A Framework for Global Twenty-First Century Scenarios and Models of Biological Invasions

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Biological invasions have emerged as an eminent feature of global change, with substantial impacts on the environment and human livelihoods. Current research demonstrates that the numbers and impacts of alien species are rising unabatedly. At the same time, we lack a thorough understanding of potential future trajectories for the decades to come. With the recent establishment of comprehensive global databases, it is, for the first time, feasible to develop and quantify future scenarios of biological invasions. Therefore, we propose a conceptual framework for how to develop alien species scenarios for the twenty-first century and how to identify relevant steps and challenges along the way. The concept will be important to inform research, policy, stakeholders, and the general public. Furthermore, we call for the scientific community to join forces and to operationalize the framework for scenarios and models of biological invasions to develop an important baseline for understanding and managing future biological invasions.

Keywords: alien species, impacts, management, projections, scenarios

Humans have fundamentally altered the biophysical environment of the Earth (Crutzen 2006), and the rates of change have accelerated during the recent decades (Lewis and Maslin 2015). Often, these environmental changes are *de facto* irreversible. Worryingly, the full consequences of global environmental change and degradation often manifest themselves with substantial time lags (Essl et al. 2015). Therefore, a better understanding of the long-term consequences of human pressures on the environment is urgently needed. Such assessments have to take into account the range of alternative future trajectories—that is, scenarios—of relevant pressures and societal responses (box 1). Scenarios of the future can be coupled with models that capture the relevant processes and their interactions and that deliver quantitative projections of future changes of focal components of the biophysical environment. Scenarios and models have been developed and have been widely applied for many important aspects of global environmental change such as climate (IPCC 2014), land use (Hurtt et al. 2011), human population development (Lutz et al. 2014), stratospheric ozone depletion (Prather and Watson 1990), and nitrogen deposition (Lamarque et al. 2005). They have become crucial for policy and decision-making, because they elucidate the consequences and impacts of human actions under different future developments (IPBES 2016). However, the long-term impacts of biological invasions have so far not been explored with scenarios and models.

Biological invasions substantially affect biodiversity, ecosystem services, and human livelihoods alike (Bellard et al. 2016, Maxwell et al. 2016, Pyšek et al. 2017). They drive species extinctions worldwide (Bellard et al. 2016), particularly on islands (Bellard et al. 2017) that contribute strongly to global biodiversity, causing high mitigation and adaptation costs (Pimentel et al. 2005, Kettunen et al. 2008). These impacts of invasions will further rise in the future as the rate of establishment of alien (i.e., nonnative) species has increased strongly during the last decades with no sign of saturation (Seebens et al. 2017a).

Consequently, several international initiatives and agreements such as the United Nations Sustainable Development Goals (SDG), the Convention on Biological Diversity (CBD) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) consider the assessment and control of biological invasions as a crucial step to sustain global biodiversity, ecosystem services, and human livelihoods (see box 2). The rising numbers (Seebens et al. 2017a) and impacts (Tittensor et al. 2014) of alien species, the *de facto* irreversibility and often limited

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Box 1. Glossary presenting definitions and relevant frameworks used in this manuscript.

Driver, pressure, impact: The terminology follows the DPSIR (driving forces, pressures, states, impacts and responses) framework developed by the European Environment Agency (*www.eea.europa.eu*) that describes how societies interact with the environment.

Integrated assessment models (IAM): IAM's represent a quantification of parts of Earth's system by acknowledging a set of interacting natural and social systems. These subsystems are described through different scenarios (see below) that provide the narrative foundation of IAMs. IAMs produce projections on how the system might change under different assumptions explored in the scenario storylines (see below; Parson and Fisher-Vanden 1997, Harfoot et al. 2014).

Prediction: A prediction is a numerical estimate of a specific output (e.g., alien species numbers or impacts) for a specific time point in the future based on a quantitative model and ideally associated with a certain degree of confidence or uncertainty (IPCC 2014).

