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Words matter: a systematic review of communication in non-native aquatic species literature

Elizabeth J. Golebie[1], Carena J. van Riper[1], Robert Arlinghaus[2,3], Megan Gaddy[1], Seoyeon Jang[1], Sophia Kochalski[2,4], Yichu Lu[1], Julian D. Olden[5,6], Richard Stedman[7], Cory Suski[1]

1 *Department of Natural Resources and Environmental Sciences, University of Illinois Urbana-Champaign, 1102 S Goodwin Ave, Urbana, IL, 61801, USA* **2** *Department of Biology and Ecology of Fishes, Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587 Berlin, Germany* **3** *Division of Integrative Fisheries Management, Faculty of Life Sciences and Integrative Institute on Transformations of Human-Environmental Systems (IRI THESys), Philippstrasse 13, Haus 7, 10115 Berlin, Germany* **4** *CRETUS, Department of Applied Economics, University of Santiago de Compostela, Santiago de Compostela, 15782, Spain* **5** *School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA* **6** *Department of Wildlife, Fish and Environmental Studies, Swedish University of Agricultural Sciences, Umea, Sweden* **7** *Department of Natural Resources and the Environment and Center for Conservation Social Sciences, Cornell University, 111-B Fernow Hall, Ithaca, 14853, NY, USA*

Corresponding author: Elizabeth J. Golebie (golebie2@illinois.edu)

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Abstract

How scientists communicate can influence public viewpoints on invasive species. In the scientific literature, some invasion biologists adopt neutral language, while others use more loaded language, for example by emphasizing the devastating impacts of invasive species and outlining consequences for policy and practice. An evaluation of the use of language in the invasion biology literature does not exist, preventing us from understanding which frames are used and whether there are correlations between message framing in scientific papers and local environmental impacts associated with invasive species. Thus, we conducted a systematic literature review of 278 peer-reviewed articles published from 2008–2018 to understand communication styles adopted by social and natural scientists while reporting on aquatic non-native species research. Species-centered frames (45%) and human-centered frames (55%) were adopted to nearly equal degrees. Negative valence was dominant in that 81.3% of articles highlighted the negative risks and impacts of invasive species. Additionally, the use of terminology was found to broadly align with the stage of invasion, in that "invasive" was most commonly used except when the research was conducted at early stages of invasion, when "non-native" was most commonly used. Terminology use therefore enables readers of scientific papers to infer the status and severity of ongoing invasions. Given that science communication within the peer-reviewed literature affects public understanding of research outcomes, these findings provide an important point of reflection for researchers.

Keywords
invasive species, message framing, science communication, spatial analysis, terminology

Introduction

Biological invasions pose escalating threats to natural ecosystems, economies, and human well-being on a global scale (Pyšek et al. 2020), although impacts vary by taxon, ecosystem and region (Wolter and Röhr 2010). There is a longstanding debate in invasion science of how to appropriately communicate about invasive species so as to shape public understanding of the issue (Brown and Sax 2004, 2005; Cassey et al. 2005; Verbrugge et al. 2016; Clarke et al. 2020). Several papers (Larson et al. 2005; Janovsky and Larson 2019), have analyzed the use of militaristic language (i.e., referring to a "battle" or "war" against invasive species), which seeks to emphasize the urgency of responding to the risks of invasive species. Although not necessarily supporting militaristic language, several researchers agree that within published literature, scientists should advocate for the control of non-native species, even if it remains uncertain whether the species has negative impacts (Lodge and Shrader-Frechette 2003; Larson 2007). By contrast, other researchers believe objectivity is most important, and have asserted that value-laden terms such as "battle" introduce bias that diminishes trust in science (Lackey 2007; Keulartz and van der Weele 2008). Further, when management decisions associated with non-native species are reported in the popular press, reporters often present counterarguments (Kueffer and Larson 2014) that condemn such decisions, accusing them of being arbitrary and xenophobic (Comaroff and Comaroff 2010; Verbrugge et al. 2016; Sagoff 2017). This reporting outcome is problematic because it creates controversy after management decisions are implemented and erodes support for the scientific process. In short, the way scientific results are communicated strongly affects public understanding of research outcomes and is thus important to study (Nisbet and Scheufele 2009; Fischhoff 2013).

Investigations of language use in literature can yield insight into the reasons "why" different framings are used across the social and natural sciences. It is possible that loaded language, such as militaristic framing, is a response to the degree of risk associated with invasive species (Otieno et al. 2014), whereas less provocative scientific communication styles may be adopted when the likelihood of invasions is lower, or when a management approach shifts from eradication to resilience (Druschke et al. 2016). Another possibility is that scientists may adopt vivid language to engage and capture the attention of readers (Simberloff 2006), without considering potential consequences of their language use. Militaristic framing remains common in news coverage (Clarke et al. 2020), lending support to the idea that such vivid language is believed to be appealing to the public. Evaluating the reasons why researchers across different fields of study communicate in specific ways highlights disciplinary norms of language use and the potential consequences that ensue from such word choices.

There are three fundamental facets of invasive species communication. First, scientific results – among all other forms of information – are interpreted through message frames (Nisbet and Mooney 2007). While framing underpins long-standing debates among invasion biologists over the merits of dramatic vs. less dramatic language, a comprehensive assessment of message framing related to aquatic non-native species has yet to be conducted. Message framing is defined as a phenomenon that occurs as people develop an understanding of a concept and communicate their interpretation (Chong and Druckman 2007). Although frames are often expressed and processed subconsciously, they can be intentionally invoked to make concepts comprehensible to a specific audience or to persuade people to change their behavior (Lakoff 2010). For example, framing of environmentalism has become particularly important to shape how information is exchanged because this topical area is increasingly politicized (Druckman 2017) and interpreted using incomplete knowledge and heuristics (Preston et al. 2015). Different opinions on the dangers of biological invasions and the role of scientists (Young and Larson 2011) have resulted in divergent message frames used in both academic literature and environmental outreach. For instance, narratives that position organisms as active agents of change are particularly adept at cultivating higher risk perceptions and greater willingness to take action (Hart and Larson 2014). Although past work has identified common frames used to discuss non-native species (e.g., Clarke et al. 2020), it has not quantified patterns in frame use and investigated the possible reasons why particular language is chosen.

A second fundamental facet of communication is valence – defined as the positive, neutral, or negative tone adopted – which is considered highly influential in shaping judgment and behavior (Russell 2003). Articles written with a positive valence may celebrate biodiversity brought about by new species (Keulartz and van der Weele 2008; Schlaepfer 2018) or highlight learning opportunities provided by non-native species (Larson 2010). Ostensibly neutral valences position humans as passive observers as nature takes its course (Kueffer and Larson 2014; Shackleton et al. 2019), while negative valences highlight the problems posed by invasive species and may frame them as being inherently "bad" and management efforts as "waging war" against biological invasions. Previous research on the effects of valence is mixed, in that positively positioned information has been more persuasive (Muchnik et al. 2013) and encouraged trustworthiness (Lim and Van Der Heide 2014), whereas negative comments have caused reactance or unpleasant motivational arousal (East et al. 2008). Further, repeated exposure to communication campaigns can lead to message fatigue, a negative response to the messages based on perceived overexposure, redundancy, tedium, and a feeling of being burned out (So et al. 2017). The risk of message fatigue can be mitigated by using messages that take a more positive approach (Guan and Monahan 2017). However, there are competing arguments that negative information is more memorable (Baumeister 2001) and helps contribute to higher risk perceptions (Otieno et al. 2014). Although there are divergent opinions among scientists on whether it is their role to advocate for particular management outcomes (Young and Larson 2011), the way scientists communicate, even if opting to be as objective as possible, influences public understanding of research results (Nisbet and Scheufele 2009; Fischhoff 2013). Thus, considering how valence is used in peer-reviewed literature is an important point for research and reflection.

