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Measure and Reduce the Harm Caused by Biological Invasions

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Invasions by alien species continue worldwide, causing tremendous harm to biodiversity and human well-being. Post-2020 discussions of the Convention on Biological Diversity must link targets to monitoring innovations and decision support for a maximally effective and global response.

Introduction

The consequences of the ongoing introduction and spread of invasive alien species are increasingly felt as their impact on species, ecosystems, and human well-being grows. When species arrive, establish, and spread outside of their historic geographic ranges (see Figure 1), they introduce new traits, behaviors, and genes and alter ecosystems by introducing new biological interactions, causing species extinctions, and changing habitats. In addition to direct impacts on human health and agricultural production, the environmental consequences of biological invasion include changes to fire regimes, disease transmission to native species, forest loss, reduction in water flows, and habitat transformation, among others. Invasive alien predators have driven species extinction and severe population depletion in hundreds of cases.[1] Unintentionally introduced fungal pathogens continue to cause widespread declines in taxa ranging from bats and amphibians to corals and native forests.[2] Intentionally introduced feedstock and biofuel crops that go on to invade carry high financial and environmental risk, as realized in Africa and Asia. Invasive pines (*Pinus* species) transform habitats and fire regimes in the biodiverse South African fynbos and Brazilian cerrado. Woody alien plants such as these affect multiple ecosystem services, causing losses of water, pollination, and export produce. Invasive insects, such as the red imported fire ant (*Solenopsis invicta*), which is invasive on multiple continents, severely affect agriculture, public health, local economies, and native ecosystems. Thousands of introduced and invasive species such as these are now known across all major taxa and affect even the most remote geographic regions.

An ever-more-connected world favored under scenarios of economic prosperity joined with ongoing changing climate suggests that these range-expanding species and their concomitant effects on ecosystems will be an increasingly commonplace feature. The rate and extent of species-range expansions are destined to increase further, especially in biodiverse tropical countries, as economies and transport links grow and changing climates open up new dispersal pathways and habitats,[3] all making the expected transboundary movement of species unrivalled as an internationally shared biodiversity issue (Figure 1). The most recent estimate placed the financial burden of damage from alien species at over 5% of the global gross domestic product, and individual countries spend billions of dollars to manage invasive pathogens, weeds, and animal pests annually.[4,5]

The urgent need for a more effective global response to biological invasion is recognized by the recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) global assessment[6] and the IPBES member countries' request for a dedicated assessment on invasive alien species, due in 2023.[7] The Convention on Biological Diversity's (CBD's) current 2020 Target 9 on invasive alien species ("by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated and measures are in place to manage pathways to prevent their introduction and establishment") and its representations in UN Sustainable Development Goals (SDGs) 14 and 15 were defined without mechanisms for measuring or evaluating progress. To date, robust and meaningful indicators to support targets for dealing with invasions are lacking. For example, the pertinent SDG indicator (15.8.1 on the adoption of legislation and resourcing of invasive alien species) is disconnected from the species data critical to identifying and preventing the spread and impact of invasive species (e.g., Fournier et al.[8]). Moreover, national legislation in support of Target 9 has been patchy in coverage and often ineffectual.[9] Although Target 9 has focused efforts by encouraging the prioritization of high-risk species and pathways, progress is unclear, and the target has largely failed to bring about geographically or biologically explicit information that would guide actions in its support. We argue that missing evidence on core attributes of the problem has been a key contributor to the failure to make and adequately quantify progress.

The current renegotiation of the 2020 targets of the CBD now offers a vital opportunity to develop a roadmap,[10] with goals linked to science-driven tools for invasion monitoring and decision support, to meet this challenge. Since the previous CBD target discussions a decade ago, new data streams, data integration methods, and online information tools now offer an entirely different prospect of linking a revised Target 9 to a global monitoring and decision-support system for biological invasions and their impacts.[11,12] More than measuring progress, these developments have the potential to offer actionable guidance on the prevention, mitigation, and management of invasive species. We suggest that the post-2020 deliberations

