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Global networks for invasion science: benefits, challenges and guidelines

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Global networks for invasion science: benefits, challenges and guidelines

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Abstract Much has been done to address the challenges of biological invasions, but fundamental questions (e.g., which species invade? Which habitats are invaded? How can invasions be effectively managed?) still need to be answered before the spread and impact of alien taxa can be effectively managed. Questions on the role of biogeography (e.g., how does biogeography influence ecosystem susceptibility,

resistance and resilience against invasion?) have the greatest potential to address this goal by increasing our capacity to understand and accurately predict invasions at local, continental and global scales. This paper proposes a framework for the development of ‘Global Networks for Invasion Science’ to help generate approaches to address these critical and fundamentally biogeographic questions. We define global networks on the basis of their focus on research questions at the global scale, collection of primary data, use of standardized protocols and metrics, and commitment to long-term global data. Global networks are critical for the future of invasion science because of their

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potential to extend beyond the capacity of individual partners to identify global priorities for research agendas and coordinate data collection over space and time, assess risks and emerging trends, understand the complex influences of biogeography on mechanisms of invasion, predict the future of invasion dynamics, and use these new insights to improve the efficiency and effectiveness of evidence-based management techniques. While the pace and scale of global change continues to escalate, strategic and collaborative global networks offer a powerful approach to inform responses to the threats posed by biological invasions.

Keywords Biogeographic · Biological invasions · Collaboration · Global change · Global research network · Multitrophic · Transdisciplinary

Introduction

Considerable progress has been made on multiple fronts in understanding the many dimensions of invasion science (as defined by Richardson 2011). Despite such advances, the three fundamental questions that have driven most research on biological invasions since the 1980s have not been fully answered (Drake et al. 1989; Mooney et al. 2005): Which species invade? Which habitats are invaded? How can invasions be effectively managed? Plant

invasions have been more intensively studied than any other major group of alien organisms (Pyšek et al. 2006, 2008) and have contributed most to our theoretical understanding of organism-focused (what determines invasiveness of particular taxa?) and ecosystem-centered (what makes a community, ecosystem or region susceptible to invasion?) questions in invasion science. Observations of invasions and associated biotic and abiotic processes have historically been important in informing invasion science (e.g., Richardson et al. 2004). More recently, manipulative experiments (garden and field-based), predictive modeling, and conceptual/theoretical approaches have helped to integrate our understanding of species invasiveness with that of community invasibility (Catford et al. 2009). Research areas contributing substantially to invasion science include the characteristics that predispose taxa to become invasive (van Kleunen et al. 2010; Guo et al. 2014; Suda et al. 2015) and interactions between biological invasions and environmental change at multiple scales (Walther et al. 2007; Pyšek et al. 2010; Kueffer et al. 2013). There is increasing realization that solutions to problems associated with invasions must be sought by placing the phenomenon firmly within the domain of social-ecological systems (Meyerson and Mooney 2007; Hui and Richardson 2017). Despite the progress, many fundamental questions in invasion science remain unresolved. Answers to the four research questions below are among those that hold the greatest potential to deepen our understanding of biological

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invasions and improve our capacity to manage invasion dynamics (see also Richardson 2011):

1. How does biogeography influence ecosystem susceptibility, resistance and resilience against invasion?
2. How does biogeography influence the ecological (e.g., enemy release and invasional meltdown) and socio-economic (e.g., dynamic travel and trade routes) mechanisms and impacts of biological invasions?
3. Are ‘space for time’ substitutions effective to predict the likelihood of an invasion, and the vulnerability of ecosystems to potential impacts, as the global environment continues to change?
4. What is the role of adaptation and evolution in determining invasion success, specifically:
 - a. evolutionary history within the native range prior to invasion?
 - b. adaptation to environments, and evolution, in the invaded range?

To facilitate progress on these global priorities for invasion science, researchers must consider which critical questions can realistically be answered (Strayer 2012; Kueffer et al. 2013) and then strategically collect and analyze data to address them. The vast spatial scale and breadth of experience required to address these big-picture questions presents a logistical challenge for research groups working in isolation. In this paper we focus on plant invasions to explore the benefits and challenges of addressing these otherwise intractable questions with global-scale research via transdisciplinary networks (*sensu* Wickson et al. 2006; see also Meyerson and Mooney 2007; Fraser et al. 2013) and provide a road map to encourage new, and more effective, international collaborations.