Lastly, terminology and the associated definitions of key concepts are central to non-native species communication. Debate among scientists regarding the precise uses of various terms, including "invasive," has been ongoing for decades (Colautti and MacIsaac 2004; Copp et al. 2005; Blackburn et al. 2011). For instance, many terms are used to describe a species that exists outside of the region in which it evolved. These terms include non-native, foreign, nonindigenous, alien, invasive, and exotic. Some of these terms are technically incorrect and others can easily be misinterpreted, thus impeding collaboration among scientists and stakeholder understanding of invasive species prevention and management (Richardson et al. 2000). Invasion science is generally replete with value-laden differences in communication strategies (Kapitza et al. 2019), and consistency in the conceptualization of key terms will increase the likelihood that all relevant perspectives are considered, mutual acceptability is increased, and misunderstandings are avoided (Colautti and Richardson 2009; Iannone et al. 2021).

Conceptual model that guided this study

Messaging frames, valence and terminology used in the invasion science literature may be influenced by a variety of factors (Fig. 1). Included among these factors are: (1) the disciplinary approach, (2) the study focus, (3) the stage of invasion describing the study population, (4) the transportation vector addressed, and (5) the biodiversity context in which the study is based. Empirical insights into the relationships across these characteristics will illuminate the underlying reasons why different communication strategies are used throughout the aquatic invasive species literature.

Characteristics of authors conducting and publishing research on non-native species may also influence the frameworks adopted, and, in turn, their strategy for communicating scientific results. Indeed, previous research has indicated that communication is influenced by the professional background of scientists and worldviews that emerge from different disciplines (Hakkarainen et al. 2020). For instance, the use of militaristic frames in studies of invasive species was shown to be absent among coastal restoration managers because their management goals did not include eradication (Druschke et al. 2016). Another study assessed the use of militaristic language in work with invasive species across several influential journals and found that applied journals tended to use less militaristic language than basic science journals (Janovsky and Larson 2019). These professional backgrounds, including disciplinary approaches adopted in the study, may translate into different communication strategies.

The objectives or goals of a scientific article, referred to in this paper as "study focus," can also affect its communication style. Previous research on non-native species

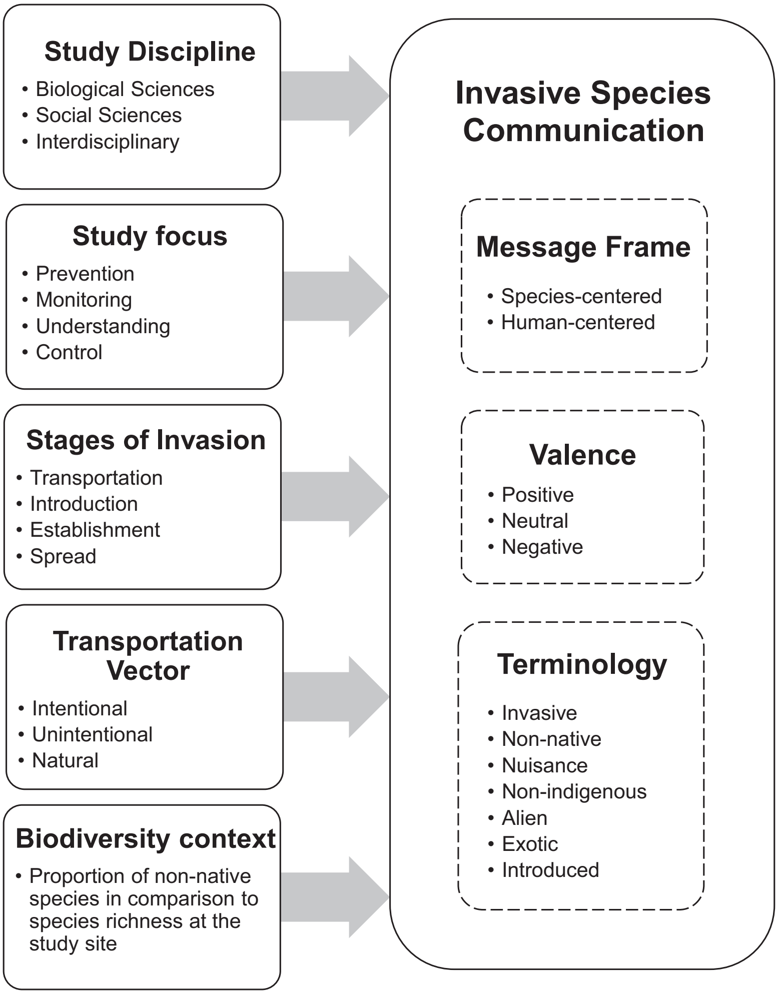

Figure 1. Illustration of relationships explored in this study, including five explanatory variables (i.e., study discipline, study focus, stages of invasion, transportation vector, and biodiversity context) that influenced three facets of invasive species communication (i.e., message frame, valence, terminology).

has been motivated by a variety of concerns that can be categorized into four areas of inquiry. First, many studies have sought to assess the risk of invasive species transport or determine the most effective prevention methods (Byers et al. 2013; Davidson et al. 2016; June-Wells et al. 2013). Second, researchers have monitored and detected aquatic invasive species through a variety of research methods, including environmental DNA (eDNA), citizen science, and remote sensing (Larson et al. 2020), with eDNA studies increasing in popularity (Rees et al. 2014; Klymus et al. 2017). Third, researchers have expressed a goal of understanding non-native species, including their relationships with other species and impacts on ecosystems (Lawrence et al. 2014). Finally, the extant literature has determined the effectiveness and suitability of management or control strategies (Sembera et al. 2018). These key goals in scholarship have indicated that study focus is often closely linked to the stage of invasion most relevant to the study. For instance, studies focused on assessing the risk of invasion or evaluating prevention techniques are typically undertaken in response to a population of non-native species at the transport stage of invasion. In contrast, researchers tend to embark on studies evaluating control options for non-native species when a population is at the establishment or spread stage of invasion. Consequently, communication style adopted by an article reporting research results may be related to the research focus.

Previous research has underscored the importance of recognizing stages of invasion to unify approaches to understanding invasions and the ways they are discussed (Blackburn et al. 2011). Researchers have argued for bridging language gaps between disciplines and standardizing language use across stage of invasion (Colautti and MacIsaac 2004). Each population of a species can be classified as existing along a gradient from "transportation" to "spread", with designated terminology to be used at each stage (Robinson et al. 2016). At the "transportation" stage of invasion, whereby species move to a new location, the neutral term "non-native" is most appropriate, given the uncertainty of the species survival and impacts. The terms "introduced" and "established" directly correspond to the second and third stages of invasion: "introduction", involving the arrival and release of species in a new location, and "establishment" when the introduced species survives and reproduces. Finally, when species "spread" aggressively beyond their established range or begin causing negative ecological or economic impacts, they are dubbed "invasive" (Lockwood et al. 2013). These terms and stages are tied to particular locations; for instance, a species may be at the "introduced" stage in one lake, while in a different lake, a different population of the same species is at the "spread" stage. Thus, language use may be related to differences in the abundance of species at each stage of invasion across a region.

Transportation vectors, defined as the mechanism by which species are carried along a pathway, may affect the way that researchers communicate about non-native species in the literature. For instance, intentional vectors, such as biocontrol, fish stocking (Gozlan 2008), and the aquarium trade (Padilla and Williams 2004), may result in more positively valanced language given the benefits of introducing these species (Carey et al. 2011). By contrast, unintentional vectors, such as ballast water (Bailey 2015) and recreational equipment (Clarke Murray et al. 2011) may result in more negatively valenced language that highlights the need for humans to be aware of their unintentional impacts (Lauber et al. 2020).

