

Invasion Culturomics and iEcology

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Introduction

Biological invasions are a major threat to global biodiversity and can have substantial socioeconomic costs. Although invasive non–native species have been studied extensively, their monitoring and management are often inadequate (Pergl et al. 2020). Moreover, the great harm invasive non–native species cause tends to be underestimated by the public and their management often opposed (Courchamp et al. 2017). There is a need to better understand societal awareness, perceptions, values, and attitudes toward invasive non–native species and the level of societal support for management plans. However, research to gauge these factors is rare and difficult to implement (Verbrugge et al. 2013; Lindemann–Matthies 2016).

Conservation culturomics focuses on the study of human interactions with nature through the quantitative analysis of voluminous digital data to aid conservation (Ladle et al. 2016). It has great potential to inform invasion science and practice by providing new opportunities to gauge societal awareness and attitudes toward invasive non–native species. Digital data can also provide information on distributions, spread dynamic, life history, and impacts of invasive non–native species within the framework of iEcology (Jarić et al. 2020). iEcology is the study of ecological patterns and processes based on ecological data generated for other purposes and stored digitally. Culturomics and iEcology use similar data sources, but iEcology focuses on broad ecological patterns and processes, rather than human–nature interactions.

Major applications of conservation culturomics and iEcology relevant to biological invasions include analysis of

internet search activity and social media to gauge societal awareness and effects of information dissemination and management; use of sentiment analysis to study societal attitudes toward invasive non–native species and their management; use of digital media for taxonomic identification and early warning of invasive non–native species introductions; assessment of geotagged digital media to map and monitor distribution, spread, and impact of invasive non–native species; and analysis of digital media to study their life history, phenology, and novel biotic interactions.

We examined the state of the art of invasion culturomics and iEcology, explored potential applications for invasive non–native species research and management, and considered future challenges and developments in these areas.

Awareness and Effects of Information Dissemination and Management

Public awareness strongly affects public support for and effectiveness of invasive non–native species management (Fukano & Soga 2019). Culturomics can provide voluminous and accurate spatiotemporal insights into public awareness of invasive non–native species and control measures. Public attention can be gauged using internet salience (i.e., frequency of species names online), web page visitation frequency (e.g., Wikipedia page views), and relative search volumes (e.g., through internet search engines) (Correia et al. 2021 [this issue]) (Fig. 1a). For example, Fukano and Soga (2019) analyzed spatiotemporal trends in public attention to fire ant (*Solenopsis invicta*) invasion in Japan based on relative search volumes estimated using Google Trends. Wyckhuys et al. (2019) studied internet salience of invertebrate