Global networks for invasion science: a delimitation

We define ‘Global Networks for Invasion Science’ through their primary purpose of collecting new primary data to answer specific questions about patterns, mechanisms and impacts of biological invasions at the global scale (e.g., the effect of sea level rise on the distribution of cosmopolitan littoral taxa) or finer resolutions that are best addressed by multiple

regions contributing to a global synthesis (e.g., the effects of rising temperatures on the invasion of grasslands in arid biomes). Although most existing large-scale collaborations focus on a particular taxon (e.g., *Ambrosia artemisiifolia*, www.ragweed.eu) or specific invasion issues (e.g., effectiveness of sentinel plants as an early warning system; Roques et al. 2015), networks could also use model systems (e.g. *Phragmites australis*; Meyerson et al. 2016b) to accelerate deeper understanding of the patterns (e.g., changing spatial distributions; Dietz et al. 2006) and processes (e.g., the mechanisms by which invasive plants disrupt pollination networks; Lopezaraiza-Mikel et al. 2007) of invasion dynamics.

To qualify as ‘global’, we suggest that networks cover gradients (e.g., latitudinal and longitudinal, and from natural to human-dominated ecosystem) with nodes (network partners and/or sites) spanning biogeographic zones over both hemispheres and including at least three continents. This suggestion is motivated by the need for a practical operational definition of networks for international—and potentially transdisciplinary—research teams that aim to study invasion dynamics at a representative set of locations and regions (Kueffer et al. 2013). Transdisciplinary refers to the generation of new knowledge and solutions to real-world problems through shared, standardized and iterative methodologies drawn from two or more disciplines (adapted from Wickson et al. 2006). The current distribution of most invasive organisms, in both their native and introduced ranges, spans two or more continents but rarely covers the entire globe (*cf.* Rejmánek and Richardson 2013). Limiting the selection of focal taxa to those that have a large global range would focus research efforts on a manageable set of cosmopolitan, model systems that are well-represented spatially and with good coverage in the literature (Table 1).

The objectives of Global Networks for Invasion Science can be summarized by four defining characteristics. (1) Global networks address research questions on biological invasions at the global scale (as defined above) through a biogeographic synthesis of insights from multiple localities across large regions (Hiero et al. 2005; Colautti et al. 2014b; Cronin et al. 2015). (2) Primary data on model systems are collected to address specific global questions, for example through common gardens, field experiments and/or field observations. Collaborations that use existing

Table 1 Examples of species/genera which may make useful model organisms, their native and introduced distributions, and key characteristics which make them suitable candidate species for global network studies

| Model organism (Family) | Model system category | Distribution | Key characteristics |
|---|---|--|--|
| <i>Acacia</i> spp. (Fabaceae) | Intensively studied species Specialized research | Native: Australia Introduced: Africa, Asia, EU, New Zealand, NA, SA | Multiple invasive and native species Global distribution Known invasion history Habitat generalists Vegetative reproduction (stem cuttings) Interspecific hybridization Major economic and environmental impacts (displacement of native vegetation, disruption to water flow leading to streambank erosion and changed nutrient cycling patterns) |
| <i>Alternanthera philoxeroides</i> Alligator weed (Amaranthaceae) | Intensively studied species | Native: SA Introduced: Asia, EU, NA, Oceania | Intraspecific genetic and phenotypic variability Global distribution Known invasion history Habitat generalist Vegetative reproduction (stem cuttings) Fast growing Major economic and environmental impacts (deleterious effects on other plants and animals, water quality, aesthetics, hydrology; degrades pasture, turf and crop production in terrestrial ecosystems) |
| <i>Ambrosia artemisiifolia</i> Common ragweed (Asteraceae) | Intensively studied species Specialized research | Native: NA Introduced: Africa, Asia, EU, Oceania, SA | Pre-existing research network Global distribution Known invasion history Habitat generalist Fast growing Major economic, environmental and social impacts (decreases crop yield, displaces native species, allergenic pollen) |
| <i>Arundo donax</i> Giant reed (Poaceae) | Understudied species | Native: Asia Introduced: Africa, Asia, EU, NA, Oceania, SA | Global distribution Known invasion history Habitat generalist Vegetative reproduction (rhizomes or plant fragments) Fast growing Major economic, environmental and social impacts (outcompetes native species, alters hydrology and fire regimes) |
| <i>Colocasia</i> spp. Elephant ear/taro (Araceae) | Understudied species Genera/families with an underrepresentation of invasive species | Native: Asia Introduced: Africa, Asia, EU, NA, Oceania, SA | Multiple invasive and native species Global distribution Known invasion history Habitat generalists Vegetative reproduction (corm) Fast growing Interspecific hybridization Major economic, environmental, and social impacts (displacement of native vegetation, altered hydrology and aesthetic qualities, agricultural crop) |