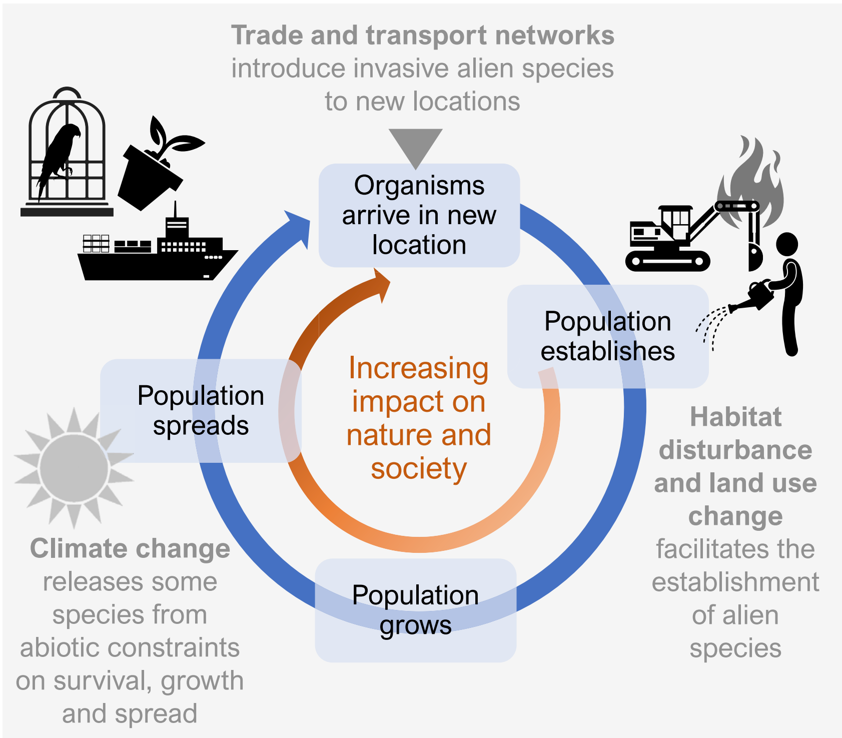

Figure 1. Factors that Facilitate the Arrival, Establishment, and Spread of Invasive Alien Species—Resulting in Negative Outcomes for Biodiversity, Ecosystems, and Society

Humans introduce invasive alien species intentionally and unintentionally from their historic native ranges into new locations via multiple pathways associated with trade and transport, such as trade in timber and agricultural products and transport of ornamental plants, pets, and ship ballast water. Once introduced, the initial survival and establishment of a species is often greater in disturbed areas, such as those associated with human activity and habitat conversion. The population dynamics and spread of some invasive species are further facilitated by climate change as, for example, warming temperatures extend growing seasons and increase species growth rates. This exacerbates invasion because species abundance and spread now increase faster than under historical climate conditions. The species population-dynamics loop is closed when secondary invasion occurs from introduced populations, either by natural spread or by local trade and transport networks originating from the introduced range.

address these innovations upfront and tightly link policy targets to measurement and decision support (Figure 2).

A Target Aligned with Information Needs

Unequivocal targets supported by robust, sustainable indicators of progress are essential to turning the invasion tide and must include strong alignment between a global invasion target focused on outcomes and scientifically rigorous indicators that use directly relevant measures (Figure 2). Such a target would guide and leverage effort by countries to deliver data central to understanding, monitoring, and alleviating the ongoing risks posed by species invasions. To this end, we suggest a stronger post-2020 target: to reduce the impact and limit the spread of alien species harmful (both potential and realized) to biodiversity and ecosystems by 2030. A multinational commitment to this target implies access to vital information about biological invasions in three areas that most directly characterize the invasion problem: spread, impact, and intervention effectiveness.

Spread. The spread of species, i.e., the geographic expansion of populations beyond their native range into new areas, occurs naturally after speciation or newly arisen dispersal or habitat opportunities. This spread is now much accelerated over its natural background level as a result of direct (transport) and indirect (habitat alteration and climate change) human facilitation. These drivers combine to create novel pathways and destinations for the dispersal and establishment of species, some of which cause undesirable change.[13]

Measuring this spread across the pathways over which it occurs is the vital first step to gauging growing risk caused by alien species and to guiding and measuring the success of potential interventions. Because their harm to local systems is sometimes unclear until they arrive, and because climate change is making redistributions increasingly commonplace, we argue that the monitoring of distribution change should apply to alien species irrespectively of documented harm.

The monitoring of species redistributions is supported by a variety of raw data (see Figure 2, Data), such as incidental records, inventories, and expert-based information coming from a growing range of sources. Citizen science, visual and acoustic sensors, remote sensing and GPS tracking data, and more traditional expert-opinion-based checklists can all offer valuable and rapid information on species occurrences, but on their own they suffer high errors of omission in space and time, and emergent signals are often largely driven by observer effort.[14] For known alien species, complimentary information comes in the form of roughly country-scale datasets addressing invasive occurrences and first detection dates. For example, the Global Register of Introduced and Invasive Species holds expert-verified information on country occurrences of species with evidence of environmental harm and includes a process for updating.[12] Although valuable for policy and prioritization, these country-level data suffer from errors of both omission and commission, and emergent patterns are strongly driven by species detection at a spatial resolution that is too coarse to effectively guide species management and control. We can address these shortcomings of single-occurrence data types by combining them with one another and with environmental data through models, as conceived for Species Population Essential Biodiversity Variables (SP EBVs).[11] Defined as the probabilistic presence or absence over contiguous spatial and temporal units addressing species ranges, the species-distribution EBV (and equivalently the species-abundance EBV) has the potential to directly estimate trends in range expansions and their associated uncertainty. Such data integration conducted in near real time and used to drive predictions to finer spatial units offers the prospect of sustained monitoring, including citizen-

