

Opinion

Culturomics and iEcology provide novel opportunities to study human and social dimensions of alien species introductions

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Invasive alien species negatively impact ecosystems, biodiversity, human societies, and economies. To prevent future invasions, it is crucial to understand both the ecological and the human and social factors determining whether a species is picked up, transported, and introduced beyond their native range. However, we often have little or no information on key human and social factors. Here, we explore how alien species introductions are shaped by a combination of ecological and human and social factors and highlight the potential of the emerging fields of conservation culturomics and iEcology for disentangling their relative importance. We argue that quantifying and assessing the relative importance of the human and social dimensions of alien species introductions can substantially improve our understanding of the invasion process.

The role humans play in alien species introductions is not fully understood

Humans have been moving species to regions beyond their natural biogeographic boundaries for centuries [1]. A small proportion of the introduced species become naturalized, that is, start to reproduce in the wild without the assistance of humans, and a subset of them become invasive, spreading over large distances from the points of introduction [2,3]. Invasive alien species negatively affect the functioning and services of natural ecosystems, cause species extinctions [4], and exert severe negative impacts on societies, human well-being [5], and economies [6,7]. As the rate of new introductions, naturalizations, and invasions shows no sign of saturation [8], management actions are being developed to prevent and reduce the negative impacts of biological invasions [9].

The introduction of alien species represents a key stage in the invasion process [3,10] and one where timely management measures are most cost-effective [11]. Understanding the multiple factors that determine introduction success [12–14] is the first step toward improving the robustness of invasion risk assessments and effectiveness of management actions. Unfortunately, despite emerging awareness of the importance of human and social factors [15,16], such as public perceptions and attitudes, we often have limited information on their role in the invasion process, especially at large scales. Here, we demonstrate that the ongoing digital revolution and the currently available large volumes of online data allow us to overcome this current gap in knowledge.

The past decade has seen enormous advances in our ability to identify, access, and analyze online digital data, that is, data stored digitally on web pages, social media, citizen science platforms, and various other online platforms. This progress led to the development of the emerging fields of conservation culturomics and iEcology. Conservation culturomics focuses on the study of human culture and its engagement with nature [17]. It has been applied to assess various topics,

Highlights

To prevent future invasions, it is essential to understand the multiple factors that determine which alien species are being introduced and where.

It is not yet fully understood how ecological factors and a set of human and social factors together shape alien species introductions.

The emerging fields of conservation culturomics and iEcology offer low-cost and broad-scale valuable tools for studying the factors influencing the introduction of alien species.

By adopting an interdisciplinary approach, we can advance our understanding of the factors determining alien species introductions and plan conservation outcomes more effectively.

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including societal interest in nature and attitudes toward biological invasions [18,19]. iEcology uses similar data sources and analytical tools as conservation culturomics but focuses on addressing ecological questions [20]. iEcology can provide valuable information on species occurrences, population dynamics, species interactions, and life history and allow improved monitoring of target taxa, such as alien, invasive, rare, or protected species [19,20]. In a broad sense, data generated by citizen science can also be perceived as part of the culturomics and iEcology family of resources, even though they differ in some aspects. However, unlike citizen science, which aims to engage citizens to proactively and voluntarily provide data that can be used in scientific research and monitoring [21], conservation culturomics and iEcology aim to harvest and analyze digital data generated by people for other purposes to provide novel insights into human nature and ecological interactions [17,20,22]. Thus, data provided by citizens for one particular purpose (e.g., recording the presence of a particular species in one area) can be used in conservation culturomics and iEcology studies for a different purpose (e.g., to assess motivations, awareness, and attitudes of citizen scientists, whether they perceive recorded species positively or negatively, or to spot the interactions of the recorded species with other taxa).