Table 1 continued

| Model organism (Family) | Model system category | Distribution | Key characteristics |
|--|---|--|---|
| <i>Eucalyptus</i> spp. (Myrtaceae) | Understudied species Genera/families with an underrepresentation of invasive species | Native: Australia, Asia Introduced: Africa, Asia, EU, New Zealand, NA, SA, EU | Multiple invasive and native species Global distribution Known invasion history Habitat generalists Vegetative reproduction (stem cuttings) Interspecific hybridization Major economic and environmental impacts (loss of native biodiversity, alteration of water and nutrient regimes) |
| <i>Lythrum salicaria</i> Purple loosestrife (Lythraceae) | Intensively studied species Specialized research | Native: Africa, Asia, Australia, EU Introduced: New Zealand, NA, SA | Intraspecific genetic and phenotypic variability Global distribution Known invasion history Habitat generalist Vegetative reproduction (stem cuttings) Fast growing Interspecific hybridization Major economic and environmental impacts (harmful to livestock and crop production, alters hydrology and nutrient cycling, displaces native species) |
| <i>Opuntia</i> spp. Prickly pear (Cactaceae) | Genera/families with an underrepresentation of invasive species | Native: NA, SA Introduced: Africa, Asia, EU, NA, Oceania, SA | Pre-existing research network Multiple invasive and native species Global distribution Known invasion history Habitat generalists Vegetative reproduction (cladodes) Interspecific hybridization Major economic, environmental and social impacts (harmful to livestock, native plant and arthropod community, hinders human use of recreational areas, cultivated crop) |
| <i>Phragmites</i> spp. Common reed (Poaceae) | Intensively studied species Specialized research Genera/families | Native: Africa, Asia, EU, NA, Oceania, SA Introduced: NA, Oceania | Pre-existing research networks Multiple invasive and native species Intraspecific genetic and phenotypic variability Global distribution Known invasion history Habitat generalists Vegetative reproduction (rhizomes or plant fragments) Fast growing Intraspecific and interspecific hybridization Major economic and environmental impacts (alters hydrology, ecosystem function and degrades habitat for native species) |
| <i>Rumex</i> spp. Dock/sorrell (Polygonaceae) | Intensively studied species Genera/families with an overrepresentation of invasive species | Native: Africa, Asia, EU Introduced: Africa, Asia, NA, Oceania, SA | Multiple invasive and native species Intraspecific genetic and phenotypic variability Global distribution Habitat generalists |

Table 1 continued

| Model organism (Family) | Model system category | Distribution | Key characteristics |
|-------------------------|-----------------------|--------------|---|
| | | | Vegetative reproduction (roots) |
| | | | Fast growing |
| | | | Interspecific hybridization |
| | | | Major economic impacts (decreases crop quality) |

The model system categories are based on Kueffer et al. (2013), and distributions include Europe (EU), North America (NA), and South America (SA). Genera/families with an under-representation of invasive species enable phylogenetically controlled contrasts between native and invasive taxa, furthering understanding of mechanisms underlying invasion success. As pointed out by Kueffer et al. (2013), groups of species with an underrepresentation of invasive species have attracted less research interest, but understanding why these groups have not become invasive may help to advance invasion science significantly

