, but not the main drivers of impact (MacDougall and Turkington 2005). Our results show that both scientific studies and manager records are skewed to sites near roads, compared to random points within each plant's distribution, though managers are more strongly skewed than scientific studies across all species (Fig. 4, Figure S1). While managers report invasions near roads, scientists focus on less disturbed areas, further from roads. Because invasion science tends to target sites that are farther from roads than many reported infestations, it is likely that studies are more representative of natural areas rather than highly disturbed areas. However, reports on one species, *T. ramosissima*, did not skew towards roadsides, this is likely linked to the species' lifecycle: *T. ramosissima* spreads via water and is thus less likely to be found near roads than the other species (Zouhar 2003). This outlier may indicate that the reason managers and researchers focus on roadsides is because that is where these plants are mostly located, rather than a bias towards roadsides per se.

Scientific studies are, however, biased towards proximity to colleges and universities. This finding is not surprising given a desire for easy access to field sites and is consistent with past research showing high proportions of herbarium specimens collected near herbaria (Daru et al. 2018). Nonetheless, proximity to universities can lead to larger-scale biases because higher learning institutions are not evenly distributed throughout the country. This may be particularly problematic for species located in the western U.S., such as *B. tectorum* and *T. ramosissima*, where universities are less common. While our results do not suggest that this bias affects the geography of ecological research on invasive plants, the bias towards a more populated and university-dense eastern U.S. may contribute to the overrepresentation of these ten plants in invasion literature.

The large proportion of manager records on public lands in comparison to researchers is likely due to their focus on public land management. Nonetheless, public land is overrepresented in both datasets, representing only 7.8% of the total land area in the lower 48 (Jenkins et al. 2015) but 67% manager records and 50% literature records. Public lands tend to have more natural areas and accessibility to federal researchers, so this finding is consistent with larger trends in ecology that focus on natural areas (Martin et al. 2012). However, cities and suburban landscapes are experiencing faster warming with climate change and have different plant succession than surrounding environments (George et al. 2009). These landscapes are also more disturbed and thus prone to invasions, they could therefore provide insight into the behavior of invasive plants under future climates. Furthermore, if research is mostly focused on natural environments, we may not have an accurate portrait of invasion processes that affect most of the land area in the country. This bias could also affect predictive models, which often use manager records for calibration, by overrepresenting phenomena at natural sites.

Finally, the inclusion of a plant on a noxious weed list did not seem to impact the reporting of that plant. These lists are designed to regulate the sale and distribution of these plants and do not always include plants that are found in unmanaged areas (Quinn et al. 2013). It is therefore unsurprising that they do not affect where these plants are reported or studied.

Data limitations

The results from these two datasets highlight differences between where studies occur and where invasive plants are found, however, they are both imperfect records. Considering the volume of literature records analyzed, it was not possible to confirm site locations with more precision than was given in an article. This means that some sites could be up to 11 km (~ 0.1 decimal degrees) away from their recorded locations, this uncertainty is even greater for studies that present locations as broad, regional-scale maps. Nonetheless, 69% of study locations were recorded with greater than 0.1 decimal degree precision, so these errors are a small portion of the overall dataset (Table S3). We also find consistent trends with regard to distance to roads and to colleges and universities, the two most sensitive variables to these imprecisions, which suggests that our data reasonably capture where studies occur. Not all states record the presence or distribution of invasive species in accessible databases, which can create gaps in manager datasets. It is also possible that certain counties and states have priority species for monitoring and management that could lead to overreporting in certain areas. For example, *A. petiolata* has been reported throughout Wisconsin in EDDMapS, but is practically unreported in neighboring states. Ultimately this work reflects where researchers and managers report the presence of these plants rather than their potential or even actual range.