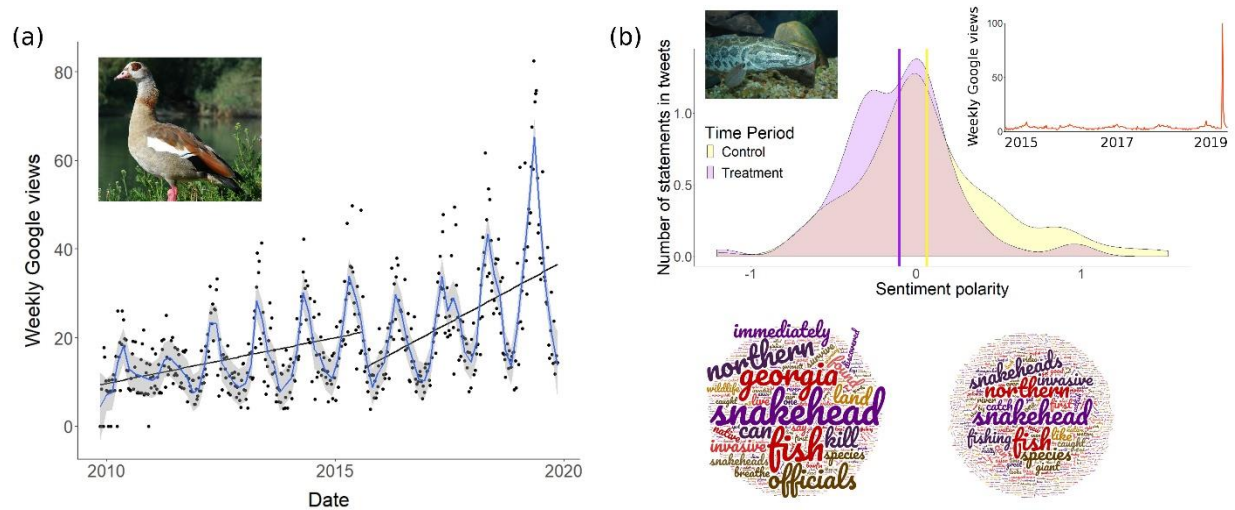


Figure 1: (a) Relative search volumes (Google Health–Trends–API) for Egyptian Goose (*Alopochen aegyptiaca*) in Germany over 10 years (2009–2019; structural break in August 2015) ($p < 0.01$) (photo by V. Buhl) and (b) results of a sentiment analysis of tweets on northern snakehead (*Channa argus*) invasion in the United States posted during the period of high media attention (treatment) due to new records of species introductions (6–12 October 2019) and during a control period when there was no media attention (January–June 2019) (t test, $p < 0.01$) (vertical lines, median values; inset graph, U.S. public interest in northern snakehead from 2014 to 2019 based on Google Trends) and word clouds for the target period (left) and the first 6 months of 2019 (right) (photo by B. Gratwicke). See Appendix S1 for method details.

biological control agents in different countries worldwide. Such studies provide information on awareness–raising campaigns and public visibility of management actions and help guide public policy by identifying awareness gaps and priorities and providing real–time awareness tracking (Wyckhuys et al. 2019).

Culturomics tools can also be used to explore pet and ornamental species trade, such as societal attention and preferences, charismatic traits driving interest and choices, and online trade patterns. Such research can be used to assess risks from these introduction pathways (Measey et al. 2019).

Attitudes Toward Invasive Non–Native Species and Management Measures

Researchers use R–based user–developed packages to conduct sentiment analyses (Lennox et al. 2020; Correia et al. 2021). These analyses quantify polarity of attitudes

expressed in texts by assigning sentiment values to text strings based on algorithms and established lexicons (Lennox et al. 2020). Sentiment analysis provides an inexpensive metric to examine public perceptions or attitudes, for example, in support or opposition to management measures (Fig. 1b). For example, Mehmet et al. (2018) applied sentiment analysis to assess stakeholder attitudes toward management of an invasive fish in Australia.

Sentiment analysis has been applied rarely in conservation and invasion science. Nevertheless, invasion scientists tend to use militarized language (Larson 2005) that can effectively be categorized by sentiment algorithms for rapid assessment of large pools of data.

Taxonomic Identification and Early Warning of Introductions

Early detection of the spread of invasive non–native species improves chances of rapid and effective control before species