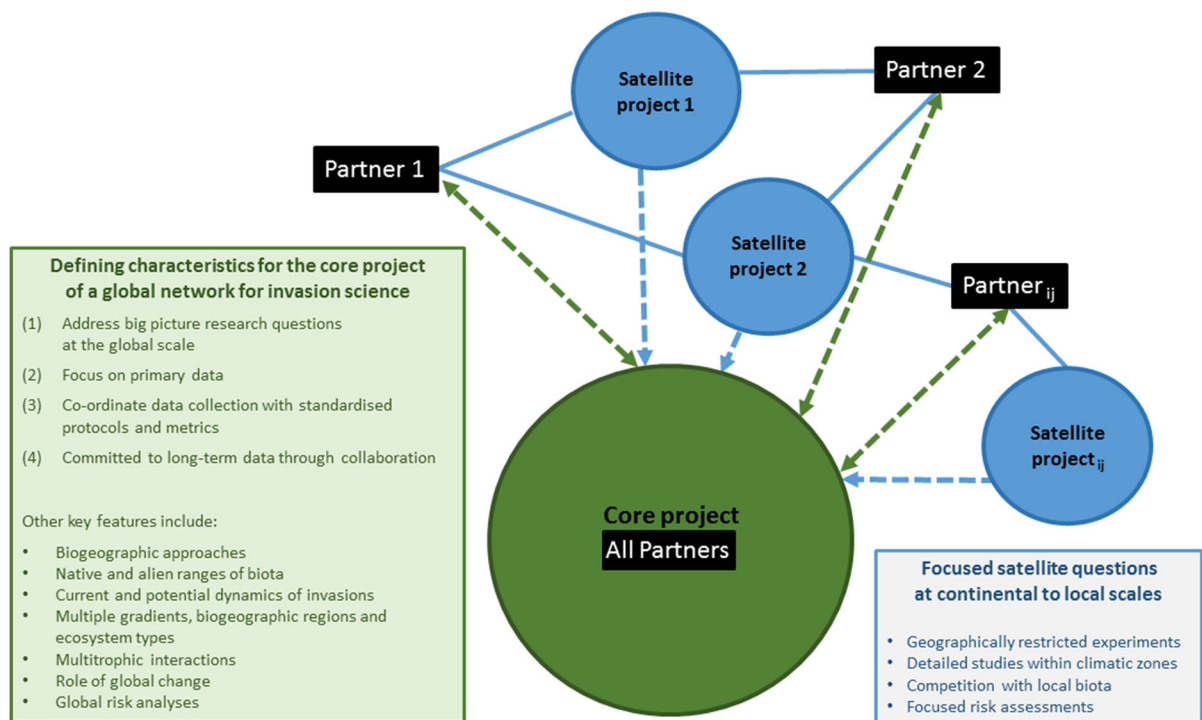


Fig. 1 Structure of a global network on invasive species. The core project (*in green*) involves all partners and addresses big picture research questions at the global scale through: collection of primary data; use of standardized protocols and metrics; and commitment to long-term global data. Knowledge, and iterative global research questions, are generated by the core project and are exchanged (*green arrows*) with all partners through mutual dialogue. Satellite projects (*in blue*) that are performed by

secondary information to answer global questions (e.g., GloNAF database of naturalized alien floras, van Kleunen et al. 2015, and international invasion monitoring, Latombe et al. 2016) are therefore not included in this definition. (3) Data collection is coordinated using standardized protocols and metrics (e.g., Wilson

individual partners, or among partners, focus on questions that are biogeographically restricted to certain partner contexts or priorities (e.g., the competition of the focal taxa with a locally present congener, or addressing the effect of Mediterranean climates only). Satellite projects contribute (*blue line*) to the overall knowledge base within the core project; these inform the iteration of hypotheses and questions, some of which are addressed by other satellite projects

et al. 2014) that ensure comparability of data captured at different locations, and rigorous data analysis. (4) Global networks are enduring collaborations that collect long-term data over an agreed timeframe (e.g., 10 years) to address complex invasion dynamics. Ongoing networks may also initiate shorter-term

“snapshot” satellite projects to address specific questions that relate to the main research direction of the respective network (see Fig. 1) (e.g., Richardson et al. 2011; Woodford et al. 2016).

Why global networks are critical for invasion science

Collaborative global networks are a powerful approach with many benefits for invasion science because they increase our collective capacity to: (1) set global priorities for research agendas (such as the strategic priorities we have outlined above); (2) identify and assess the risks that emerge from global trends; (3) unravel the mechanisms that mediate genetic diversity at multiple scales of space and time—the elucidation of such complexity cannot practically be achieved through experimental manipulation at a single site (Fig. 1); (4) understand biogeographic influences on the interactions between alien plants and other biota, both native and introduced, across different trophic levels; (5) build our collective capacity to predict future invasion dynamics; and (6) tap into the innovative approaches that diverse, transdisciplinary networks can generate to integrate new knowledge and evidence-based management of biological invasions.

Identifying and assessing the risk of emerging trends

Networks provide unparalleled opportunities to identify and assess emerging trends in the distribution patterns, ecology, genetics, and risk of the target taxa and their close relatives. Invasion processes are context-dependent and likely to evolve differently across biogeographic regions and environmental settings (Richardson and Bond 1991; Cronin et al. 2015; Packer et al. 2016). Some species or genotypes are therefore likely to vary in response to different environments (Meyerson et al. 2016a) suggesting that early warning signals of invasiveness could come from a single site rather than from multiple locations. For this reason, coordinated experiments that span bioclimatic zones on multiple continents can also utilize natural gradients to predict the influence of future climatic conditions.

Any emerging risks can be assessed rapidly through informal discussions (online and/or face-to-face) and more formal risk-assessment processes developed by the network or partner agencies. Active networks then have the opportunity to use the wider associations of members to notify the relevant policymakers, managers and broader community of the risk (nature and magnitude) and to present a clear, consistent plan on the appropriate priority actions, across multiple locations if necessary, to address the threat (e.g., Wilson et al. 2014 for Australian acacias).