Finally, scientists develop their communication styles in the specific social and ecological environment in which their study sites and own experiences are situated. There is spatial variation in the fraction of local species richness from non-native species, the degree of impacts attributable to these organisms and the corresponding policy efforts. Researchers are personally exposed to variation in the strength and impacts of non-native species, which may affect their language in scientific studies. Specifically, the use of strong language may be a response to the degree of risk associated with invasive species in the region given the relationship between risk perceptions and message framing

(Van't Riet et al. 2016). Whereas concerns about objectivity may be less pressing when risks are higher, it may be easier to adopt a less alarming viewpoint and communication style when a researcher works in a context with lower risk. As such, an argument could be made that stronger language is necessary to induce change. Finally, many invasive species managers report being limited by funding (Beaury et al. 2020) with the understanding that the capacity to enact and enforce policies varies by region (Peters and Lodge 2009), leading to further spatial differences in communication approaches.

Study Objectives

We conducted a systematic review of aquatic non-native species literature to explore the message frames, valence, and terminology used in research, as well as the reasons why these communication strategies were adopted. Aquatic invasive species cause significant ecological impacts (Gallardo et al. 2016) inflicting costs of at least US$345 billion annually (Cuthbert et al. 2021), but concurrently contain many species that serve important human needs, such as recreational fishing (Carey et al. 2011; Moore 2012; Fabrizio et al. 2021), making them an ideal context for understanding both positive and negative perceptions. We limited our review to the United States to minimize cultural difference in language use and focus our scope on the role of study characteristics and geographical factors. Given that the vast majority of news articles discussing non-native species comment on management actions (Clarke et al. 2020), we sought peer-reviewed articles that pertained to management, thereby generating implications directly relevant to public messaging, such as communicating management plans, raising awareness of risk, and influencing recreationist behavior. This systematic literature review was guided by the following objectives: 1) Characterize invasive species communication across message frames, valence and terminology in peer-reviewed articles published on non-native species management in the United States from 2008–2018; 2) Define the effects of study discipline, study focus, stage of invasion, and transportation vector on message frames; 3) Quantify the effects of study discipline, study focus, stage of invasion, and transportation vector on valence; and 4) Analyze the relationships among study discipline, study focus, stage of invasion, transportation vector, and terminology. We seek to provide insights into communication and message framing in research conducted by scientists from multiple disciplines that are advancing the study of biological invasions.

Methods

Search criteria and article identification

This systematic literature review (Gough et al. 2012) involved an examination of peer-reviewed articles discussing aquatic non-native species from a variety of disciplinary perspectives (Fig. 2). We selected Thomson Reuters Web of Science and Scopus da-

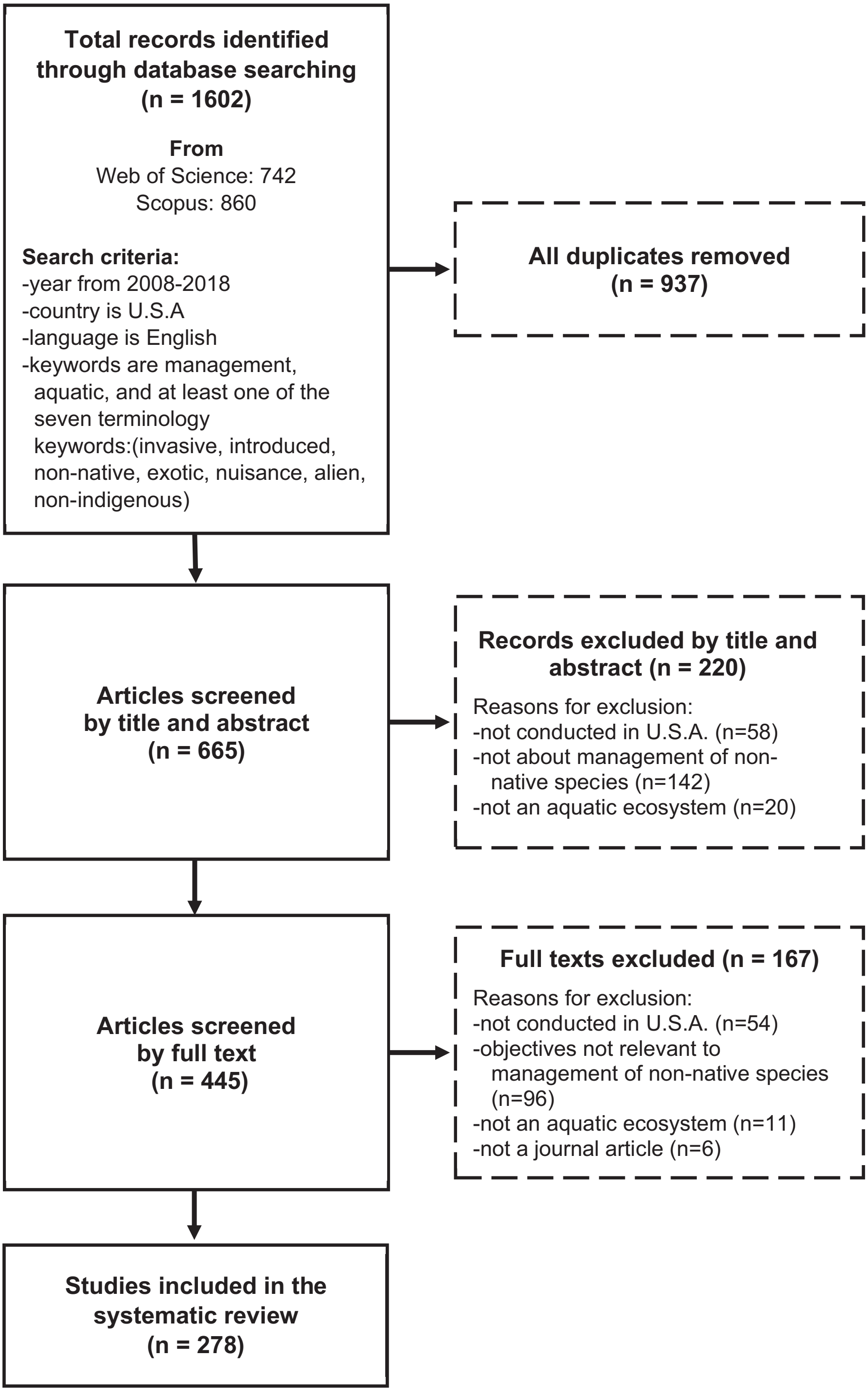

Figure 2. Flow diagram detailing the article search and screening process for a systematic review of aquatic non-native species management.

tabases because of their common use in systematic reviews (Mongeon and Paul-Hus 2016), and searched them on July 3, 2018 using a search string that included seven keywords commonly used to report invasive species research (Colautti and MacIsaac 2004), as well as additional terms to target aquatic species and ecosystems and research that addressed management implications. Specifically, the sets of keywords were:

- invasive species AND (management OR conservation) AND aquatic;
- non-native species AND (management OR conservation) AND aquatic;
- introduced species AND (management OR conservation) AND aquatic;
- alien species AND (management OR conservation) AND aquatic;
- exotic species AND (management OR conservation) AND aquatic;
- non-indigenous species AND (management OR conservation) AND aquatic;
- nuisance species AND (management OR conservation) AND aquatic.

In addition to searching keywords in the topic (TS), the search strings specified the language to be English and the country (CU) to be the United States. We limited articles to English-language studies from the United States (including Puerto Rico) given the focus on communication; accounting for cultural differences or variation across languages was outside the scope of this study. Additionally, we used a 10.5-year time from January 2008 through July 2018. The 10.5 year timeframe was chosen to provide a snapshot of recent articles published after considerations around language were brought to light (e.g., Brown and Sax 2004).