Representative concentration pathways (RCP): A set of scenarios for climate change that include a set of climate forcing agents. The RCPs were produced in 2014 for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and are the successor scenarios of the ones used in the Special Report on Emissions (SRES). They act as the reference scenarios for different radiative forcing scenarios in climate research (van Vuuren et al. 2011).

Scenario: Following the definition of the Intergovernmental Panel on Climate Change (IPCC), a scenario describes a "coherent, internally consistent and plausible description of one possible future state of the world." Generally a set of scenarios is described to capture the range of possible future states of a system (IPCC 2014).

Shared socioeconomic pathways (SSP): A set of socioeconomic scenarios first published in 2015 to supplement the RCP climate scenarios developed by the IPCC. They explore alternative pathways of global socioeconomic developments and aim to inform climate research about adaptation and mitigation strategies (O'Neill et al. 2014).

Storylines or narratives: The two terms are used interchangeably. They are the core of each scenario and describe the main characteristics, drivers and dynamics of the system. Furthermore, they provide information on relationships and feedback loops between key drivers (IPCC 2014). Prominent examples are the storylines developed for the "Shared socioeconomic pathways," "Sustainability: Taking the green road," "Middle of the road," "Regional rivalry: A rocky road," "Inequality: A road divided," and "Fossil-fueled development: Taking the highway" scenarios (O'Neill et al. 2017).

manageability of alien species introductions, and the substantial time lags associated with different stages of biological invasions (Essl et al. 2015) underpin the need for understanding the long-term trajectories—scenarios—of biological invasions.

The availability of global data sets for biological invasions across taxonomic groups has improved dramatically in the last decade. Furthermore, a large body of literature in invasion science has emerged that contributes to the understanding of the underlying mechanisms of biological invasions and informs the models that investigate the spread, establishment, and impacts of alien species. We believe that, for the first time, it is now feasible to develop a global reference framework for future biological invasions in the twenty-first century. Therefore, we propose a conceptual framework and a roadmap on how to achieve this goal by simultaneously illustrating key challenges and possible solutions along the way.

Scenario exercises have proven that they can invoke a transformative impact on societal awareness and shift societal perception of relevant environmental topics. They are, for example, essential for developing policy and management strategies regarding future human food supply in the twenty-first century (Muller et al. 2017) or for assessments of land-use effects on biodiversity conservation (Newbold et al. 2015). It is, of course, difficult to anticipate the impact of our proposed biological invasion scenarios. However, on the basis of the experience gained in other fields (e.g., climate change), we are confident that our framework and the resulting scenarios will have a strong impact on our understanding of the relevant processes and the future option space for reducing biological invasions, as well as on public awareness and decision-making.

Exploring the future of biological invasions: A conceptual scenario framework

We present a conceptual framework for the development of scenarios and models on how alien species richness and impact might change in the twenty-first century (figure 1). This includes two main tasks: First is the establishment of qualitative scenario narratives (i.e., the alien species scenario narratives; ASN) based on current and historic knowledge available to identify the relevant pressures that drive biological invasions, to identify their potential developments in the future, and to generate a set of consistent storylines about plausible trajectories of drivers and their effect on biological invasions in the future. Second is the quantification of pressures and impacts for these storylines based on the quantification of the effects of the drivers on alien species invasions in the future under different socioeconomic and biophysical assumptions. This work is the basis for the subsequent development of numerical models. For reasons of consistency, the

Box 2. Overview on the most important global environmental policy frameworks and their relationship to biological invasions.

United Nations Sustainable Development Goals (SDG)

The SDGs consist of 17 universal sustainable development goals that have been agreed on by 193 countries and national territories to be achieved by 2030. The SDGs are a successor of the 8 Millennium Development Goals (MDG) established in 2000. Alien species impact is addressed in the SDGs 14 ("Life below water") and 15 ("Life on land") that aim to "conserve, protect, restore and promote sustainable use of terrestrial [and aquatic] systems." Both targets urge that "by 2020, [we] introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on the land and water ecosystems, and control or eradicate the priority species."