Facilitating biogeographic insights into the genetics of invasion

A growing body of literature suggests that a biogeographical approach is fundamental to understanding the current and potential dynamics of invasions in their alien and native ranges (e.g., Hierro et al. 2005; Colautti et al. 2009; Hejda 2013; Parker et al. 2013; Cronin et al. 2015; Pyšek et al. 2015; van Kleunen et al. 2015). The distribution of genetic variation within taxa that have a broad geographic range (spanning several biogeographic regions and continents) is changing due to increased dispersal opportunities across continents and post-invasion evolution (e.g., Thompson et al. 2015 for *Acacia saligna*; see also Eriksen et al. 2014). Studies from single sites or regions cannot distinguish phenotypic variation in traits related to invasiveness (genotype \times environment interactions) from post-invasion adaptation and evolution (Maron et al. 2004; Hierro et al. 2013). There is increasing evidence that global change factors (such as warming, drought, precipitation, and their spatiotemporal variation) can alter macroevolutionary patterns and, eventually, the genetic diversity and structure of plant populations within just a decade (Avolio et al. 2013; Ravenscroft et al. 2015). A lack of information on intraspecific genetic diversity currently hampers our ability to understand potential responses of species to these global changes (Pauls et al. 2013; Meyerson et al. 2016b). It is not possible to accurately predict such responses by individual invasive species from isolated studies of local populations (which may not necessarily be representative of the fitness of the species in total, or of the genus) (Meyerson et al. 2010). The cultivation of a common set of genotypes representing intraspecific

phylogeographic variation (e.g., the global genetic structure of a species) in combination with field studies of natural populations and common garden studies can simultaneously identify lineages of high fitness and the interaction of biogeographic factors crucial for the success of these lineages at a specific location. Global networks can thereby help to predict and monitor invasion risk even before potentially invasive genotypes are introduced to new areas accidentally or on a larger scale intentionally.

Establishing collaborative common gardens on all continents through a global network also provides an opportunity to assess the role of environmentally influenced genetic traits such as epigenetics (e.g., DNA methylation status; Schrey et al. 2013) and phenotypic plasticity in the adaptation and spread of potentially invasive plants. For instance, Guarino et al. (2015) demonstrated that ramets of the same clone of white poplar (*Populus alba*) had a different methylation status, and thus potentially different gene expression regulation and invasion risk, in relation to their geographical provenance on the island of Sardinia.

Understanding biogeographic influences on trophic interactions

Global networks that focus on a model system can provide important insights into complex species interactions that limit or facilitate invasion processes. The geographic structuring of alien plant distributions (e.g., higher rate of invasions in temperate than tropical or polar regions; e.g., Lonsdale 1999; Fridley et al. 2007; van Kleunen et al. 2015) may intensify trophic interactions where alien species are more common (Iannone et al. 2016) and cause large-scale geographic shifts in species interactions and distributions (e.g., He et al. 2013; Lord and Whitlatch 2015). Invasional meltdowns may also be more common in regions where introductions are more likely. Long-term coordinated experiments across multiple biomes may help to identify anthropogenic drivers of change, including human-assisted introductions, and the mechanisms underpinning trophic interactions in response to these.

Herbivores and other natural enemies are widely recognized as having a strong influence on the establishment and subsequent spread of invasive plant species (Keane and Crawley 2002; Rogers and Siemann 2004; Jeschke et al. 2012). Controlled common garden experiments, one of the core approaches that

can be used by global networks, are often performed to assess the importance of the Enemy Release Hypothesis at different localities (whether invasive species are more resistant to natural enemies than native species) and whether invasive species evolve in response to their natural enemies in their introduced range (e.g., Agrawal et al. 2005; Joshi and Vrieling 2005; Rapo et al. 2010). Coordinated research across multiple sites has also been influential in advancing our understanding of how climate change variables, plant genetics (genomic, ploidy and genotypic variation), epigenetics (e.g., variation in DNA methylation status), and geographic origins affect invasive/native plant-herbivore interactions (e.g., Lee and Kotanen 2015; Lu et al. 2015; Meyerson et al. 2016a).

Mutualisms play a key role in facilitating plant invasions (Richardson et al. 2000), but the roles of many symbionts in influencing progress at different stages along the introduction-naturalization-invasion continuum (sensu Richardson and Pyšek 2006) are poorly understood. Contrasting the levels of performance of the same species in different biogeographic regions is useful for understanding the roles of mutualisms in invasions. For example, cross-region comparisons have shed crucial light on the role of nitrogen-fixing bacteria in facilitating invasions of Australian *Acacia* species around the world and in determining the extent to which introduced legumes can form novel associations with resident bacteria (Rodríguez-Echeverría 2010; Ndlovu et al. 2013).

Predicting the future of invasion dynamics

Another incentive for globally coordinated research is the increased capacity to develop reliable predictions on invasive species responses to global change (incorporating both anthropogenic and climatic drivers) and future dynamics of their spread in general (Dukes and Mooney 1999; Guisan and Thuiller 2005). Predictive modelling could incorporate data from the network, including both data from natural invaded environments and responses from standardized common gardens. Identifying whether some characteristics predispose a species or genotype to naturalize or become invasive under projected future conditions would be particularly useful for biological security risk assessments and planning (Kolar and Lodge 2001; Meyerson and Reaser 2003; Pyšek and Richardson 2007; van Kleunen et al. 2010; Guo et al. 2014, 2016;

Suda et al. 2015; Tho et al. 2016). The responses of plant functional traits across invasion stages differ (Pyšek et al. 2009, 2015) and can be used as predictors of response of an introduced species to multiple interacting global change factors (e.g., stages in the invasion process reached by the same species differ by region; Richardson and Pyšek 2012). The network approach offers the opportunity, by comparing the conditions under which the same alien taxa occur as casual, naturalized or invasive, to determine how the environmental context in a particular biogeographical setting interacts with functional traits in its invasion success.

