Conservation Biology

Diversity

Need for routine tracking of biological invasions

Jan Pergl,[1]* Petr Pyšek,[1,2,3] Franz Essl,[4] Jonathan M. Jeschke,[5,6,7] Franck Courchamp,[8] Juergen Geist,[9] Martin Hejda,[1] Ingo Kowarik,[7,10] Aileen Mill,[11] Camille Musseau,[5,6,7] Pavel Pipek,[1,2] Wolf-Christian Saul,[3,5,6,7] Menja von Schmalensee,[12,13] and David Strayer[14,15]

[1]Czech Academy of Sciences, Institute of Botany, Department of Invasion Ecology, CZ-252 43, Průhonice, Czech Republic
[2]Department of Ecology, Faculty of Science, Charles University, Viničná 7, CZ-128 44, Prague, Czech Republic
[3]Centre for Invasion Biology, Department of Botany and Zoology & Department of Mathematical Sciences, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa
[4]Division of Conservation Biology, Vegetation and Landscape Ecology, Department of Botany and Biodversity Research, University of Vienna, 1030, Wien, Austria
[5]Freie Universität Berlin, Department of Biology, Chemistry, Pharmacy, Institute of Biology, Königin-Luise-Straße 1–3, 14195, Berlin, Germany
[6]Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587, Berlin, Germany
[7]Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), Königin-Luise-Straße 2–4, 14195, Berlin, Germany
[8]Université Paris-Saclay, CNRS, AgroParisTech, Ecologie Systématique Evolution, 91405, Orsay, France
[9]Technical University of Munich, Aquatic Systems Biology Unit, Muehlenweg 22, 85454, Freising, Germany
[10]Department of Ecology, Technische Universität Berlin, Rothenburgstr. 12, 12165, Berlin, Germany
[11]Modelling Evidence and Policy Group, School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, U.K.
[12]West Iceland Nature Research Centre, Hafnargata 3, 340, Stykkishólmur, Iceland
[13]Faculty of Life and Environmental Sciences, University of Iceland, Askja, Sturlugata 7, 102, Reykjavík, Iceland
[14]Cary Institute of Ecosystem Studies, P.O. Box AB, 2801 Sharon Turnpike, Millbrook, NY, 12545, U.S.A.
[15]Graham Sustainability Institute, University of Michigan, 625 East Liberty Street, Ann Arbor, MI, 48104, U.S.A.

Monitoring programs track environmental changes and are used to deepen scientific understanding, develop forecasts, and improve management (e.g., Sullivan et al. 2018; USGS 2019). Like other drivers of global environmental change, non-native invasive species (NIS) reduce biodiversity and ecosystem services and imperil human health (Kumschick et al. 2015; Latombe et al. 2017). Estimates of NIS economic impacts are in the hundreds of billions of U.S. dollars per year globally (Kettunen et al. 2009; Bradshaw et al. 2016). The extent and severity of NIS impacts are growing and likely to increase further as new invaders increase and established invaders expand their ranges (Seebens et al. 2017). Future damages are not inevitable because the number, range, and impacts of invaders can be at least partially reduced through management actions, including legislation, trade agreements, education, and targeted control (Pluess et al. 2012).

In contrast to well-established coordinated programs that track anthropogenic drivers, including climate change and pollution (Sutherland et al. 2016; Sullivan et al. 2018), programs tracking invaders are fragmented, poorly coordinated, reactive, ephemeral, and geographically limited. Broad-scale programs usually record only the presence or absence of species (e.g., USGS 2018), and programs that record abundance, impacts, or other attributes are usually local, short-lived (e.g., Strayer et al. 2019), and focused on a few high-profile NIS (Pyšek et al. 2008). Short-term studies are sensitive to short-term environmental and population fluctuations, including stochastic variation and rare or episodic disturbances (Dodds et al. 2012; Vogel 2017).

Monitoring NIS usually begins only after problems have become obvious (e.g., loss of threatened species, decrease of environmental quality, and economic damage). This reactive approach results in delayed action and ultimately higher environmental damage and economic costs. The dramatic difference between immediate and delayed response is well illustrated by the case of