Intergovernmental Panel on Climate Change (IPCC)

In the Fifth Assessment Report of the IPCC, alien species are mentioned in several sections. For terrestrial systems (sections 4, 11, 19, 22, and 27), the IPCC mentions among the key risks to ecosystems and ecosystem services the "Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms." Similar risks are formulated for marine ecosystems (sections 5, 6, 7, 9, 11, 19, 22, and 27), concerning the "Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services."

Convention on Biological Diversity (CBD)

The CBD promotes sustainable development with a strong focus on biological diversity. Implemented in 1992 and signed by 150 countries, the later adopted Strategic Plan for Biodiversity proposes 20 biodiversity targets (Aichi targets) that are aimed to be accomplished by 2020. Aichi target 9 specifically deals with alien species, stating that "by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled and eradicated, and measures are in place to manage pathways to prevent their introduction and establishment."

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)

The IPBES assessment that is currently in progress for the development of a first report on the global status of biodiversity is going to devote a working group to invasive alien species. The "Deliverable 3bii: Thematic assessment on invasive alien species and their control" scenario aims to comprehensively "assess the threat that alien species pose to biodiversity, ecosystem services, and livelihoods and the general status of and trends in impact of invasive species by region and subregion, taking into account various knowledge and value systems."

development of such models of biological invasions should use, as much as possible, the output of already existing quantitative scenario frameworks (i.e., global land use or vegetation models) to numerically characterize the possible future trajectories of important drivers of biological invasions.

The development of the qualitative storylines (ASNs) together with the quantification of the pressures and impacts of biological invasions will undergo evaluation, adaptation, and refinement via interaction with stakeholders with expertise in a wide range of relevant fields.

Narratives for the possible futures of biological invasions

Environmental change scenarios are based on qualitative storylines that capture the trajectories of important drivers (i.e., components) of the focal system and how they might change in the future under different assumptions how the world develops (Rounsevell and Metzger 2010). Although several procedures have been developed that suit the varying needs of environmental scenarios, each with its individual benefits and drawbacks (see Alcamo 2001, Jaeger et al. 2007, 2008, Henrichs et al. 2010, Wodak and Neale 2015), new emerging storylines need to be tailored to the focal system and the scope of the scenario exercise (i.e., biological invasions).

In this section, we propose a structure to develop such qualitative global storylines for biological invasions. We dissect this process into three components that deal with defining the scope of the scenario exercise, identifying the relevant drivers of biological invasions, and the storyline development process (figure 2). This structure rests on the schemes proposed by Jaeger and colleagues (2007) and Henrichs and colleagues (2010).

Defining the scope of the scenario exercise. The scenario process starts by defining the scope of the exercise with respect to the overarching theme and the specific components of the system we want to explore. Setting a clear scope from the beginning helps structuring the process and defining main targets and outputs the project wants to achieve (Henrichs et al. 2010). In our case, the scope is to develop the first global storylines to derive robust future predictions on how numbers, abundances, distributions and impacts of alien species might change throughout the course of the twenty-first century (figure 2a). These storylines are intended to explore how these aspects of biological invasions might change under different assumptions on how the global socioecological system and its components likely develop. In addition, this exercise is intended to advance invasion