Generating innovative solutions through diverse perspectives

A further benefit of global networks is their potential to overcome one of the greatest challenges within invasion science; translating new knowledge into action that will prevent or minimize biological invasions (Hulme 2003; Lindenmayer et al. 2008). The spread of invasive species globally is linked so closely to human influence that developing lasting, effective solutions to reverse this trend demands iterative and collaborative input from applied and fundamental perspectives (Wickson et al. 2006; see also Hulme 2006; Hui and Richardson 2017). Kueffer (2010) argues that trans-disciplinary perspectives are not only desirable, but essential, because of the fundamentally socio-ecological aspects of plant invasions, including: (1) dynamic patterns of propagule pressure along evolving trade and transport routes; (2) the potential risk of novel organisms created through synthetic biology; and (3) variable human perceptions on the nature of invasions and the mechanisms underpinning them.

Better systems are needed to identify and assess these threats globally, to understand the underlying mechanisms, to develop and prioritize response actions, and communicate levels of threat and recommended interventions to policymakers and practitioners worldwide. The scale and breadth of these roles are clearly beyond the scope of a single research group, profession or discipline. Integrating theoretical and applied approaches can help to ensure that research questions address the most current and pertinent aspects of these global priorities, and that the management actions being implemented are the most effective and efficient.

To bridge the gap, where it exists, research scientists, policymakers and managers need to create new ways of exchanging knowledge and designing effective solutions together (Nassauer and Opdam 2008; Kueffer 2010; Ahern 2013; Richardson and Lefroy 2016). Global networks that span multiple approaches as well as continents have great potential to foster innovation by drawing on complementary expertise and experience on the focal issue or taxa (Max-Neef 2005; Pohl 2005; Wickson et al. 2006). The “virtual global acacia college” that was assembled in 2010–2011 to compile a collection of 20 papers on the invasion ecology of Australian acacias (Richardson et al. 2011) was a short-term demonstration of bringing together 104 researchers from 18 countries representing diverse subdisciplines in biology (e.g., genetics, invasion ecology, population ecology, plant pathology, plant physiology) and humanities (history, geography, philosophy) to develop a comprehensive overview of the many issues involved in acacia introductions and invasions. Although this initiative does not strictly correspond to our definition of a global network, it provides a tangible example of the benefits of invasion scientists working together across scientific disciplines.

Longer-term collaborations are needed to move from identification of issues to the implementation of effective solutions. The European Cooperation in Science and Technology (COST; www.cost.eu) Actions are bridging this gap with practical research outputs, such as the illustrated guide to invasive taxa and rapid assessments in the Mediterranean Sea (Zenetos 2015). The MIREN group (www.mountaininvasions.org) is well regarded for the innovative solutions it generates through long-term partnerships between scientists and practitioners across multiple continents. South African MIREN partners have contributed to developing an emerging global threats system to identify potential risks (e.g., pompom weed; *Campuloclinium macrocephalum*) and recommend management strategies to deal with outbreaks in KwaZulu-Natal Province (McDougall et al. 2011). More recently, MIREN has capitalized on long-term relationships and trust between network members to explore innovative ways to overcome the ecological and economic burden of international travel by reducing their face-to-face network meetings (Kueffer 2016). As it becomes increasingly difficult to access sufficient resources to cope with the growing

Table 2 Examples of existing multilateral collaborations within invasion science (see also Box 2 in Lucy et al. 2016)