*Address correspondence to Jan Pergl, email: jan.pergl@ibot.cas.cz
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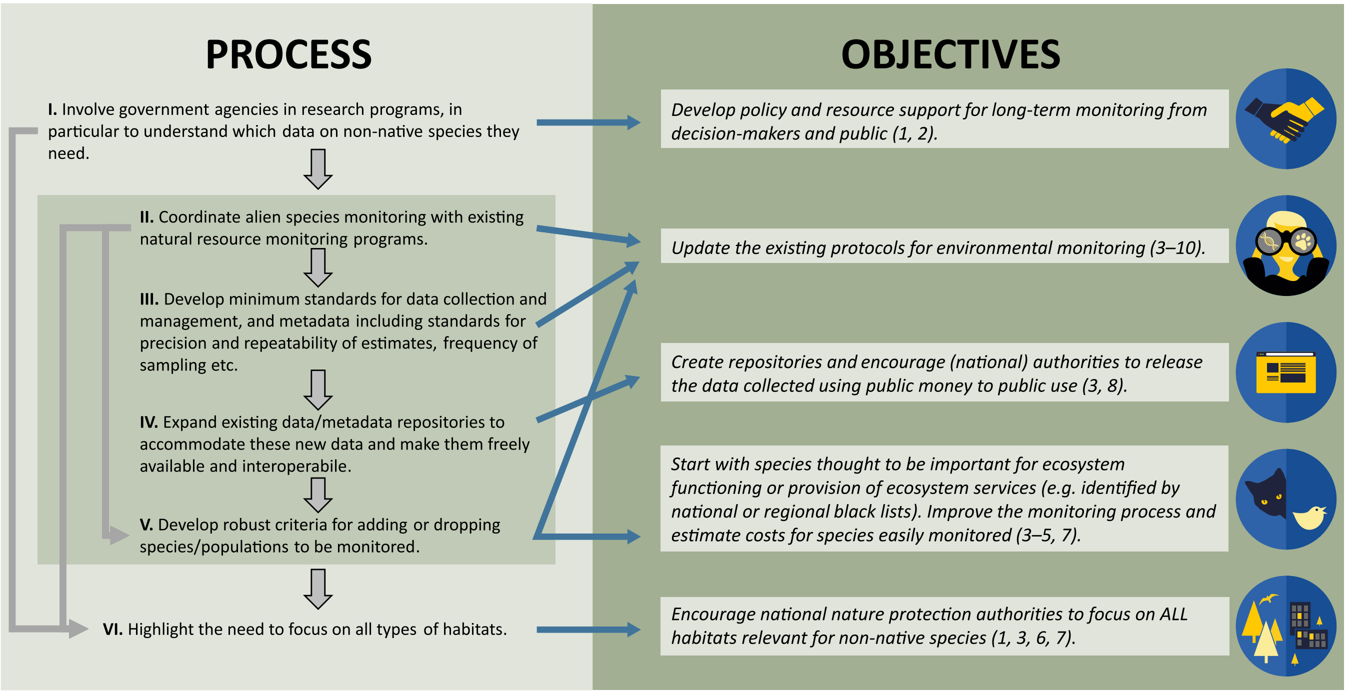

Figure 1. Guidelines to promote and improve long-term monitoring of biological invaders (gray arrows, sequential steps we suggest; narrow arrows, primary objective of each step). Numbers in brackets refer to the principles listed in Table 1. The description of processes and objectives summarizes the core topics of the 10 principles described in text.

contrasting attitudes to the initial phase of *Caulerpa taxifolia* invasion in the Mediterranean versus California (Locke & Hanson 2009).

Data are held by many entities (e.g., government agencies and academic researchers), typically with little coordination across political borders or institutions. Essential attributes of data (data standards, sampling designs, data archiving, data availability, etc.) vary among monitoring programs, frustrating attempts to track trends or synthesize data (e.g., Strayer et al. 2019). Research and monitoring of NIS is strongly biased toward wealthy countries (Pyšek et al. 2008), although negative impacts of NIS can be much higher in developing countries-as illustrated by the invasions and impacts of triffid weed (*Chromolaena odorata*), cassava mealybug (*Phenacoccus manihoti*), and witchweed (*Striga hermonthica*) in such countries (Early et al. 2016). As a result, current information is insufficient to track, understand, or manage invasions and their impacts.

This situation would be intolerable for other environmental monitoring. Imagine if weather were monitored in a few countries for only a few years and with only one variable. It is time to address these shortcomings, and to develop monitoring programs that provide essential information to track, understand, and manage biological invasions. Calls for better monitoring of NIS (e.g., Latombe et al. 2017; Jetz et al. 2019) consider chiefly their negative influence on native biodiversity and human livelihoods and focus on better documenting the spread of NIS. The broader view that NIS have major effects on many aspects of ecosystem function and services and are capable of positive and negative effects emphasizes the need to track not just the presence and absence of IAS, but also their abundance, distribution, and other specific biological or ecological attributes and to monitor sites where native biodiversity is threatened and invaded sites providing ecosystem services.

Furthermore, previous calls have not led to the widespread establishment of NIS programs to monitor NIS. Even the new, ambitious European NIS legislation (Regulation EU 1143/2014) lacks adequate long-term monitoring to evaluate the efficiency of implementation, allocation of resources, and NIS management (Genovesi et al. 2015). More extensive, better coordinated, and more reliable and long-term data on NIS and their impacts would have multiple uses just as long-term data on hydrology and climate have multiple uses in ecology and environmental management (Lindenmayer et al. 2012)–they would better describe the extent of and temporal trends in invasions, characterize and quantify invasion impacts and improve the effectiveness of control measures. In addition, they would aid in the identification of long-term trends in NIS populations and their impacts, analyses of context dependence of population dynamics

Table 1. Ten principles that contribute to efficient long-term monitoring of biological invasions.