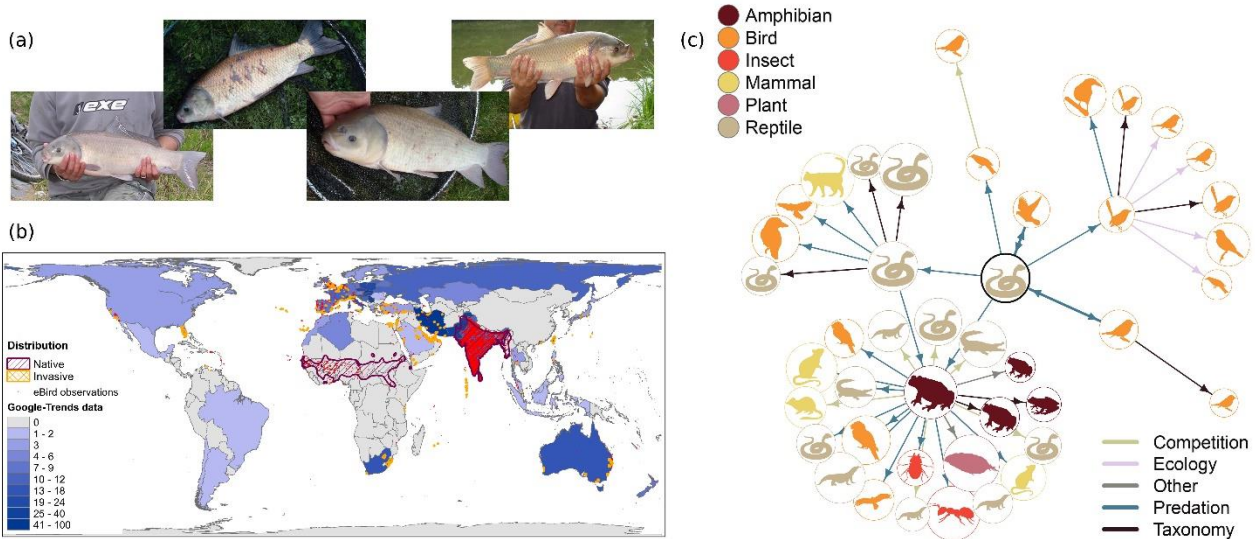


Figure 2: (a) Images obtained from angler websites of North American buffalo fishes (*Ictiobus* sp.) in natural environments in the Czech Republic (Kalous et al. 2018), (b) global distribution of Rose-ringed Parakeet (*Psittacula krameri*) based on relative search volumes (Google Trends), BirdLife and Birds of the World data (purple and yellow areas), and eBird distribution data (red points), and (c) directed network of the second-order linked-out species from the English Wikipedia for the brown tree snake (*Boiga irregularis*) page (node size, relative to number of views each page received from 1 July 2015 to 28 November 2019; arrows, direction of web links between pages; node, taxonomic group; edge colors major interaction types between species). See Appendix S1 for method details.

become established. Images and videos posted on social media and online forums represent important sources of invasive non-native species records. Imagery can be used for species identification and detection of novel introductions or range expansions. This can be accomplished either through assessment of digital data by expert teams or through machine-learning methods. For example, Kalous et al. (2018) identified the presence of two invasive fishes in the Czech Republic based on images obtained from angler websites (Fig. 2a). Similarly, Schifani and Palionelli (2018) identified an invasive fly in Sicily based on biodiversity-focused internet forums and Facebook groups.

Mapping and Monitoring Invasive Non-Native Species Distribution, Spread, and Impact

Digital data and associated spatial information can provide valuable insights into the distribution of environmental features, including invasive non-native species ranges and spread (Proulx et al.

2014). Considerable resources are invested each year to monitor invasive non-native species status and distribution, which could be supported and complemented by iEcology data, for example, geotagged text, videos, and images posted on social network and media-hosting platforms (e.g., Instagram and Twitter) (Daume 2016; Allain 2019) and spatially differentiated relative search volumes (e.g., Google Trends) (Proulx et al. 2014; Fukano & Soga 2019) (Fig. 2b). Such voluminous and instantaneously accessible data could prove key to quick assessments of distribution and spread of many invasive non-native species.

Quality, coverage, resolution, and reliability of these data are expected to improve as use of the internet and social media grows, automation of web crawling methods increase, and geotagging features of digital data and their integration with other information sources, such as citizen-science data, improve.

Invasive Non–Native Species’ Life History, Phenology, and Novel Biotic Interactions

Digital data can also be analyzed to address iEcology research questions on population structure and dynamics, life history, phenology, behavior, functional roles, interspecific interactions, community dynamics and diversity, and regime shifts. For example, researchers can use images to study morphology and biometry, videos to study behavior, and spatiotemporal metadata to assess phenology and interspecific co–occurrence (Jarić et al. 2020). Such applications are especially valuable for biological invasions, typically characterized by novel and often unexpected interactions, ecosystem functions, and life–history shifts, which makes timely information critical for effective management planning (Jarić et al. 2019). For example, Daume (2016) studied invasive non–native species phenology of vertebrate, insect, plant, and fungi invasive species based on tweet contents, and Jagiello et al. (2019) explored the behavior of an invasive mammal with YouTube videos.