Conclusion

On a global scale, North America is overrepresented in invasion literature (Pyšek et al. 2008, Hulme et al. 2013, Lowry et al. 2013), and, at a finer scale, most invasion science is conducted in close proximity to roadsides and research institutions (Graham et al. 2004, Daru et al. 2018). Because landscape-scale environmental variables affect invasions (Vilà and Ibáñez 2011), landscape level biases in the literature could skew our understanding of the ecology and best management practices of invasions. The distribution of studies reveals that research encompasses these plants' invaded ranges, but different study types tend to occur in a subset of that range. Geographic biases in study types lead to an uneven distribution of knowledge that could lead to an unnecessary focus on species with minor impacts in the local environment as well as a lack of management of important emerging invasives. Studies that encompass a range of environmental conditions and/or fill in gaps in the current geographies of invasion science are strongly needed.

Declarations

Funding

Funding provided from the Fonds de Recherche Nature et Technologie Québec, the National Institute of Food and Agriculture, U.S. Department of Agriculture, the Massachusetts Agricultural Experiment Station and the Department of Environmental Conservation under Project No. MAS00033, and by Grant No. G19AC00091 from the U.S. Geological Survey and a Department of Interior Northeast Climate Adaptation Science Center graduate fellowship awarded to L. Munro.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The datasets generated during and analysed during the current study are available in the Scholarworks @UMass Amherst repository, https://scholarworks.umass.edu/data/118.

Acknowledgements

We thank Eve Beaury, Evan Johnson, and Courtney O'Connell for their work with data extraction and article searches. Funding provided from the Fonds de Recherche Nature et Technologie Québec, the National Institute of Food and Agriculture, U.S. Department of Agriculture, the Massachusetts Agricultural Experiment Station and the Department of Environmental Conservation under Project No. MAS00033, and by Grant No. G19AC00091 from the U.S. Geological Survey and a Department of Interior Northeast Climate Adaptation Science Center graduate fellowship awarded to L. Munro. Author contributions: LM and BB conceived of the idea. BL created the data extraction protocol. LM and BG collected the data. LM analyzed the data. LM and BB led the writing with contributions from all authors.

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Supplementary Tables

Supplementary Tables are not available with this version.

Supplementary Figures

Supplementary Figures are not available with this version.