In the first stage of screening, we read 665 titles and abstracts to determine whether the following criteria were met: 1) conducted in the United States; 2) speaks to management of non-native species; 3) studies an aquatic ecosystem. The 445 articles that met the first stage of screening criteria were advanced to the second stage of screening. During the second stage of screening, we read the full article, and articles that did not meet the following criteria were excluded: 1) conducted in the United States, 2) study objectives pertain to management of non-native species; 3) the study ecosystem is aquatic; 4) peer-reviewed article that is article-length and not a book. The final pool included 278 articles, distributed across the 10.5-year window used for the review (Fig. 3). Screening and management of the articles was conducted using EPPI Reviewer 4 software (Thomas et al. 2010).

Coding process

To provide an overview of the types of studies included in the review, we recorded key characteristics of each study, including location of the study site, species studied, journal outlet, and affiliation of the lead author. Our systematic review unearthed published studies that were conducted across the United States (Fig. 4). Species of study were grouped into the broad categories of plants (37%) and animals (45%), with 17% featuring both plants and animals. In line with the study objectives, we coded each article for the seven features in our conceptual model (Fig. 1).

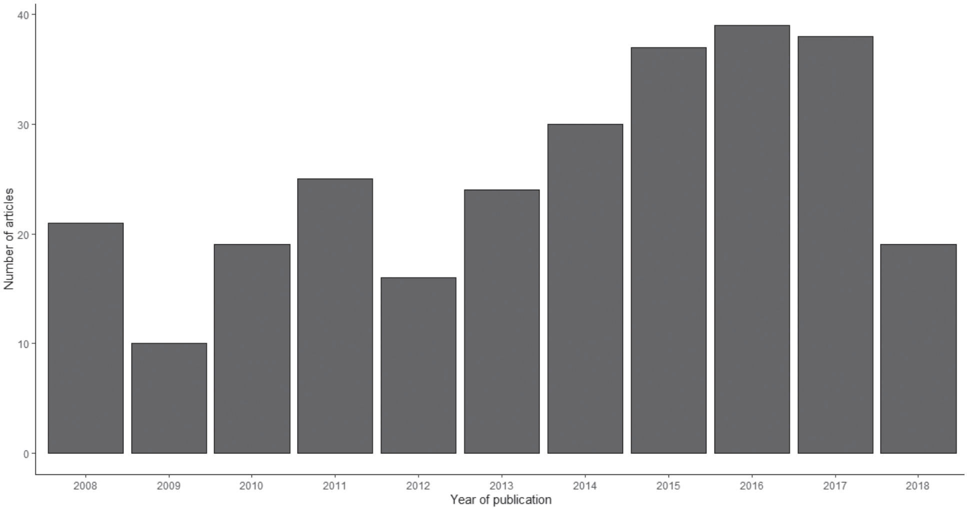

Figure 3. Publication year of 278 articles published from January 2008 through July 2018 that assessed non-native aquatic species management in the United States.

First, we coded each article for three facets of communication: message frame, valence and terminology. Message frame was categorized as either human-centered or species-centered (Table 1). Specifically, two independent coders identified the message frame adopted in the introduction section of each article, using the following definitions: "Human-centered frames" were those that focused on the human drivers or causes of species introductions or centered human responsibility for taking action, whereas "species-centered frames" were those that did not discuss human influences on species introductions but focused on the species themselves as the drivers, at times anthropomorphizing the species. These codes were mutually exclusive, in that whenever human influence was mentioned, the article was classified as human-centered. To assess agreement between coders, we used Cohen's Kappa ($\varkappa$) a measure of interrater reliability (McHugh 2012), which indicated substantial agreement ($\varkappa$ = 0.760; percent agreement = 89%). For each article with an initial disagreement on code (n = 31), the coders discussed the article until an agreement was reached.

Each article was next categorized according to its positive, negative or neutral valence. Specifically, the introduction section was coded as expressing positive valence when the benefits of a study species were discussed or predicted, whereas negative valence was indicated when the study species was described as problematic or its negative effects were detailed. The article was coded as having neutral valence if positive and negative impacts were both described, or no effects at all. Again, two independent coders identified the valence; interrater reliability indicated substantial agreement ($\varkappa$ = 0.620; percent agreement = 88%), and when there was disagreement on valence (n = 33), the article was discussed until agreement was reached. Terminology was assessed quantitatively. The text of each article, excluding the references, was searched for seven common terms used to refer to aquatic non-native species (i.e., alien, exotic,

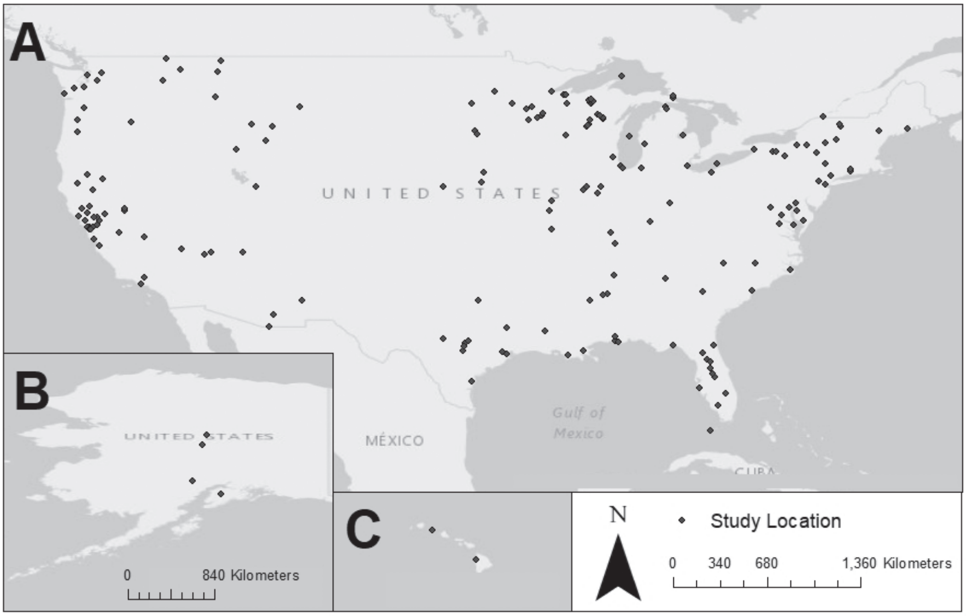

Figure 4. Geographic locations of study sites across 278 articles that reported on findings from aquatic non-native species research. Each point represents one study and shows its location in relation to other studies across **A** the contiguous United States **B** Alaska and **C** Hawaii.

introduced, invasive, non-indigenous, nuisance, non-native), and the number of times each term appeared in the article was tallied.

Second, data reflecting four explanatory variables – study discipline, study focus, stage of invasion, and transportation vector – were extracted from each article. Study discipline was classified by identifying whether the disciplinary orientation and methods used were in line with the biological sciences, social sciences or an interdisciplinary approach. Data drawn from plants, animals or ecosystems were classified as "biological sciences", whereas data drawn from humans (e.g., methods involving surveys or interviews) were classified as "social sciences". Study focus was derived from the stated objective of the paper and categorized as: "prevention" when objectives related to risk assessments or analysis of prevention measures; "monitoring" when objectives dealt with detecting or identifying non-native species; "understanding" when objectives pertained to analyzing the impacts or ecological characteristics of a species; and "control" when objectives related to the evaluation of management or control methods. The stage of invasion was identified based on the description of the study population provided in the introduction or methods of the paper. In some cases, the stage of invasion was explicitly stated; when it was not stated, articles were coded as "transportation" if the species was in the process of moving to a new location, "introduction" if the species had been released at a new location, "establishment" if the species had survived at the new location or "spread" if the species had spread beyond the initial point of introduction (Blackburn et al. 2011). Articles that could not be classified as occuring

Table 1. Message frames and valences that were coded from peer-reviewed articles about non-native aquatic species management.