Here, we present a scheme for the intentional and unintentional introduction of alien species, aiming at disentangling the role of human and social factors and their interactions from the traditionally considered ecological factors (i.e., the alien species traits and the characteristics of the ecosystem) at the beginning of the invasion. By focusing on human and social factors, as well as other ecological factors that can be studied through the use of conservation culturomics and iEcology approaches, the scheme presented here is compatible with the Macroecological Framework for Invasive Aliens (MAFIA) [10] and can be used as its extension. It is restricted to the initial stages of the process up to the introduction of a species to the new region. Also, we propose a set of approaches from the fields of conservation culturomics and iEcology that can be used to obtain proxies to quantify the outlined factors influencing alien species introductions.

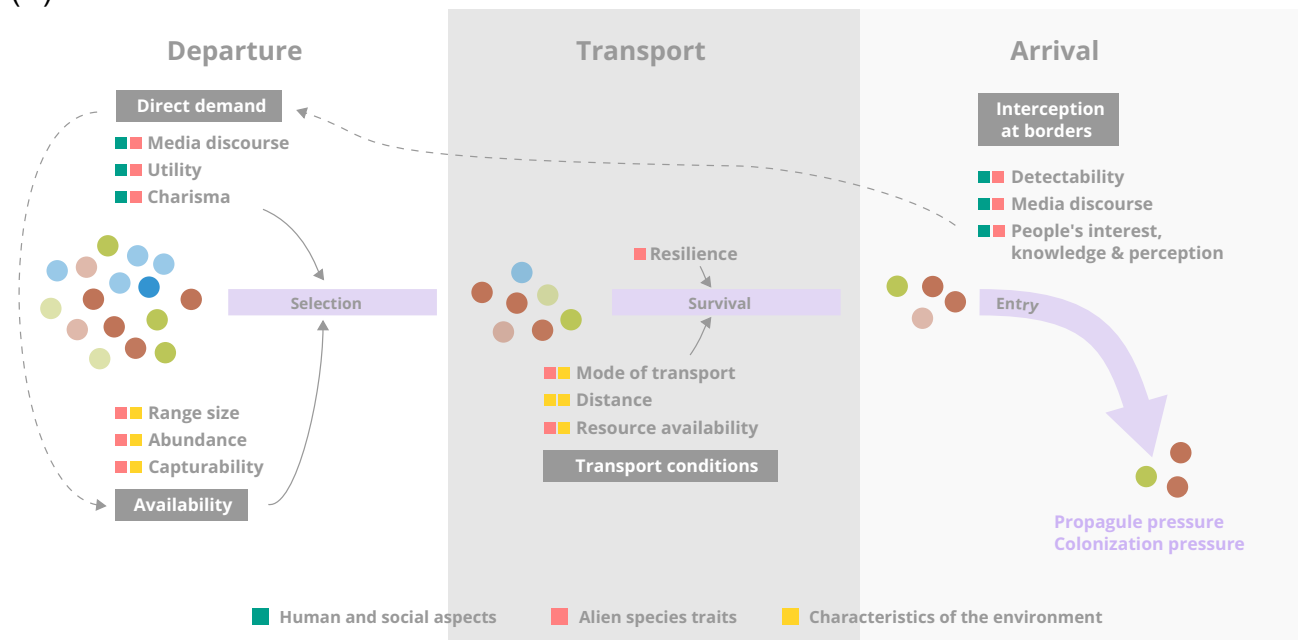
The scheme

At the core of the scheme is the notion that there are three stages that lead to the introduction of alien species: (i) departure from the native range, (ii) transport from its native range to the introduced range, and (iii) arrival in the introduced range [23,24]. This process is driven by an interplay of three classes of factors related to (i) the alien species traits (i.e., the attributes that determine how alien species interact with their abiotic environment and with other species), (ii) the characteristics of the environment (i.e., the biotic and abiotic characteristics of the native and introduced ranges), and (iii) the human and social aspects of the introduction event (i.e., the interactions of people with the alien species as well as the social, economic, political, and cultural context in which the introductions take place) [5,10,12,25,26]. The interactions between these factors are also key drivers of introduction success (see Figure 1, which shows the factors influencing the introduction process, and Table 1, which describes those factors that can be studied by extracting and analyzing information from digital data sources using conservation culturomics and iEcology approaches).