Figures

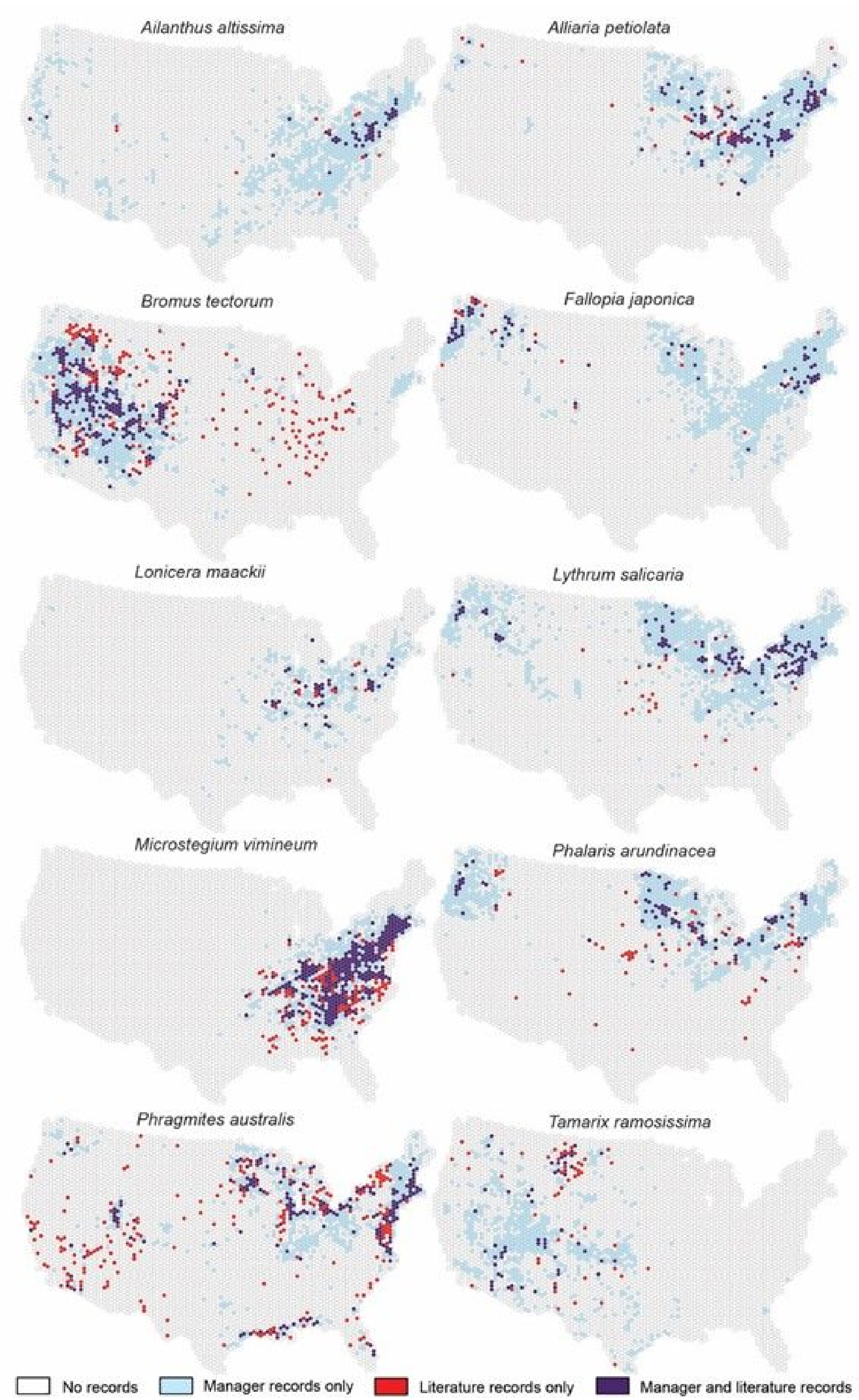

Figure 1

Distribution of literature and manager records in the United States. Each color represents a 1624 km^2 hexagon in which one or more manager record (light blue), literature record (red), or both (purple) were present.