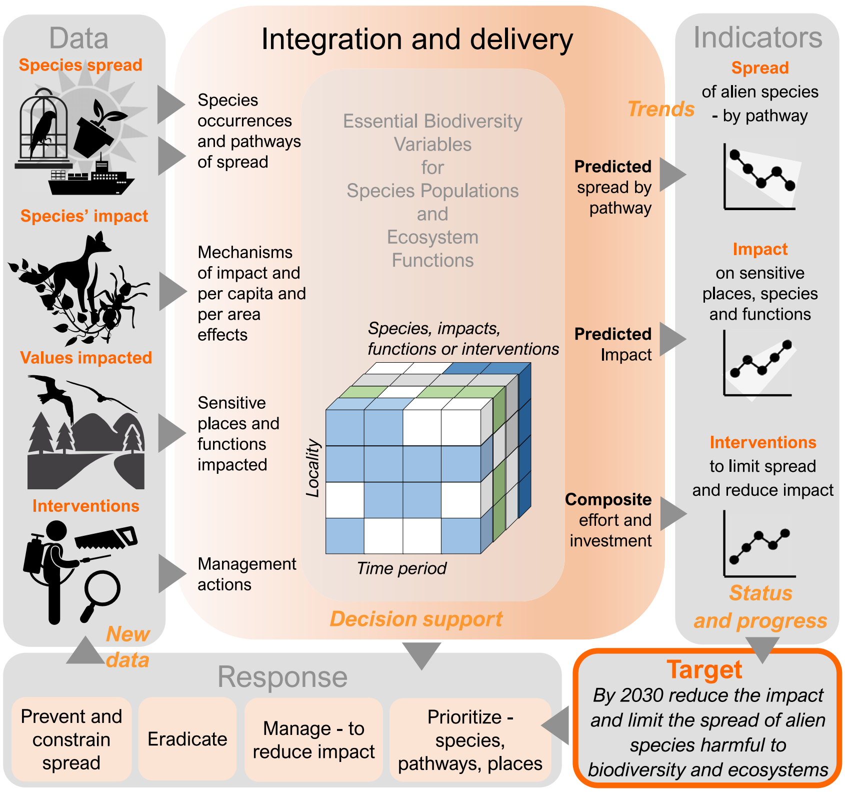

Figure 2. Sustainable Knowledge Delivery for Invasive Alien Species

Shown is a proposed framework for closely linking a revised invasion target with the data and tools needed for measuring and responding in its support. Combined in digital, modular platforms with custom tools and interfaces, the framework enables both evaluation of global progress and decision support for local actions:

The target (lower right) frames and guides data generation, integration, and delivery via modeled decision-support products and indicators to target responses for more effective intervention and a next generation of improved outcomes on biological invasion.

Data (left) on the three key dimensions of the problem—(1) spread, (2) impact (both its type and consequence), and (3) interventions—are integrated in a set of workflows that combine primary evidence in informatics infrastructure. Data providers are multiple and include, for example, the Global Biodiversity Information Facility (GBIF), Global Register of Introduced and Invasive Species (GRIIS), Invasive Species Compendium (CABI), Environmental Impact Classification for Alien Taxa (EICAT), and World Database on Protected Areas (WDPA). Currently, data on interventions for invasion and their effectiveness are poorly collated with no dedicated infrastructure.

Integration and delivery (center) are at the core of the framework. Data, with the support of models, are used for predicting occurrences or abundances of invasive species across pathways of introduction and spread and over contiguous spatio-temporal units, representing the SP EBVs for invasive alien species. Example platforms with the potential to support this integration include Map of Life. This is supplemented with data and essential variables that capture ecosystem functions and sensitive priority areas affected by invasion, as well as data on management actions to predict impact and quantify intervention effort.

Indicators (right) build on the delivered invasion-relevant EBVs and are populated by modeled predictions with associated uncertainty on spread, impact, and interventions.