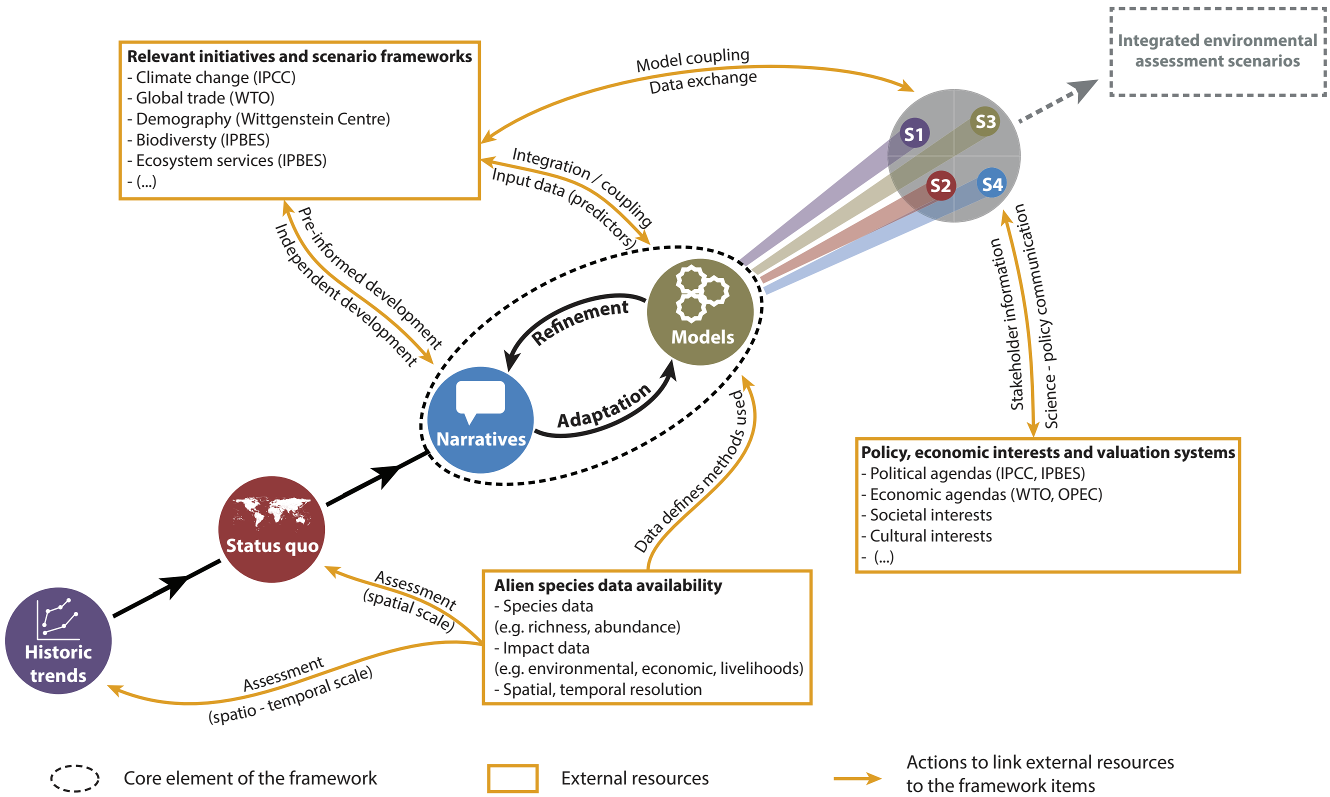

Figure 1. The key elements and key steps for developing a framework for scenarios and models of biological invasions. The figure is composed of a conceptual layer (circles) that describe the stepwise scenario development process from initial data assessment and mobilization to storyline construction, model quantification, and, finally, to full scenarios of biological invasions. The grey circle (top right) resembles the potential option space of biological invasions in the future and the explored space by four exemplary individual alien species scenarios (S1–S4). The boxes depict components that influence the development process or that might be influenced by it. The arrows between the conceptual and influencing properties indicate strong interactions. The grey dashed arrow and box represent the potential long-term aim of fully integrated environmental assessment scenarios including all relevant parts of the Earth's system.

science by identifying key aspects of the system and emerging challenges in the near and distant future.