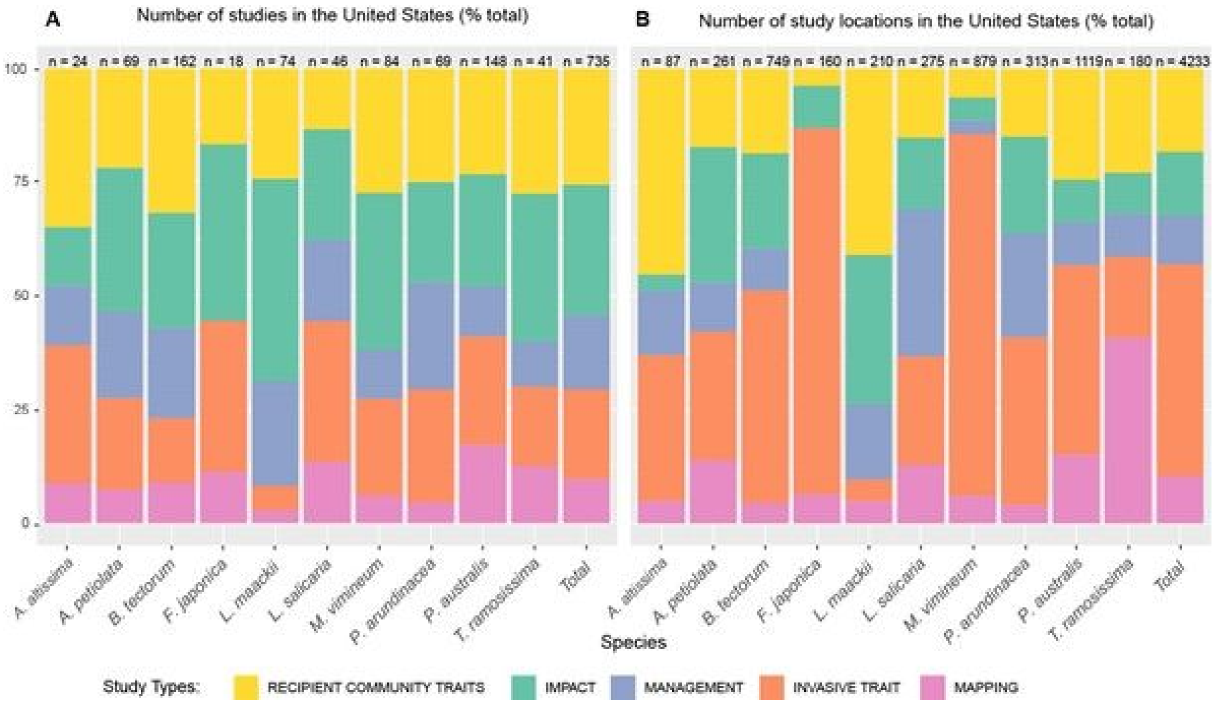

Figure 2

Proportion of each study type attributed to each species (A) and distinct study locations (B) in the lower 48.