Principle	*Description*
1. Increase support	Increase support for and use of long-term studies of invaders by policy makers to a level commensurate with the damages they cause and the benefits that can be obtained from better management.
2. Integration and coordination of data	Integrate and coordinate across data sources and countries to provide robust, trustworthy, and consistent monitoring across large areas, including representative habitats and environments. Databases could use global, regional, or local scales, but should build on a shared integrative and coordinated foundation (e.g., GRIIS, GBIF, and GloNAF). Local or regional programs that reflect varying capacities of individual countries could be used to compose a global strategy, as suggested by Latombe et al. (2017). Data format should insure interoperability.
3. Link to existing, successful monitoring schemes	Borrow ideas from programs already successfully used to track other important drivers of environmental change (hydrology, climate, nutrient inputs, and air pollution), or from conservation programs that monitor native species to design NIS monitoring networks. Foci of interest include data sharing, harmonization, and archiving, and coordination across jurisdictional borders (Lindenmayer & Likens 2018).
4. Adapt existing programs	Adapt or expand existing programs that serve other purposes, so that they also deliver useful data for NIS.
5. Tiered approach	Develop a tiered approach to monitoring and design monitoring programs to match different budgetary constraints (e.g., basic programs with minimal costs, more effective programs with modest costs, and most effective programs when these can be afforded). Make the basic monitoring programs the default option, instead of the current norm of "no program."
6. Species selection	Monitor a representative set of NIS that goes beyond the environmentally and economically "most important" invaders, to achieve a broad understanding of biological invasions.
7. Habitat coverage	Track NIS in human-made habitats, such as cities and agricultural areas in addition to "natural" areas. NIS often are first introduced into human-made habitats, where they can reach high densities and have large ecological and economic impacts.
8. Methods of low impact	Develop and use methods of monitoring and sampling with low impact on the environment, low resource needs, and high efficiency.
9. Citizen science	Develop and benefit from networks of citizen scientists to collect information about NIS, using modern means of communication (e.g., social media and smartphone apps) wherever possible, even if it introduces some identification bias.
10. Emerging technologies	Monitor NIS with emerging technologies (e.g., DNA barcoding, environmental DNA, analyses of water filters, visual and acoustic sensors, and drones), which may provide information at low cost and little environment impact.

and impacts across different invaded ecosystems (e.g., Higgins & Vander Zanden 2010; Strayer et al. 2019), and comparisons across species (Supporting Information).

Long-term data on NIS dynamics could help scientists and managers interpret corresponding runs of data on temporal variation in ecosystem goods and services (e.g., water clarity and fishery yields) and understand the extent to which such long-term variation is caused by interannual variation in populations of NIS versus other causes (e.g., weather and changes in land use). Long-term NIS studies are essential to identify the species, times, and places for which management interventions are most needed. When coupled with control, mitigation, or restoration actions, long-term NIS data would allow better evaluation of these management actions, making NIS management more evidence based, weeding out ineffective actions, and speeding development of effective approaches (Geist & Hawkins 2016). Ultimately, this would improve management, allocation of resources, and outcomes (Hulme 2014; Terauds et al. 2014; Scheele et al. 2018) This includes better allocation of scarce resources to the species and regions that produce the highest benefits, as well as a better balance between efforts to monitor and control of NIS, mitigate their effects, and restore ecosystems (e.g., Holden et al. 2016; Bolam et al. 2019).

Increased effort to monitor NIS could divert resources away from management activities to control NIS. However, current management of NIS, often based on faulty or even no data, can waste time and money in trying to control invaders that are not problematic, ignoring those that are, or spending money on ineffective actions. The 10 principles in Table 1 could improve the tracking of NIS and their impacts (Fig. 1, Table 1, & Supporting Information).

Working groups should convene to design, adapt, or expand monitoring programs based on these principles, evaluate their costs and benefits, offer them to funders and policy makers for discussion, and move to implement the best designs. Monitoring should be considered for regions that provide substantial ecosystem services and contain NIS or are threatened by future invasions. Cost–benefit analyses need to be design specific (optimal allocation of funds to monitoring vs. management

[Bolam et al. 2019]), take full advantage of modern analytical methods (e.g., Maxwell et al. 2015; Bolam et al. 2019), and consider that long-term monitoring programs often have substantial benefits that are not immediately apparent (Supporting Information). In today's globally connected world, sound decisions on international trade, agricultural, fisheries, forest management, local eradications, etc., need reliable data on long-term population trends and impacts of NIS. It is time to move from basing these decisions on guesswork and intuition toward using sound data.

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Supporting Information

Examples of benefits (Appendix S1) and principles of efficient long-term monitoring (Appendix S2) are available online. 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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