Identifying drivers and stakeholder involvement. Biological invasions depend on a range of different biotic, abiotic, socioeconomic, and sociocultural drivers (a nonexhaustive selection of likely relevant major drivers is shown in supplemental table S1). Their importance, however, differs with respect to the spatial and temporal context, the environmental realm (marine, freshwater, terrestrial), and the taxonomic groups considered. Identifying these drivers and evaluating which might be most important for biological invasions in the future is a daunting task. Making use of available knowledge requires the inclusion of different experts (i.e., scientists, stakeholders, and decision-makers) with a broad range of expertise to ensure that all relevant facets of the system are addressed. Stakeholders can adopt different roles related to the degree of involvement and resulting responsibilities. These can range from mere consultation and decision support to codesigning or leading specific decisions in the storyline evolution (Volkery et al. 2008, Henrichs et al. 2010). In addition, the expert panel should not only encompass various scientific and nonscientific backgrounds but should also be well balanced in terms of gender and geographical and cultural backgrounds (Hannagan and Larimer 2010, Krueger et al. 2012, IPBES 2016).

We propose that the driver assessment for the biological invasion scenarios should follow a two-step procedure that involves different groups of participants at the different stages. In a first step, experts in invasion science and thematically closely related fields of environmental change identify a long list of drivers, mechanisms, and pathways of biological invasions. Such an assessment should be done in a systematic manner using established methods such as systematic literature reviews, meta-analysis, or participatory surveys (e.g., Lortie 2014, Kuebbing et al. 2018).

Subsequently, a scientist and stakeholder panel with expertise in the previously identified drivers should be invited to discuss individual features and trajectories of the drivers and how they interact (figure 2b). Within this