Challenges and Limitations

Key challenges when using culturomics and iEcology include inherent biases in the spatiotemporal representativeness of data, which are highly skewed toward the last decade and areas with internet access, as well as biases toward larger–bodied, charismatic and easily recognizable taxa, those found in more accessible habitats, and those with more immediate impacts. Additional risks arise from potential species misidentification generated by data producers, experts assessing digital data, or by automated species identification software (Jarić et al. 2020). As data accumulate,

more hardware requirements and computational know–how will be needed. Handling people’s uploaded data or online interactions also presents ethical challenges (Di Minin et al. 2021 [this issue]). Further developments in this field will depend strongly on the involvement of interdisciplinary research teams and cross–field collaborations. For more detailed information on these and other challenges and limitations, see Correia et al. (2021) and Jarić et al. (2020).

Future Directions

Digital data and culturomic methods are becoming more user–friendly, facilitating their uptake by the larger scientific community. This could greatly increase the volume of available information on invasive non–native species, especially once web crawlers are used more commonly to automatically scrape the web, identify and validate species’ mentions, and flag range expansions. Moreover, these data open many avenues for novel research on invasion management campaigns and societal interactions with invasive non–native species at scales previously unfathomable.

As the spread and effects of invasive non–native species increase globally, new approaches and tools will be needed to tackle this problem. Invasion culturomics and iEcology represent promising options to track and study invasions as well as societal attitudes and interactions with invasive non–native species.

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Supporting Information

Additional information is available online in the Supporting Information section at the end of the online article. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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Invasion culturomics and iEcology - Appendix S1

1) Relative search volumes for Egyptian goose (*Alopochen aegyptiaca*) in Germany over 10 years (November 15th 2009-2019). The Egyptian goose (*Alopochen aegyptiaca*) was added to the EU list of invasive alien species in 2017 (European Commission, 2017). In Germany, the species was first observed in 1866, has been breeding since 1981, and by 2000s was considered a fully established alien species in the country (Bauer and Woog 2008; Gyimesi and Lensink 2012).

We obtained relative Google weekly search volumes for the topic ‘Egyptian goose’ using Google-Health-Trends-API (Application Programming Interface) and a dedicated Python library (google-api-python-client; <https://pypi.org/project/google-api-python-client/>). Topic search volumes include searches on a collection of related search terms including synonyms and typos. The results represent the proportional search volume relative to all searches made in the sampled area (Germany) at the sampled time spanning 10 years (15 November 2009 - 14 November 2019) (Deiner et al. 2019, Vardi et al. 2021). Breakpoint regression analysis was used to test for structural breaks in the trend using R. Relative search volumes in Germany over 10 years (2009-2019) revealed an increasing trend (Fig. 1), with a structural break in August 2015 ($p < 0.01$).

2) Sentiment analysis of tweets related to northern snakehead (*Channa argus*) invasion in the United States, posted during the period of high media attention due to new records of species introductions (6-12 October 2019). Northern snakehead (*Channa argus*) was introduced in the eastern United States, where it established viable populations (Orrell and Weigt 2005; Landis and Lapointe 2010). Its discovery in October 2019 in the southeastern United States, in a pond in Georgia (Culver 2019), was followed by a strong coverage by news and social media and high level of public attention (Fig. 1) during the week following those reports (6-12 October 2019).

We performed sentiment analysis of tweets that mention the species posted during 6-12 October 2019 ($n = 79$) and compared it with the control group, represented by tweets mentioning the species that were posted during 1 January - 30 June 2019 ($n = 120$).