	Definition	Example
Message frame		
Human-centered	Research focused on the human drivers or causes of species introductions or centered on human responsibilities for taking action	Zebra mussels are spread by recreational boaters
Species-centered	Research focused on the species themselves as drivers, at times anthropomorphizing the species; no discussion of human influences	Zebra mussels filter water and reduce food availability lower in the food web
Valence		
Positive	Benefits of the study species are discussed or predicted	Zebra mussels filter algae and make water clearer
Neutral	Both positive and negative impacts, or no effects at all, are described	Zebra mussels make water clearer, but also reduce food availability for desirable species in the food web
Negative	A study species is described as problematic or its negative effects are detailed	Zebra mussels make water clearer but also reduce food availability for desirable species in the food web

at one particular stage or for which stage of invasion was entirely irrelevant were coded as a fifth category. Finally, transportation vector was classified as natural, human-intentional and/or human-unintentional (Lockwood et al. 2013). Specifically, a vector was coded as "natural" if the study population was transported by dispersal patterns not directly mediated by humans, "human-intentional" if invasive species were transported deliberately by humans (e.g., stocking, biocontrol, aquaculture), and "human-unintentional" if the study population was transported accidentally by humans (e.g., ballast water, recreational equipment). Full details on the coding approach are available in the supplementary information.

Finally, we collected information on biodiversity context. We defined biodiversity context as watershed-level estimates of the percent of aquatic species classified as non-native where the study was conducted. We determined native and non-native species occurrence within watersheds of the contiguous United States using the NatureServe Central Database, the United States Geological Society (USGS) Non-indigenous Aquatic Species Database, the Early Detection and Distribution Mapping System (EDDMapS) and the USGS Biodiversity Serving Our Nation (BISON) database. These databases contained native and non-native species occurrences (defined as a species introduced from outside its native range) that were sourced from the literature, museums, databases, monitoring programs, state and federal agencies, professional communications, online reporting forms, and hotline reports. Occurrence records were geo-referenced to watersheds according to USGS hydrological unit code 8 (HUC 8) using ArcGIS (v. 10.3.1).

Analysis

Quantitative analyses were performed to define relationships between language use and the selected characteristics in the included articles. First, predictors of message frame were assessed using multinomial logistic regression with study discipline (i.e., biological science, social science and interdisciplinary), study focus (i.e., prevention, monitoring, understanding, or control), invasion stage (i.e., transportation, introduction, establishment, or spread) and transportation vector (i.e., natural, unintentional, intentional, both, all, or not mentioned) as fixed effects. The model did not exhibit large over-dispersion (residual deviance = 243, with 226 degrees of freedom). Second, predictors of valence (i.e., biological, interdisciplinary or social) were assessed using multinomial logistic regression with the same fixed effects used in the message frame model. Because only one study was coded as positively valanced, that study was excluded from analysis. Thus, the dependent variable was a binary categorical variable; studies were either negative or neutral. This model also did not exhibit large over-dispersion (residual deviance 212 on 224 degrees of freedom). Finally, the use of terminology was modeled as a function of four explanatory variables (i.e., study focus, study discipline, stage of invasion, and transportation vector) using multivariate redundancy analysis (RDA) in the R package 'vegan' (Oksanen et al. 2020). Because most papers did not use all terms, we used the Hellinger distance function to account for the many zeros in the dataset (Legendre and Gallagher 2001). The correlation biplot was based on the covariance matrix and omitted the reference levels of the explanatory variables to avoid collinearity (Zuur et al. 2007). To test the hypothesis that the four variables explained a larger degree of variation than a random contribution, an ANOVA-like permutation test for RDA was performed (Oksanen et al. 2020). All analysis was conducted in the R programming language version 4.1.2.

Lastly, we tested whether language use in articles was associated with the biodiversity context in which the study was conducted. Comparisons of the percent of non-native species and types of message frames and valence were assessed using Wilcoxon rank sum tests with continuity correction and the relationship between percent non-native species and the overall article frequency of invasive species terminology (number of occurrences of the words: invasive, introduced, exotic, non-native, alien, nonindigenous, nuisance) was evaluated using simple linear regression.

Results

The articles included in this systematic review exhibited diverse patterns in message framing, valence and terminology. An approximately equal number of articles were classified as using species-centered language (45.0%) versus human-centered language (55.0%). Valence was predominately negative (81.3%) across articles, with only one study framed positively (0.4%), and the remainder framed neutrally (18.3%). Finally, the term "invasive" was used most often in the published literature; 95.3% of the articles included this term on at least one occasion. Many articles also included the terms "introduced" (70.5%), "non-native" (57.9%), "nuisance" (29.9%), "exotic" (27.7%), "non-indigenous" (23.4%), and "alien" (10.4%).

Examining study discipline, we found that biological sciences (84.5%) was dominant, with a minority of studies drawing on environmental social science (12.6%) and interdisciplinary methods (2.9%). Study focus was split among prevention (25.2%), monitoring (9.4%), understanding species impacts (31.3%), and control of the species (27.0%). A majority of articles (61.5%) were conducted during the spread stage of invasion, with fewer results published on the transport (5.4%), introduction (10.8%) or establishment (14.0%) stages. Stages of invasion were not relevant for several articles (8.3%); this category was excluded from further analysis. Intentional and unintentional spread were each discussed in approximately one quarter (24.1%) of the articles. Many studies (37.1%) did not report transportation vector, 9.0% covered multiple types of vectors, and only 5.8% focused on natural dispersal rather than human causes.

Both transportation vector ($\chi^2(5) = 38.600$; p<.001) and study focus $\chi^2(3) = 15.616$; p<.001) significantly predicted message frames. Message frame, transportation vector and study focus showed strong associations within the published literature ($\chi^2(13) = 89.756$; p<.001). Specifically, species-centered frames were used more frequently when the study

Table 2. Predictors of human-centered (reference level) vs. species-centered framing in peer-reviewed articles focused on non-native aquatic species management. Significant results are highlighted in bold.

Variable	B	Standard error	Z	p	Exp(B)
Intercept	0.272	0.954	.286	0.775	1.313
Study discipline[1]					
Interdisciplinary	-0.315	1.168	-0.270	0.787	0.730
Social sciences	0.381	0.832	0.457	0.647	1.463
Study focus[2]					
Monitoring	-0.920	0.626	-1.469	0.142	0.398
Understanding	**-1.187**	**0.488**	**-2.433**	**0.015**	**0.305**
Control	**-1.886**	**0.496**	**-3.804**	**<0.001**	**0.152**
Stage of invasion[3]					
Introduction	0.074	1.034	0.072	0.943	1.077
Establishment	-0.287	0.967	-0.297	0.766	0.750
Spread	-0.340	0.886	-0.384	0.701	0.712
Transportation vector[4]					
Natural	0.999	0.591	1.690	0.091	2.716
Human (unintentional)	**2.159**	**0.479**	**4.503**	**<0.001**	**8.660**
Human (intentional)	**2.014**	**0.400**	**5.043**	**<0.001**	**7.494**
Human (Both)	**1.616**	**0.780**	**2.071**	**0.038**	**5.033**
All	2.198	1.156	1.902	0.057	9.005

[1]Biological sciences served as the reference level; [2]Prevention served as the reference level; [3]Transportation served as the reference level; [4]Vector not mentioned served as the reference level; Note: Results: $\chi^2(13) = 89.756$; p < .001; Nagelkerke's Pseudo $R^2 = 0.416$.

focus was "understanding" impacts or "control", whereas human-centered frames were used more frequently when the study focus was "prevention" (Table 2).