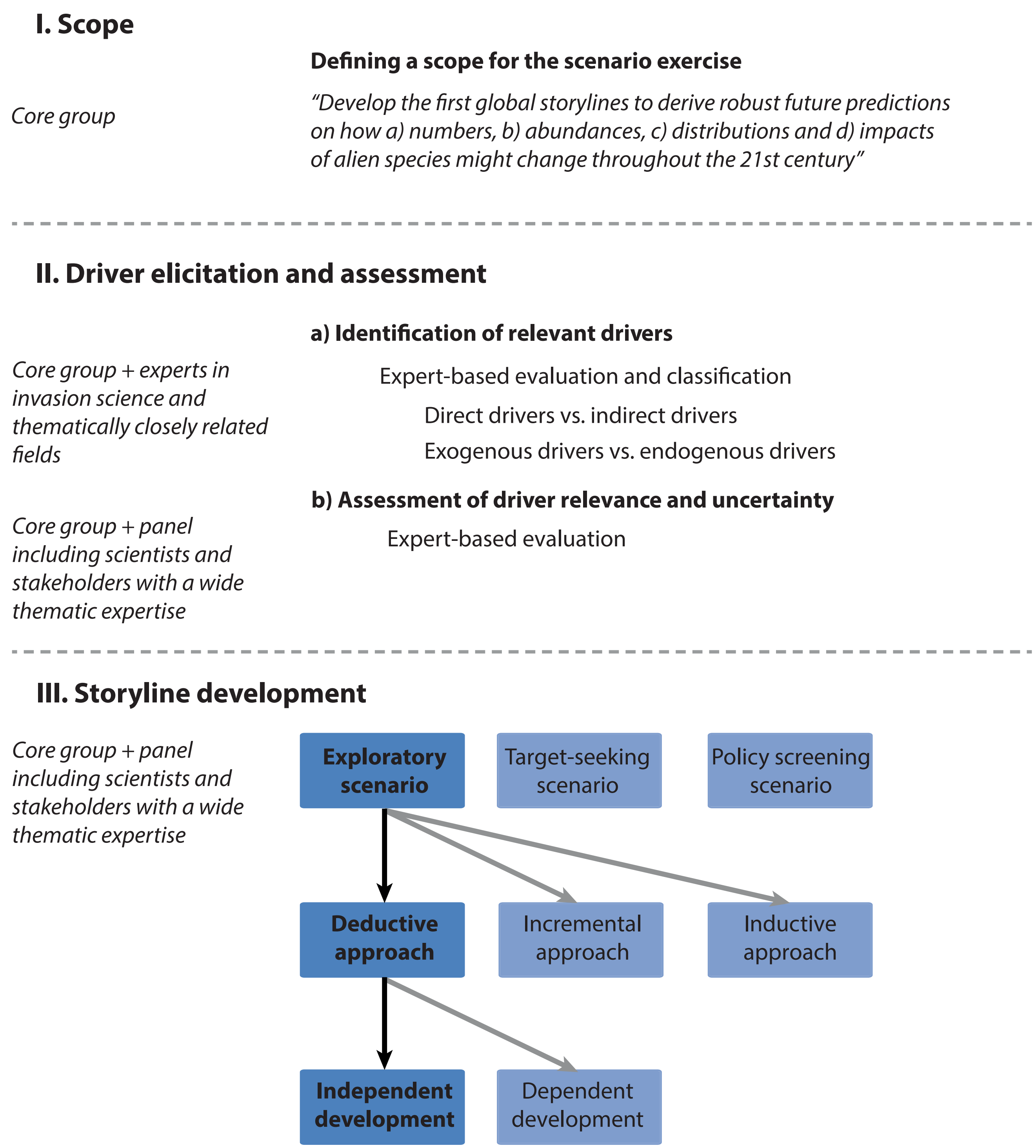

Figure 2. The proposed steps for the development of storylines for biological invasions in the twenty-first century. For each step, the relevant tasks are highlighted. In addition, we propose a set of participants that should contribute to each of the steps (the left hand side in italics). For step 3, we show multiple possibilities for the storyline development, as is explained in the text. The darker boxes show the development procedure we propose as the most suitable.

context, the drivers can then be classified into different categories to provide a more nuanced assessment on their impacts and how they interact. We can distinguish between direct drivers with immediate effects and indirect drivers with cascading effects (Secretariat of the Convention on Biological Diversity 2014, IPBES 2016) or between exogenous drivers, whose effects are beyond immediate human control (e.g., climate change, market or technology development), and endogenous drivers, whose effects can be mitigated by human control (e.g., species introduction or removal, land-use change). Understanding these different facets of the drivers and their interactions is crucial for identifying possible societal interventions, uncertainties, and thresholds (Henrichs et al. 2010).

The process of driver discussion and prioritization can be structured by using a variety of different techniques that reduce the uncertainty in the assessment and increase reproducibility (e.g., Delphi technique, Okoli and Pawlowski 2004; fuzzy set theory, Kok et al. 2015; multiagent role games, Bousquet et al. 2002).

Constructing qualitative storylines. There are different ways to construct storylines on the basis of the previously defined subset of driving forces (IPBES 2016). Storylines can explore a range of possible futures (exploratory scenarios; Kok et al. 2011), develop pathways to a specific predefined target (target-seeking scenarios; Alcamo 2001), or explore the effects of different policies (policy-screening scenarios; IPBES 2016).

Furthermore, storylines can be constructed inductively, incrementally, or deductively (Henrichs et al. 2010, Wodak and Neale 2015). Inductive storylines are based on the description of individual events and likely effects that result from specific decisions made in the present. They provide a large degree of freedom to explore possible futures but, at the same time, are less systematic in their construction (Henrichs et al. 2010). Incremental storylines describe deviations from a most plausible reference scenario (i.e., business as usual). Such a reference scenario generally assumes that historic trajectories continue without dramatic or sudden changes and allows the assessment of how changes in system drivers lead to deviations from this scenario (Henrichs et al. 2010). Finally, the deductive approach uses a more systematic assessment of the range of possibilities on how the identified drivers are likely going to change future trends and interact with other aspects of the global socioecological system. That way, consistent logic of the different storylines can be identified providing a holistic view on the topic (Jaeger et al. 2007, Henrichs et al. 2010).