Tweets were obtained using the advanced search option on Twitter, manually extracted, and checked for mismatches (i.e. by omitting tweets unrelated to the species and its invasive population in North America). The control group represented the first 120 tweets listed in the results for the given period. Tweets from the target period and the control group were separated by a sentence using the `get_sentences` function in the R package `tidytext` (Silge and Robinson 2016). Tweet sentiments were then calculated for each group using the Jockers-Rinker library with the `sentiment` function in the `sentimentr` package (Rinker 2019). The Jockers-Rinker library includes valence shifters. A t-test was used to test for independence of the sentiments from tweets in the control and treatment periods. Figures were drawn with the `ggplot2` library (Wickham 2016).

Sentiment analysis indicated more negative sentiments related to northern snakehead during the period of high media attention due to new records of species introductions (6-12 October 2019) than for tweets posted during the first six months of 2019 (t-test, $p < 0.01$; Fig. 1). The difference was also indicated by a word cloud analysis of tweets from the two periods (Fig. 1).

3) Identification of the presence of North American buffalo fishes (*Ictiobus sp.*) in the Czech Republic based on images obtained from angler websites. Bigmouth buffalo (*Ictiobus cyprinellus*) and black buffalo (*I. niger*) have been introduced to Europe, but until recently were not observed in the wild (Kottelat and Freyhof 2007). During 17 January - 2 February 2018, an analysis of online data from Czech angler websites was performed, to test whether the two fish species were ever caught in natural waters in the Czech Republic (Kalous et al. 2018).

Data sources included the two most visited Czech angling websites (www.mrk.cz and www.chytej.cz). Both websites were searched by the Google Site Search tool, using vernacular names of the species that are used by Czech anglers. All relevant records with related information were collected, and validation criteria for all records were applied (i.e. precision of the locality description, quality of photography, contacting anglers who posted the records, etc.). Species identification followed characteristics from Page and Burr (1991).

The search resulted in 13 verified records from the two angler forums (Fig. 2), which allowed the identification of the two species and confirmed their presence in the rivers in the Czech Republic (Kalous et al. 2018).

4) Global distribution of rose-ringed parakeet (*Psittacula krameri*) indicated by relative search volumes with established populations in at least 35 countries on four

continents. Rose-ringed parakeet (*Psittacula krameri*) is considered to be the most widely distributed parrot species globally (Schwartz et al. 2009). We used Google Trends platform <https://trends.google.com/trends> to assess its global distribution. We searched for the rose-ringed parakeet as the topic 'birds', globally, with the 10-year timespan (1 December 2009-2019). Displayed are the relative search frequencies comparable between countries (Correia et al. 2019). Mapping was done in ArcGIS, using a map of global countries in a Behrmann projection (ESRI 2019).

The map also presents several additional sources of geographical information regarding the rose-ringed parakeet distribution (Fig. 2). Range maps were taken from the BirdLife HBW ranges (2018, ver. 1; BirdLife 2018), divided between native and invasive location based on the BirdLife/HBW designation. To this, we added all observations logged onto the eBird platform from the October 2019 version (altogether 290,025 observations; eBird 2019).

5) Directed network of the 2nd order linked-out species from the English Wikipedia brown tree-snake (*Boiga irregularis*) page. We looked at the second-order interaction network of species in the English Wikipedia page of the brown tree-snake (*Boiga irregularis*; https://en.wikipedia.org/wiki/Brown_tree_snake). To do this, we explored all of the cases where there are linked out Wikipedia pages (Bar-Hen 2016) for species entities (i.e., items that had a Global Biodiversity Information Facility ID – Wikidata identifier: P846; see also Mittermeier et al. 2019). We repeated this procedure for all six species with linked out page in the brown tree-snake page to obtain the 2nd order interaction network. We then obtained the number of pageviews for all of the pages in the network, received between 1 July 2015 and 28 November 2019, using the 'pageviews' package in R (R-Core-Team 2015; Keyes & Lewis 2016). The analysis was only performed for species, not for higher taxa. We then manually classified each out-linked species mention based on the text in the page as referring to: competition, predation, taxonomical similarities/differences, shared ecological characteristics, and others (Fig. 2).

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