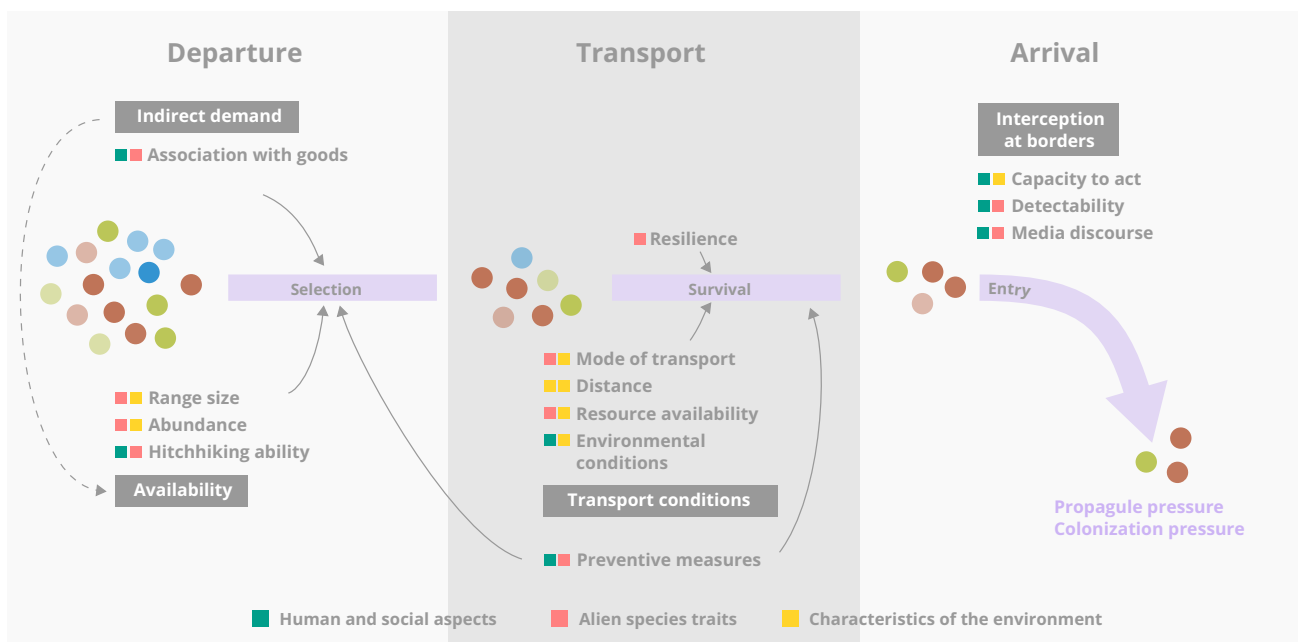
Departure

The native range is a geographical area characterized by a pool of native species and by a set of environmental, human, and social characteristics, all of which will determine whether a particular species is selected for or accidentally included in the transport. In particular, social and human aspects play an important role in this initial stage of the alien species introduction process. For example, when people know that a species is threatened and protected, they are generally less likely to intentionally select it for transport [27]. However, the opposite is also true in some cases, where uncommon and threatened species are more demanded by specialized collectors [28]. Moreover, the level of people's interest in a species and the level and polarity of people's

(A)



(B)



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Figure 1. Schematic depiction of the classes of factors, their interactions, and stages leading to the intentional and unintentional introduction of alien species, causing propagule and colonization pressures. From the initial pool of species and individuals available in the native distribution range, only a subset is selected for transport either deliberately (A), if there is demand for it, or unintentionally (B) and departs the native range, only a fraction of these survives the transport, and some of them cross the border and arrive to the non-native range [either because they are welcome (A) or remain undetected (B)]. This process is driven by three different sets of factors: (i) the alien species traits, (ii) the characteristics of the environment, and (iii) the human and social aspects of the introduction event as well as their interactions.