We found a strong relationship between frame use and transportation vector. Human-centered frames were more common when human vectors were emphasized; when no vectors were emphasized, the species-centered frame dominated (Fig. 5). Likewise, species-centered messaging became more common with increasing stages of invasion, though this was not a statistically significant result of the logistic regression. Additionally, species-centered frames were more likely to be used in research conducted in watersheds containing proportionally more non-native species (Fig. 6A; W = 3929.5, p = 0.027, Wilcox test).

Negative valence was used more often for studies that focused on preventing the spread of invasive species or the evaluation of control options, in contrast to moni-

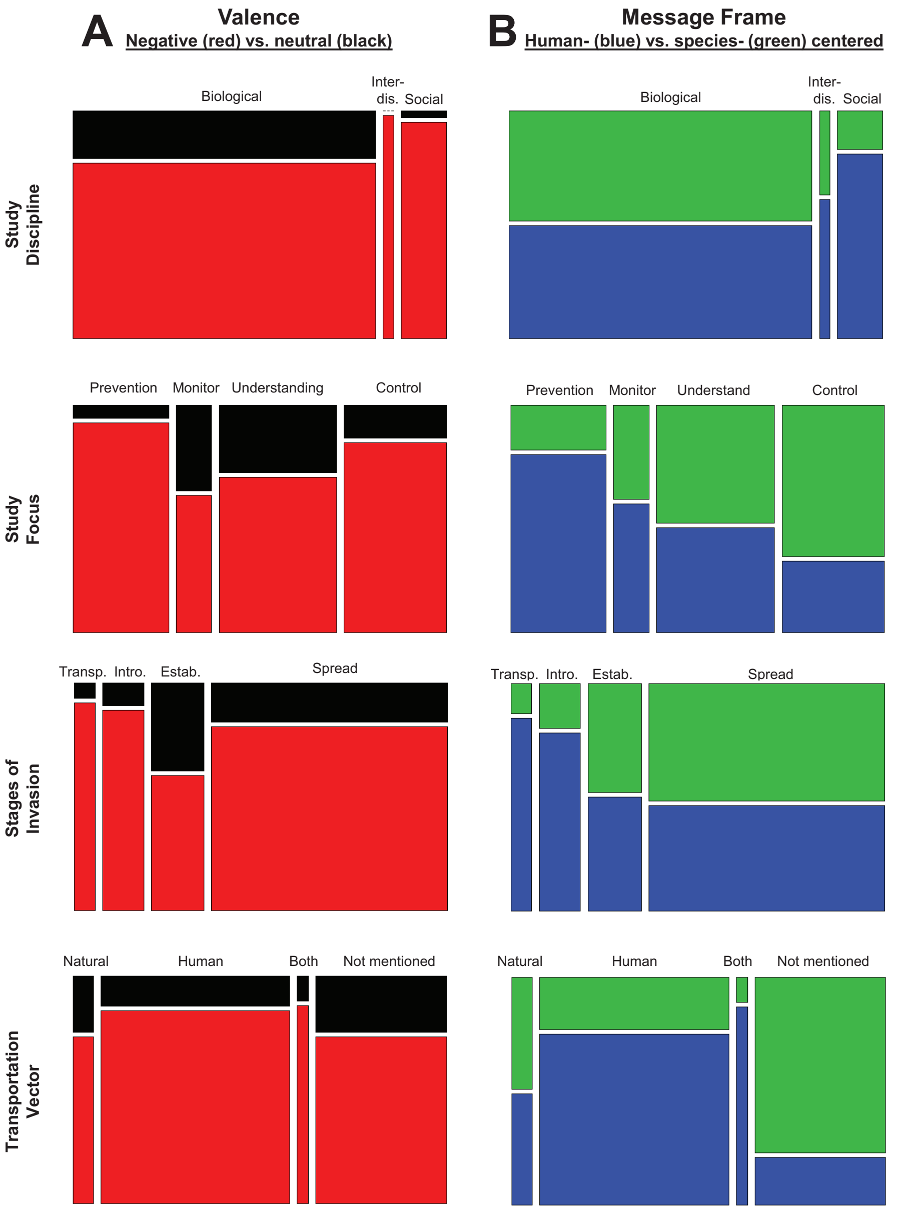

Figure 5. Comparison of **A** negative (red) vs. neutral (black) valence, and **B** human-centered (blue) vs. species-centered (green) message frames according to four study attributes including study discipline, study focus, stages of invasion, and transportation vector. Width of each column indicates the proportion of studies falling into each category. Comparisons between negative vs. neutral valence and human vs. species centered frames are likewise indicated proportionally in each graph.

toring studies (Fig. 5). This result was supported by the logistic regression model ($\chi^2(13)$ = 29.238; p=.006; Nagelkerke's Pseudo R^2 = 0.181), in which study focus was a significant predictor ($\chi^2(3)$ = 10.660; p=.014). That is, a neutral valence was

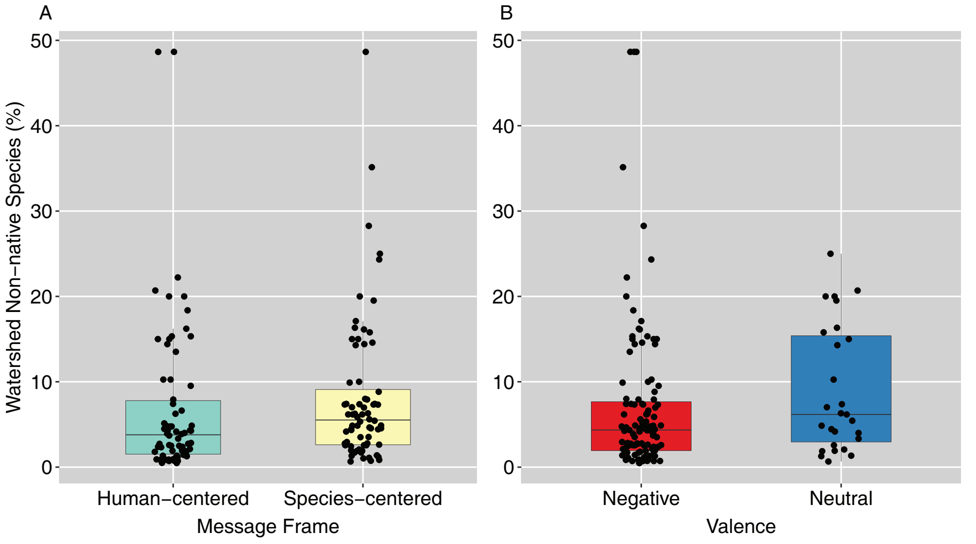

Figure 6. Relationship between non-native species richness (% of total species) in watershed of the study site and language use within the study, including message frame **A** and valence **B**.

more likely to be adopted when the study focus was monitoring or understanding the species, in contrast to studies with a focus on risk assessment that used predominantly negative valences (Table 3). Stage of invasion, transportation vector and study discipline had no influence on valence. Though the stage of invasion was not a significant predictor in the logistic regression model, there was a pattern in which negative language was used proportionally more often in studies examining establishment and spread, compared to transport and introduction (Fig. 5). Finally, we found no evidence that articles were more likely to portray non-native species negatively when conducted in watersheds containing more non-native species (Fig. 6B; W = 1235.5, p = 0.099, Wilcox test).