| Network name | Focus and scale | Status | Outputs (Expected or achieved) | Key citations |
|--|---|------------------|---|--|
| COST Action FP1401— A global network of nurseries as an early warning system against alien tree pests | Consortium of over 40 countries. Europe, EU neighboring Countries and Extra EU Countries | 2014–2018 | Early warning system and common protocols for alien tree pests and diseases to be established for countries involved | Roques et al. (2015) |
| COST Action FA1203— Sustainable management of <i>Ambrosia artemisiifolia</i> in Europe “SMARTER” | Consortium of over 40 countries. Europe, EU neighboring Countries and Extra EU Countries | 2013–2017 | Long-term management and monitoring protocols, development of innovative management solutions | www.ragweed.eu |
| COST Action TD1209 European Information System for Alien Species “Alien Challenge”. | Invasive Alien Species in Europe. Consortium of over 30 countries. Europe, EU neighboring Countries and Extra EU Countries | 2012–2016 | Knowledge gathering and sharing through a network of experts, support to a European IAS information system, implementation of EU 2020 Biodiversity Strategy targets | http://www.brc.ac.uk/alien-challenge/home |
| European Information and Research Network on Aquatic Invasive Species (ERNAIS) | Online information system on aquatic invasive species with early warning functions and decision support | 2002– current | International cooperation in research, scientific information exchange and management of aquatic invasive species in Europe and worldwide. | http://www.reabic.net/ERNAIS.aspx |
| Global Garlic Mustard Field Survey (GGMFS) | 16 countries in North America and Europe. Standardized field measurements of performance traits | 2008– current | Replicating the GGMFS approach with other invasive species | Colautti et al. (2014a) |
| Global Invader Impact Network | Impact of invaders on vegetation & soil | 2013– current | Experimental framework for a standard methodology to identify the ecological impacts of invasive plants. | Barney et al. (2015) |
| Global Invasions Research Coordination Network | International network of scientists supported by the U.S. National Science Foundation addressing the ecological and evolutionary causes of biological invasions | Ongoing | Coordination of both theoretical and empirical research on biological invasions around the globe | http://invasionsrcn.si.edu/ |
| International Plant Sentinel Network (IPSN) | Plant pest and pathogens | Ongoing | Early warning, standardized methodologies for monitoring and surveying of damaging plant pests and pathogens, risk analysis | https://www.bgci.org/plant-conservation/ipsn/ |
| INVASIVESNET | International association for open knowledge and open data on invasive alien species and their management | 2016– current | Developing a sustainable network of networks for effective knowledge exchange | Lucy et al. 2016 |
| Mountain Invasions Research Network (MIREN) | Effects of global change on plant invasions and plant biodiversity in mountainous areas | 2005– current | Database on invasive plant distribution in mountain environments | Dietz et al. 2006; McDougall et al. (2011); www.mountaininvasions.org |
| <i>Phragmites</i> Network (PhragNet) | Addressing global scale questions in ecology and biological invasions through a | 2014– current | Experimental framework and standardized methodology across common gardens to | Meyerson et al. (2016b) |

Table 2 continued

| Network name | Focus and scale | Status | Outputs (Expected or achieved) | Key citations |
|--|---|--------------|---|--|
| | global network of common gardens in Asia, Australia, Europe, North America, and South America | | identify the ecological impacts of invasive plants | |
| Southern Hemisphere Network on Conifer Invasions | All aspects of conifer invasion in the southern hemisphere | 2007–current | Promotes interaction and collaboration between researchers, managers and planners | Richardson et al. (2008); Simberloff et al. (2010) |

threat of invasive species globally, the imperative to find creative and collaborative ways to address this threat is also likely to grow.

Building on existing and previous collaborations: challenges and lessons learned

Good examples of multilateral research collaborations within invasion science exist already (McDougall et al. 2011; Colautti et al. 2014a). Some of the most extensive and important initiatives for both theoretical and applied research are summarized in Table 2. Past and current groups dealing with invasive species have mainly focused on plants rather than other organisms and have provided new tools for risk assessment and management, standardized protocols for data collection and management, and an avenue for different stakeholders to work together. Some of these global collaborations address the impact of invasive plants on a diverse range of taxa, such as the Global Invasions Research Coordination Network (www.invasionsrcn.si.edu), or The Global Invader Impact Network (<https://weedeco.ppws.vt.edu/giin>; Barney et al. 2015). Existing networks, focused on collecting primary data, are complemented by more technology-based collaborations. The Global Invasive Species Information Network (GISIN) was established to overcome the limitations of traditional approaches in responding to the growing demand for coordinated gathering, storing and disseminating information on introduced species (Ricciardi et al. 2000; Katsanevakis and Roy 2015). The GISIN has subsequently developed an online portal for standardized data (Jarnevich et al. 2015, <http://www.gisin.org>).

Establishing a productive and sustainable global research network presents many challenges, particularly in the areas of developing shared goals,

expectations, coordination, communication, and funding (Gaziulusoy et al. 2016). Below we summarize the major stumbling blocks that can limit the long-term success of networks, and outline strategies to avoid or resolve these barriers (see Online Resource 1, Protocol Guidelines in Supplementary Material, for more information). Overcoming challenges requires shared learning and authentic collaboration amongst network members. One of the many potential strategies could be facilitating “progress reports” between invasion science networks to disseminate information about data protocols, governance, and preliminary outcomes from individual networks. This would enable data trends to be more readily detected, research priorities identified and promoted, and research approaches shared amongst the scientists involved. Ecology and Management of Alien Plant Invasions (EMAPi; Richardson et al. 2010; Daehler et al. 2016), for example, has an international focus, holds conferences held every two years and could provide an accessible forum for invasion scientists to share and reflect on updates from other relevant networks. Another potential forum is the European Neobiota initiative (Kowarik and Starfinger 2009), which coordinates biennial conferences and the open-access journal *NeoBiota* which deals with biological invasions (Kühn et al. 2011).