Table 1. Examples of proxies for the human and social factors influencing alien species introductions and their interactions with ecological factors that can be obtained by using approaches from the fields of conservation culturomics and iEcology^a

Factor's class	Factor	Description	Type	Stage			Examples of proxies from culturomics and iEcology	Refs
				Departure	Transport	Arrival		
S&E	Abundance	Number of individuals of an alien species in its native range	UI	X			Number of mentions of the species on social media platforms per area in its native range	[49]
S&E&H	Capturability	Susceptibility of an alien species to being caught or taken into cultivation	I	X			Qualitative information obtained from images and text posted on social media, featuring the methods and effort people apply to capture an alien species	[55]
H&S	Charisma	Level of attractiveness or charm attributed to an alien species	I	X			Number of times an alien species is mentioned together with words associated with charisma on social media platforms and online news outlets	[56–58]
H&S	Commercial presence	Presence of an alien species in the commercial trade	I	X		X	Presence of an alien species on e-commerce websites, such as Amazon and eBay, or online plant nurseries and pet stores	[59,60]
H&S	Demand	The willingness of people to purchase an alien species	I	X		X	Number of purchases of an alien species in online shops or wishes expressed in comments in online shops or on social media	[59,60]
H&S	Detectability	The ease of locating the presence of an alien species	UI			X	Qualitative information on detections of alien species in the points of entry obtained from text analyses of social media posts or online news	[55,61]
H&S	Hitchhiking ability	Ability of an alien species to attach to another object, commodity, organism, or substrate and get transported to a new location	U	X	X		Qualitative information obtained from images and text posted on social media featuring the transport of alien species attached to objects, other organisms, or substrates	[61]
H&S	Media discourse	The ways in which the media frame an alien species	UI	X		X	Text analyses (e.g., sentiment or topic analyses) of media outlets featuring a particular alien species	[18,43,62,63]
H&S	People's interest	Interest of people in an alien species	UI	X		X	Number of searches of an alien species (Google Trends), Wikipedia pageviews, or mentions in social media and news outlets	[43,64–68]
H&S	People's knowledge	People's awareness of an alien species being protected in the native range or invasive in the introduced range	I	X		X	Number of social media posts mentioning the name of an alien species together with an invasive or conservation context	[69]
H&S	People's perception	People's perception of an alien species as favorable or unfavorable	I	X		X	Text analyses of social media posts and news outlets	[46,69]
S&E&H	Range size	Area of the native range of an alien species	UI	X			Area where the species is mentioned on social media platforms in its native range	[49]
H&S	Utility	Whether an alien species has a use for society	I	X		X	Qualitative information obtained from social media, e-commerce, or online news outlets on the uses of an alien species	[70,71]

perceptions and media discourse may also affect its intentional selection for transport outside the native range [29]. Species that are well known for their invasiveness might be intercepted at this stage and excluded from consideration.

The interactions between the three classes of factors outlined above (species traits, environment, human and social aspects) are also likely to play an important role in the departure stage. For example, abundant species with large native ranges (a factor that results from the interaction between alien species traits, such as plasticity or dispersal ability, body size/mass, and characteristics of the environment, such as climate or nutrient availability) are more likely to be intentionally or unintentionally captured in the native range and transported elsewhere since they are encountered more often [30,31]. In the case of intentional introductions, species with higher charisma or utility (factors that depend on both the traits of the species and the current preferences of people) are generally more demanded by consumers and hence are more likely to be present in commerce and transported to new regions [32–34]. Species also have better chances of being selected for transport if they are easily detected. Moreover, the likelihood of being selected for transport will be higher in species that are associated with goods [35] or with good hitchhiking ability (i.e., the capacity to attach to an object, commodity, medium, organism, or substrate that will be transported by humans to a new area [31]) or the ability to survive in captivity. The latter will depend on the capacity of the species to survive under the conditions that they will be exposed to and that differ from those in their natural environment and whether people can provide them with adequate resources during transport [33].