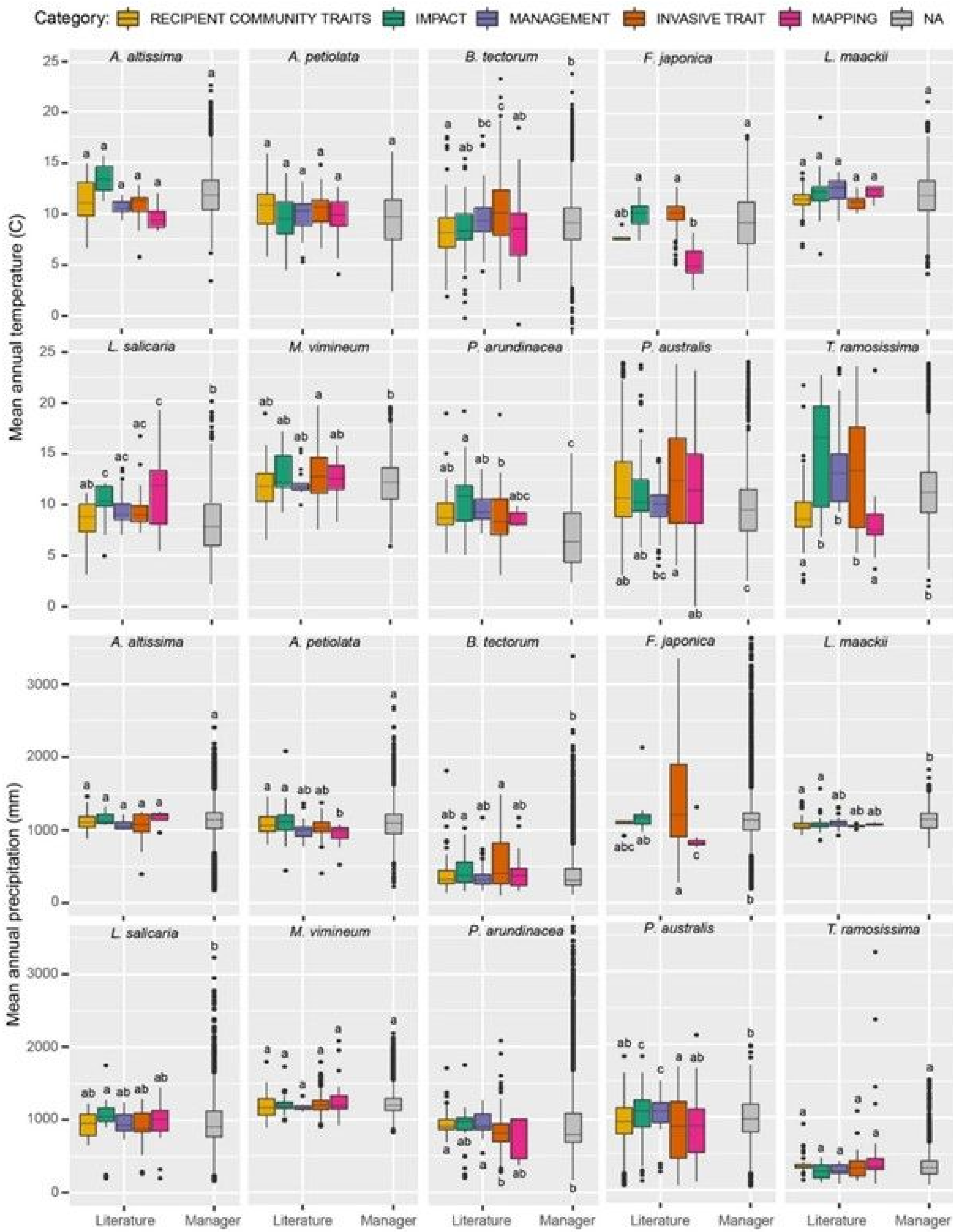

Figure 3

Mean annual temperature and precipitation of study sites and manager records for each species. Letters indicate significant differences ($p < 0.05$) between study types and/or manager records. *F. japonica* and *P. arundinacea* have a maximum mean annual precipitation of 4314 mm and 5244 mm, respectively.

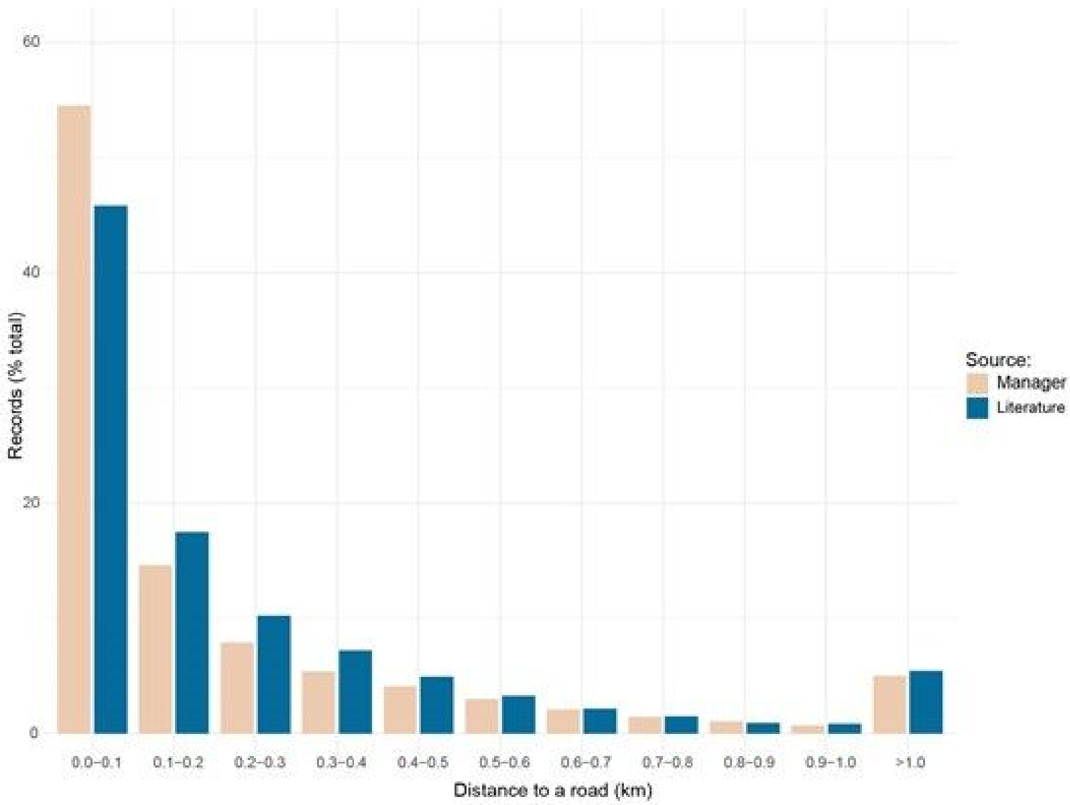

Figure 4

Combined distribution of distance to roads for manager and literature records in the Lower 48. Values represent the proportion of records found in each distance class for each dataset, all species combined.