Relationships between terminology and the four predictor variables were assessed through RDA, where the first two axes explained 13% of the variation in terminology use ($F_{13,224}$ = 3.3, p = 0.001, Fig. 7). Of the total variation explained, stages of invasion (39%) and study focus (31%) contributed the most to explaining patterns in terminology (Table 4). As shown in the correlation triplot (Fig. 7), studies that looked at the "establishment" stage of invasion and had the study focus to "understand" used the term "non-native" more often and the term "invasive" less often. By comparison, studies that had the study focus to analyze "control" measures or that looked at the stage of "spread" were more likely to use the terms "invasive" and less likely to use the term "non-native." Use of the term "introduced" correlated with intentional human introductions and the term "non-indigenous" with unintentional human introductions. Studies that looked at the "introduction" stage of invasion used the terms "introduced" and "non-indigenous" more commonly than studies addressing other stages of invasion.

Table 3. Predictors of negative (reference level) vs. neutral valence in peer-reviewed articles regarding non-native aquatic species management. Significant results are highlighted in bold.

Variable	B	Standard error	Z	p	Exp(B)
Intercept	2.394	1.191	2.010	0.044	10.959
Study discipline[1]					
Interdisciplinary	14.243	956.232	0.015	0.988	1533180
Social sciences	0.130	1.111	0.117	0.907	1.139
Study focus[2]					
Monitoring	**-1.926**	**0.731**	**-2.637**	**0.008**	**0.146**
Understanding	**-1.462**	**0.642**	**-2.275**	**0.023**	**0.232**
Control	-0.719	0.679	-1.059	0.290	0.487
Stages of invasion[3]					
Introduction	0.499	1.305	0.382	0.702	1.647
Establishment	-0.970	1.182	-0.821	0.412	0.379
Spread	-0.075	1.138	-0.066	0.948	0.928
Transportation vector[4]					
Natural	0.120	0.667	0.180	0.857	1.128
Human (unintentional)	0.364	0.551	0.660	0.509	1.439
Human (intentional)	0.228	0.430	0.528	0.597	1.255
Human (Both)	1.308	1.144	1.143	0.253	3.698
All	0.387	1.192	0.324	0.746	1.472

[1]Biological sciences served as the reference level; [2]Prevention served as the reference level; [3]Transportation served as the reference level; [4]Vector not mentioned served as the reference level; Note: Results: ($\chi^2(13) = 29.238$; p=.006; Nagelkerke's Pseudo $R^2 = 0.181$).

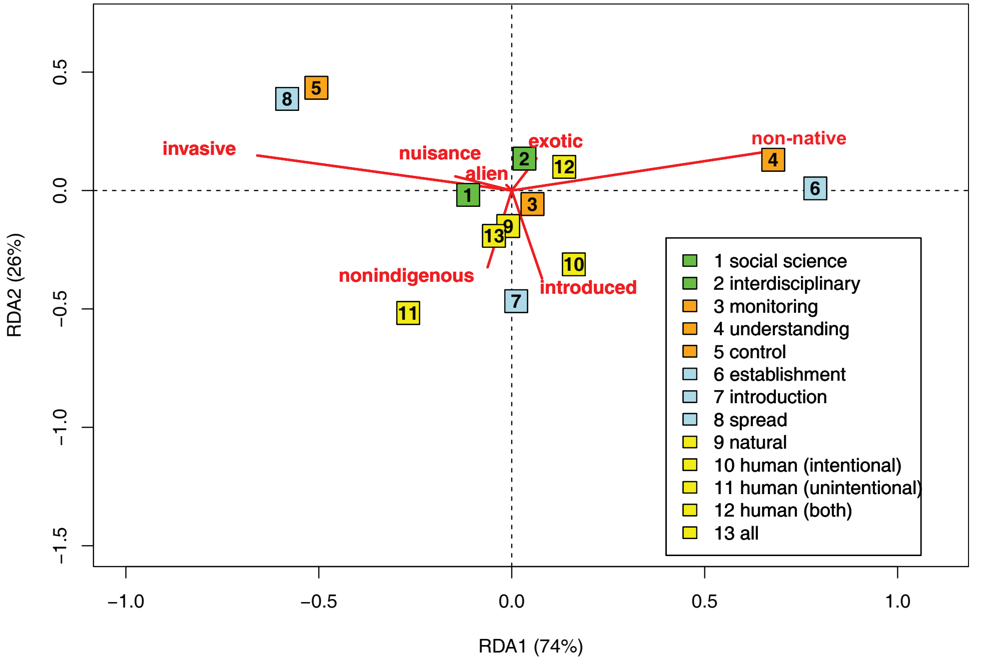

Figure 7. Redundancy analysis (RDA) of the terminology used in scientific publications (grey rectangles) concerned with invasive species management in the United States from 2008–2018. Eigenvectors (site scores) are scaled to their square-root. In total, 13.3% of variance is explained. Corresponding reference levels and further statistics are listed in Table 4.

Table 4. Permutation test and marginal effects of four explanatory variables on terminology use. The total sum of all Eigenvalues is 0.055. Significant results are highlighted in bold.

Variable	df	Variance	F	p	Eigenvalue using only one explanatory variable	Eigenvalue as %
Study discipline[1]	2	0.002	0.7	0.702	0.000	0.00
Study focus[2]	**3**	**0.014**	**3.5**	**<0.001**	**0.019**	**0.34**
Stages of invasion[3]	**3**	**0.017**	**4.2**	**<0.001**	**0.023**	**0.41**
Transportation vector[4]	**5**	**0.013**	**2.0**	**0.009**	**0.010**	**0.18**
Residual	224	0.298				

[1]Biological sciences served as the reference level; [2]Prevention served as the reference level; [3]Transportation served as the reference level; [4]Vector not mentioned served as the reference level.

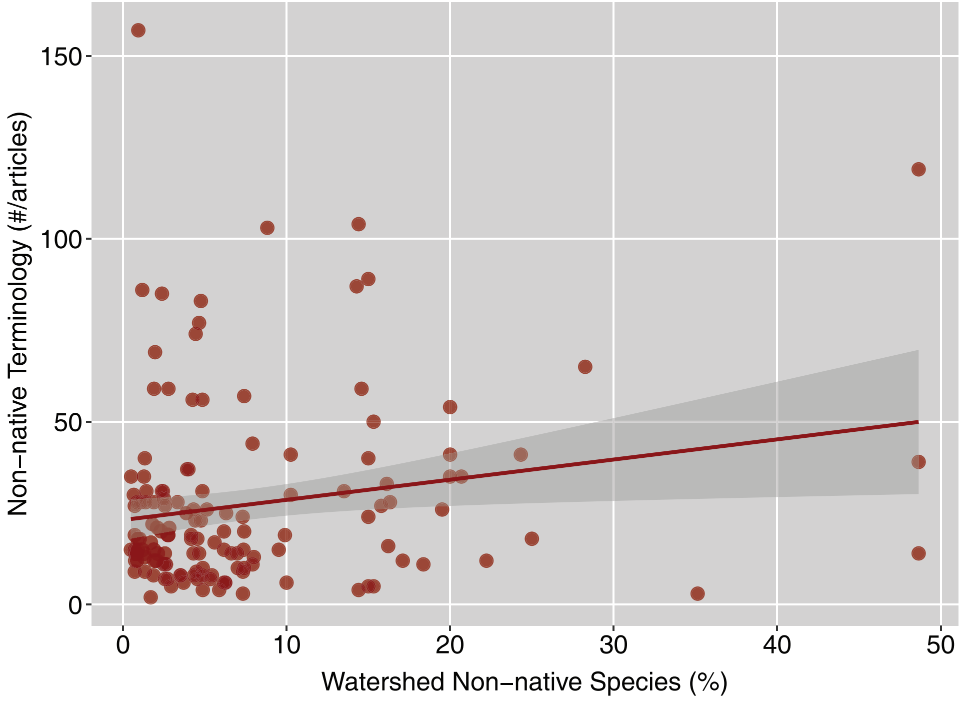

Figure 8. Relationship between non-native terminology used in each study and proportion of non-native species at the study site, assessed at the watershed level.