Transport

Whether a species is successfully transported from its native range to a new area will primarily depend on the distance between the two areas [35]. It is also essential that native and introduced ranges are connected by roads, canals, or shipping or air routes [36,37]. The socioeconomic status of the native and introduced ranges [38] will influence the characteristics and strength of this network. Moreover, whether the species is transported deliberately or not might improve its chances of survival since intentionally introduced species often have resources provided during transport (i.e., while intentionally transported species are provided with food and water and are protected from any unfavorable conditions of the outside environment, species introduced unintentionally might experience various stressful environmental conditions that can jeopardize their survival) [39,40].

The interactions between human, social, and ecological factors can also considerably influence the transport of alien species. For example, the demand for a species will influence the species availability as well as the connectivity with regard to it being transported between the native and introduced ranges [39], while its resilience or capability to survive transport will determine whether it arrives in the new area [33,40].

Arrival

The distance between the native and introduced ranges is likely to indirectly affect the likelihood of an alien species being detected upon arrival. For example, species unintentionally transported by long-distance air and shipping routes, sometimes overseas, will often need to pass through customs inspection at airports or ports, while those travelling short distances (e.g., attached to clothing, machinery, contaminants of goods, or transported in vehicles) might be less likely detected since controls are less thorough [33]. Alien species known to be invasive elsewhere are also

Note to Table 1:

^aThe type of introduction for which the factor is relevant is classified as unintentional (U), intentional (I), or both (UI). Factors are classified into alien species traits (S), characteristics of the environment (E), and social and human aspects (H) as well as interactions between them (e.g., S&E, S&H, or S&E&H). References relate to the cases when culturomics and iEcology were used to address the given factor.

generally more likely to be detected at the points of entry [28,41,42]. Moreover, species portrayed as having negative impacts by the media [43], negatively perceived by the public [29], or well known to people for their invasive potential [1] are usually considered unwanted, hence there is a higher chance to detect them at the points of entry. The socioeconomic status in the region of introduction will also influence the detection capacity of respective authorities [44,45].

Digital data sources, formats, and methods

Online digital data suitable to quantify the factors influencing the introduction of alien species can be obtained from multiple sources (e.g., social media and citizen science platforms, news outlets, e-commerce sites, etc.) and can represent different formats (e.g., text, images, videos, metadata, or user interactions with the data, including searches, views, likes, comments, or shares) [18,20,22]. Moreover, the same digital data or approaches can be used to obtain information on different factors. In the following, we describe some examples of digital data sources and their formats and methods that can be used to analyze them.

Text from social media platforms

Text posted by users on social media platforms such as Facebook or X (formerly Twitter) can be analyzed to infer people's perceptions. For example, Daume [46] analyzed 2,842 tweets mentioning invasive alien species impacting forest ecosystems in the USA and found a general consensus on the invasiveness of emerald ash borer (*Agrilus planipennis*) and that Twitter users seemed to oppose the management of oak processionary moths (*Thaumetopoea processionea*) and eastern gray squirrels (*Sciurus carolinensis*). Additionally, such text can also be used to infer societal and management effects of species charisma and utility. For example, by exploring the posts on Instagram accounts of tourism organizations based in New Zealand, Hayes *et al.* [47] found that these organizations promoted invasive lupins (*Lupinus polyphyllus*) as a tourist attraction. Sentiment or topic analyses can also be used to infer people's perceptions when applied to text extracted from social media [18].

Images and videos from social media and citizen science platforms

Images posted on social media and citizen science platforms can be used to infer the detectability and hitchhiking ability of alien species. If such images are georeferenced, they can also improve our knowledge of the location and timing of introduction events. To this end, 12 videos posted on a YouTube channel from Brazil provided insights into the complete invasion process of four alien fishes, including their transport and release in a particular basin and their subsequent establishment, spread, and negative impacts in the area [48]. Georeferenced images posted on social media can also improve our knowledge on the distribution and temporal dynamics of alien species. For example, O'Neill *et al.* [49] investigated how species occurrences vary between traditional, citizen science, and social media records and concluded that social media records can provide insights into the distribution and habitat preference of alien species that are different from those provided by traditional recording schemes and citizen science initiatives.