Response (lower left) consists of the four major interventions: prevention, eradication, management, and prioritization. These activities are guided by decision-support tools and products (such as alien-species distribution maps for protected areas and location-specific automated alerts for new invasions) provided from integration and delivery directly or via indicators. The responses in turn deliver much-needed new data, including data on intervention effort and success.

science contributions and alien "alerts." This would enable more targeted and effective data collection and species management. The same models can inform about likely pathways and causes of population spread at country and finer scales and thus guide control options, which can vary from straightforward in certain situations of human transport to infeasible in the case of new climate-change-driven dispersal corridors.[15]

We suggest that thanks to new biodiversity and remotely-sensed environmental data flows, coupled with infrastructure such as Map of Life (which facilitates their model-based integration and use), the biodiversity science community is in a strong position to deliver evidence of the growing scope and nature of biological invasions in the form of an indicator addressing "trends in the spread of invasive species by pathway of spread" (Figure 2).

Impact. The impact that aliens have varies by species, ecological context, and locality. For example, whereas alien birds affect largely urban settings, invasive plants in Mediterranean regions and invasive predators on islands have been responsible for the decimation of native flora and fauna across swathes of natural and semi-natural habitats and in protected areas. Spatiotemporally explicit data products of the impacts of range-expanding species are thus central to reducing impact.

With species-population EBVs in place to address range-expanding species, geographically explicit impact predictions can be derived from species data on impact-relevant traits (see Figure 2). Information on the ecological or extinction-risk-associated sensitivity of specific locations to invasion impact provides vital additional information for prioritizing intervention. For both trait and sensitive location data types, we envision species-locality-specific impact weighting to inform patterns and indicators of impact, such as the type, variety, and size of impacts in conservation priority areas, in water catchments, or across the distributions of threatened species. Satellite-based or aerial remote sensing can offer vital additional direct or model-supported information relevant to ecosystem function and conceptualized as a range of ecosystem-function EBVs, such as land cover or pollination services. Together, these species- and ecosystem-function-derived measures of invasion impacts will both populate a new indicator on "trends in the impacts of invasive species" and provide spatially explicit decision support for prioritization and management (see Figure 2) implemented via online infrastructure.

Intervention Effectiveness. Actions to prevent the spread and mitigate the negative impacts of aliens, such as local eradication or propagule interception, exist but vary strongly in their efficacy and documentation. Spatiotemporally explicit data on interventions, such as the number of successful population eradications, number of species or propagules intercepted, and area of habitat restored, represent a third critical information domain for measuring progress. Intervention success is defined by the resulting reduction in the spread and impact of alien species, and in our framework (Figure 2) its measurement thus emerges directly from linking intervention data to information on spread and impact. A resulting intervention indicator will provide data- and model-based ''trends in the effectiveness of actions to limit spread and reduce impact of species potentially harmful to biodiversity and ecosystems.'' And again, we suggest that, embedded in online infrastructure, this spatiotemporally explicit information can provide both measurement and guidance to enable a more effective response.

A Global Response Informed by Integrated Data and Tools

As work gets underway to formulate and implement actions to achieve invasion targets beyond 2020, it is thus time to consolidate developments made in isolation across the many dimensions and sectors of invasion research, monitoring, management, and reporting toward an integrated, collaborative information base and response. The transboundary nature of biological invasions means that information and decision-support tools addressing the spread and impact of alien species must span administrative boundaries. There exists clear potential to deliver actionable information to national and other agencies tasked with managing biological invasions by developing science-driven workflows and tools. Developed and provisioned in the framework proposed here, this information could help overcome the current inequitable distribution of knowledge and capacity across countries.

We urge the policy and science-policy communities to consider the target addressing alien species not in isolation but embedded in a unified framework that links data, indicators, and responses. This leverages the substantial innovations in evidence gathering, modeling, and informatics that have occurred over the past decade.[11,12] The biodiversity and observation science community under the Group on Earth Observations—building on partnerships including the Global Biodiversity Information Facility, Map of Life, and others—stands ready to support the production of invasion-relevant EBVs and associated indicator and decision-support products. Combined in a digital ''global invasions dashboard,'' these have the potential to support automated alerts and citizen-science campaigns about emerging invasive species and populations, the generation of sub-national lists and maps of invasive species for targeted areas, and risk prioritization for species, pathways, and localities to guide investment. We expect such a framework and supporting platform to galvanize data collection and sharing in support of evidence-based, repeatable assessments of priorities (species, pathways, and locations) for intervention. As countries develop regulations, implement management, and monitor progress, the presented framework will enable new evidence to contribute to multi-scale assessment and reporting within and across policy cycles. But more importantly, it will deliver integrated, actionable guidance for the management of the ever-growing spread and impact of alien invasive species we will see under growing transport, land-use change, and carbon emissions over the next reporting cycle.

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