Sustainability through communication and coordination

Successful global networks require active and continuing engagement of many collaborators (Petersen et al. 2014). Promoting long-term partnerships through collaborative, flexible governance can build trust and accommodate the various motivational levels and drivers over time of individuals members and the institutions they represent (Online Resource 1; see

also Richardson and Lefroy 2016). Reaching agreement through collaborative processes for potentially divisive matters, such as data management (how to collect, store, integrate, analyze and use data) and authorship, is critical yet may be highly time-intensive for large global networks in particular. Failing to define and agree on a common research agenda and approach, and to communicate the importance of this to the scientific and broader community, are sure ingredients for failure in network initiatives.

Navigating the variability in biosecurity requirements across regions

Biosecurity legislation (international through to regional) and regulations of the donor (providing plant material) and host (receiving plant material for experiments and/or analysis) countries can strongly influence the feasibility and timeframes of initiatives. Hosting a garden with living, potentially weedy species or genotypes demands strict adherence to permit requirements, responsible husbandry practices, and countries may have vastly different standards and procedures to address biosecurity risks. Australia, New Zealand, South Africa and North America are renowned internationally for their strict biosecurity standards. Within China there are a range of biosecurity measures stipulated, such as the isolation buffer (natural or man-made to separate the garden from the surrounding area) and documentation of garden management that is required in some provinces but not necessarily in others. Networks that rely on sharing plant material need to resolve these biosecurity issues early in the planning process to allow adequate time for receiving and propagating material.

Informing policy

Biological invasions can only be reduced worldwide by engaging multinational support across all sectors of society. Global initiatives can help to bring these decision-making policies and processes into alignment with each other by improving the dialogue on complex scientific issues between researchers, policymakers, stakeholder networks and the broader public (Richardson and Lefroy 2016). The COST Action TD1209 “Alien Challenge” (www.brc.ac.uk/alien-challenge/home) is one example of how a global collaboration within invasion biology can inform policy and

stakeholders. This initiative is improving knowledge gathering and sharing through a network of experts informing the European Alien Species Information System (EASIN), including assessing the pathways and gateways of alien species introductions within Europe (Katsanevakis and Roy 2015). The knowledge gained from this initiative can be used to inform policy decisions and develop shared formats for alien species information in line with the EU 2020 Biodiversity Strategy targets, Regulation EU no. 1143/2014. The Invasive Species Specialist Group (ISSG) is another global community which combines scientific and policy experts on invasive species under the auspices of the Species Survival Commission (SSC) of the International Union for Conservation of Nature (IUCN, see review by Pagad et al. 2015). While these initiatives demonstrate some effective relationships between science and policy at high levels in Europe particularly, stronger science-policy partnerships are needed in other biogeographic zones.

Funding global networks

Active, productive networks need to be resourced over at least several years. While some activities can occur with in-kind resources or minimal funding (e.g., developing shared goals, establishing a core collection of plant material, and communicating through electronic media), others demand substantial investment of time and funding (e.g., meeting face-to-face, establishing experimental infrastructure, and field surveys). Only a small proportion of funding, if any, is likely to come from grants allocated to the whole network. Multilateral funding could include regional sources such as the European Union’s Horizon 2020 and COST Actions which support collaborations with non-European Union research groups. More realistically, each network location will need to source its own funding, for example by identifying the synergies between network activities, ongoing or related research projects, and capitalizing on existing research networks and international funding opportunities. Several national or regional centers or institutes that focus on invasion science are now well established (e.g., the Laboratorio de Invasiones Biológicas in Chile—<http://www.lib.udec.cl/home.html>; Department of Invasion Ecology of the Institute of Botany, The Czech Academy of Science—<http://www.ibot.cas.cz/invasions>; or the Centre for Invasion Biology, Stellenbosch

University in South Africa—<http://academic.sun.ac.za/cib/>; van Wilgen et al. 2014). Such centers already function as hubs in global networks in invasion science, but there is scope for more focused global collaborations such as outlined in this paper.

Conclusions

The complexity and scale (spatial and temporal) of the most important biological invasion questions is well beyond the scope of individual biogeographic regions, disciplines, professions or local research groups. Despite the urgent need, only a few large-scale collaborations have been established within invasion science, and none have focused on these fundamental global (e.g., how does biogeography influence ecosystem resistance and resilience against invasion?) or high-impact applied (e.g., rapid responses to new threats) questions. Global Networks for Invasion Science are a powerful approach to address fundamental questions and transform this knowledge into appropriate policy and management recommendations. We encourage researchers, policymakers and practitioners to build global networks and generate the innovative solutions to minimize biological invasions that can only come from such a collaborative and global approach.

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