Search volume data from Google Trends

Search volume data from Google Trends can be used to obtain proxies for both people's interest and knowledge of particular alien species. For example, using Google Trends search data from 2010 to 2020 for 209 introduced plant species in the continental USA, Woodworth *et al.* [43] observed the highest public interest in abundant alien species and in those causing impacts to human health.

Entries and metadata from e-commerce sites

Data extracted from e-commerce platforms, such as Amazon, eBay, or online plant nurseries and pet shops, can be used to explore the presence of particular alien species in commerce and the demand for such species. For instance, an analysis of data on auctions completed between 2011

and 2017 from AquaBid, the largest online auction site dedicated to the aquarium hobby, revealed that a large number of aquatic invasive species are being globally traded [50].

Besides the data sources, formats, and methods mentioned here (see also Table 1), there are many more available (see, e.g., [18,19]) that we encourage researchers to explore.

Challenges of conservation culturomics and iEcology

The successful future expansion and benefits of the emerging fields of iEcology and conservation culturomics might face some challenges. For example, popular platforms might be shut down and free access and data quality might be reduced, while algorithms used by platforms are often insufficiently transparent and tend to change over time [51,52]. Representativeness of digital data can be considerably affected by socioeconomic, cultural, and political factors and biased toward certain age and social groups [22]. Digital data coverage strongly varies regionally [22] and tends to be concentrated mainly in urban and touristic areas. Online data also exhibits temporal decay, the analyses face linguistic challenges, and the issues of self-representation, false data, and the emerging problem of artificial intelligence-generated content require careful data validation [22]. It is also important to consider the ethical issues of using these methods. Open digital data often contains sensitive personal information and requires careful anonymization and adherence to legal frameworks [53]. Nevertheless, if all potential sources of bias are carefully accounted for, online digital data hold great promise to quantify and assess the relative importance of human and social factors and their interactions, along with other classical ecological factors, in studying alien species introductions.

Concluding remarks

Our understanding of alien species introductions can be greatly improved by considering their social and human dimensions, which have been largely overlooked in previous research because of the lack of appropriate data, but are essential for comprehensive invasion risk assessments and effective management actions. The digital revolution and the availability of large data volumes offer promising opportunities to fill the gaps in our knowledge and enhance our ability to understand and manage alien species introductions. By integrating factors such as charisma and people's perceptions, we can obtain a more holistic understanding of the introduction process. It is important to note that conservation culturomics and iEcology can be useful not only for the introduction stage but also for the following stages of the invasion process, such as establishment and spread. Nevertheless, we believe that the use of these approaches is by far the most relevant for the introduction stage, especially for intentional introductions, since this stage is defined by humans transporting species from their native range to new areas. By contrast, the naturalization and invasion stages depend, to a large extent, on the capacity of the species to establish, spread, and cause impacts in the introduced ranges [10]. Moreover, the introduction stage is not only the one where management measures are most effective and timely (i.e., prevention, early detection, and rapid response) [54] but also where public attitudes, values, and support for or opposition to management are most relevant, directly affecting or driving introductions [5]. Looking ahead, future research should focus on further exploring and refining the application of conservation culturomics and iEcology in studying alien species introductions. This includes validating predictions by comparing them with on-the-ground observations and traditional social science approaches, harnessing the power of machine learning and artificial intelligence for digital data processing and analysis, and integrating spatiotemporal information to track the occurrences and uses of alien species across scales (see Outstanding questions).

In summary, the interdisciplinary approach presented here integrates social and human dimensions in the study of alien species introductions by leveraging digital data sources and conducting empirical studies. This approach holds great promise for advancing the field of invasion science.

Outstanding questions

Which human and social factors affect alien species introduction dynamics?

Can culturomics and iEcology approaches help improve our understanding of alien species introductions?

Can digital data complement traditional data to study the human and social dimensions of invasive alien species introductions?

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Declaration of interests

The authors declare no competing interests.

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