The overall frequency of non-native terminology used in each article was positively related to the percent of non-native species in the watershed where the study was conducted (Fig. 8; $F = 5.4$, $p = 0.022$), although considerable variation in this relationship existed.

Discussion

Our study aimed to quantify patterns and drivers of language use in the scientific aquatic non-native species literature in the United States. We discovered considerable variation in communication strategies used by scientists, including message frame, valence, and terminology. We contend that the factors explaining variation in communication patterns can be better understood through knowledge of message framing. Specifically, we observed that species-centered vs. human-centered frames strongly related to transportation vector and study focus, indicating that the role of humans tends to be highlighted when there is greater urgency in preventing the spread of non-native species, whereas the role of the species itself is centered when transportation vectors are not mentioned and the focus is on control. Aligned with previous research (Clarke et al. 2020), we found negative valences to be most common. Additionally, terminology use corresponded with stage of invasion, indicating that researchers are following guidance by past work to use standardized and consistent language, specifically relying on more general terms like "non-native" at earlier stages of invasion, and only classifying species as invasive after accelerating spread or clear impacts are occurring (Colautti and MacIsaac 2004; Blackburn et al. 2011).

We found researchers adopted message framing that aligned with a stated study focus. When an objective pertaining to risk assessment or a focus on prevention was expressed, human-centered frames were more common, corresponding to the important role humans play in curbing the spread of invasive species (Tabak et al. 2017). The importance of self-efficacy (i.e., beliefs that one has the ability to complete an action; Bandura 1977) in enabling people to engage in preventative measures is well-documented in the literature (Niemiec et al. 2017; Landon et al. 2018; Mankad and Loechel 2020), which underscores the importance of human-centered frames that emphasize the role of humans in biological invasions. By contrast, when the focus of research was to understand a species or to analyze control measures, species-centered frames dominated the narrative adopted in reporting results. This finding aligns with past research suggesting that species-centered frames are likely to activate risk perceptions and engagement in preventative behaviors (Hart and Larson 2014). Thus, because past work indicates the ability of both species- and human-centered frames to heighten risk perceptions, more research is needed to understand public responses to these frames and their success in changing behavior in positive ways. Such research (e.g., Clarke et al. 2020; Orth et al. 2020) should focus on analysis of science communication outside of traditional scientific papers or in press releases by scientific organizations because it is unlikely that the public or policy makers are readers of scientific papers.

The finding that negative valences were predominant in scientific papers is not surprising given the focus of the literature review on non-native species management, rather than targeting bodies of work on, for instance, stocking fish for capture fisheries. Accordingly, our selection of keywords (e.g., "invasive") may not always be used in studies of introduced species that are beneficial, although this is very unlikely to be the case given the need to comment on the negative impacts of non-native species even when reporting positive outcomes (e.g., Johnson et al. 2009; Aas et al. 2018). Despite this, we recognize that studies on the positive effects of non-native species may be underrepresented in our search (e.g., Carey et al. 2011). Emphasizing the negative impacts associated with invasive species seems to be perceived by invasion biologists as necessary – or at least helpful – to inform readers and generate support for preventing or controlling invasive species. However, there is a risk associated with an overabundance of negative language: as negative valences are translated into public news media, extreme negativity can lead to feelings of helplessness and disinterest in management initiatives (Clarke et al. 2020). This is particularly worrisome given recent evidence that invasive species can, in some instances, play positive roles for local livelihoods and human well-being (Shackleton et al. 2019), and in other instances, not have measurable ecological or social impacts (e.g., Wolter and Röhr 2010).

The use of terminology broadly aligned with recommendations in previous research to be deliberate about defining concepts and study contexts in invasion biology (Colautti and MacIsaac 2004; Copp et al. 2005). "Invasive" was the most frequently used term across all study attributes except when it was appropriate by definition to use "non-native." Specifically, the use of "non-native" rather than "invasive" aligned with stages of invasion such as establishment, where the species had yet to meet the requirements to be classified as invasive, defined as a species causing negative ecological or social impacts (Blackburn et al. 2011). Terms that were synonymous with "non-native," including "exotic," "alien," and "non-indigenous" were rarely used. In summary, invasive species researchers have responded to past calls for clarity in research (Richardson et al. 2000; Colautti and MacIsaac 2004; Blackburn et al. 2011), and are using consistent terms aligned with stages of invasion.

Language use showed some evidence of being related to the regional biodiversity context in which the study was conducted. Specifically, in watersheds containing relatively more non-native species, studies were more likely to use species-centered frames. Past work has shown species-centered frames to be more effective in raising stakeholder engagement in preventative behaviors (Hart and Larson 2014), thus the correlation between this framing and increasing dominance of non-native species is notable. Additionally, there was a positive relationship between non-native species richness and overall use of non-native terminology. Researchers may be reflecting the degree of risk perceived in the study region with language that highlights these risks more clearly. Ultimately, higher-risk areas may warrant stronger language to better convey the need for greater management attention and heightened public awareness.

A strikingly small proportion of studies within the biological invasion literature were conducted through an environmental social science lens. Given the role of recreationists in non-native species transport (Johnson et al. 2009; Rothlisberger et al. 2010; Cole et al. 2019; Golebie et al. 2021) and complex and often controversial views about non-native species (Schlaepfer et al. 2011; Russell and Blackburn 2017; Schlaepfer 2018), there is a strong need for more social science research (e.g., Kochalski et al. 2019; Shackleton et al. 2019). The social science studies included in the review exclusively used negative valences, with a strong emphasis on human-centered frames. Use of human-centered frames was logical, given that social science seeks to understand the thoughts, feelings and actions of humans. Negative valences may have dominated given that the studies in our review predominantly investigated boater and angler transport of invasive species, and thus stressed the negative impacts of invasive species that could be averted by human action. Additionally, raising self-efficacy, the awareness of how individuals can play a role in invasive species spread, is an important step in encouraging people to take action. However, these results reveal an untapped area of inquiry on relationships between humans and non-native species. Several research questions should be addressed: In what ways are invasive species meaningful to humans? What are stakeholder preferences for invasive species management? On what information do people base these beliefs? Which non-native species are perceived as beneficial rather than harmful, and in what socioeconomic or cultural contexts? How can managers nudge recreationists and other people (e.g., aquarium fish holders, see Wolbers and Donnelly 2019) to refrain from further spreading non-native fishes and which messages' frames are most effective in such communication strategies (e.g., Shaw et al. 2021)? Answering these questions will enhance invasive species management practices by deepening knowledge of how people do (or do not) support decision-making outcomes.

Conclusion

In conclusion, our work quantifies how published literature on aquatic non-native species research conveys varied message framing, valence and terminology. We show that authors of peer-reviewed journal articles are effectively using standardized terminology established in past work. For instance, we found limited evidence for inflammatory or exaggerative framings being dominant within peer-reviewed published literature from 2008 to 2018. Additionally, message frames evoked in these articles are correlated with study focus and local biodiversity context, indicating that language use is tailored to contextual conditions. We encourage researchers to be aware of how their language might be influenced by such factors and actively consider whether communication choices match the study goals. Future work should seek to evaluate language use in public-facing communication to identify relationships between public and academic communication, as well as the impacts of communication style on public perceptions of invasion biology research. Understanding the role of science communication more broadly in public understanding of invasion biology and support for management decisions is an important direction for future research.

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Supplementary material 1

Codebook

Authors: Elizabeth J. Golebie, Carena J. van Riper, Robert Arlinghaus, Megan Gaddy, Seoyeon Jang, Sophia Kochalski, Yichu Lu, Julian D. Olden, Richard Stedman, Cory Suski

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