A final crucial step is to decide whether the storylines should be constructed depending on already existing scenario frameworks or independently (Zurek and Henrichs 2007). Developing dependent storylines with strong links to existing frameworks facilitates the establishment of links between them and at a later stage to adopt the new findings into integrated model frameworks. However, these storylines would be constrained on the assumptions of the existing framework that might not consider all relevant aspects. Constructing independent storylines provides the freedom to explore different facets of the focal system more rigorously and in a way specifically tailored to the respective topic. These independent storylines can then, *a posteriori*, be linked to other scenarios (see below).

Because no attempt has so far been made to develop global biological invasion storylines, we suggest to start with exploratory scenarios using a deductive approach to develop independent storylines (figure 2c). The development of independent storylines enables the exploration of plausible futures for biological invasions without being constrained by already existing scenarios of other facets of global environmental change (e.g., climate change) that do not capture all aspects relevant for biological invasions. Descriptive storylines allow us to explore the future range of possible outcomes of alien species richness, abundance, and impacts. Only when we understand the interactions between the various drivers and how they influence the future trajectories of biological invasions can we then develop more focused scenarios that provide insights into how we can arrive at specific desired targets (e.g., target-seeking scenarios on how to achieve the goals of Aichi target 9 of the Convention on Biological Diversity). Finally, we suggest following a deductive scenario process to ensure the most systematic approach to obtain storylines through standardized methods and processes. This way, other working groups and initiatives can assess, reproduce, and extend the storylines in the future.

After establishing the conceptual foundation, the first ASN storylines can be constructed. We suggest using a two-axes approach (van der Heijden 2005), in which each axis represents one of the identified influential drivers resulting in a 2×2 storyline matrix for different driver combinations (e.g., social values versus trade, land use and land cover change versus climate change). The qualitative description of futures with a focus on the respective two drivers should also include an assessment of their impact on other drivers of the system and the implications on future biological invasions. Each of these two-axes approaches will therefore result in four comprehensive storylines of the future system with a specific focus on the two drivers on the main axes. Given the complexity of the topic (i.e., biological invasions) and the multitude of influential drivers, such an assessment will result in multiple qualitative storylines. However, because all of them consider the entire system (with a different special focus on individual drivers) the storylines will, in many cases, follow similar logic. Those storylines with similar logic and underlying assumptions can be aggregated into scenario families (i.e., archetypes) that have overlapping scope and describe similar potential futures (Hunt et al. 2012, Kriegler et al. 2012). This way, a high number of storylines can be condensed to a more practical number (e.g., 4–5, as was suggested by IPBES 2016), which is essential for the communication of the ASNs to stakeholders and politicians, as well as for a targeted future development of biological invasion scenarios.

We acknowledge that alternative valid approaches for constructing storylines of biological invasions exist. Scrutinizing the validity and comprehensiveness of the driver assessment and storyline logic, as well as their construction process is crucial. Furthermore, there is substantial potential for future refinements and improvements of the ASN concept. However, we believe that the approach presented in the present article provides a useful basis for developing comprehensive qualitative storylines of biological invasions.

Models to project future biological invasions along the narratives

To convert the aforementioned scenario storylines to quantitative projections, we need to use appropriate models. This is done by identifying the response variables of interest, the relevant predictor variables that produce changes in the response variables, and the adequate models to quantify the relationships between the response variables and the predictors.

Response variable. Biological invasions can be described by different metrics that capture different facets of the phenomenon (e.g., numbers, abundance, impacts of alien species), at different spatial resolution (e.g., from small scales such as plots to larger entities such as countries), and for different taxonomic groups (e.g., on the basis of data availability; Latombe et al. 2017). Different metrics can be considered suitable under varying scale and focus of the scenarios. Although most of the above-mentioned metrics are generally positively correlated with each other, there may also be substantial differences among the conclusions that can be drawn (Hulme et al. 2013, Jeschke et al. 2014). In addition, the response variable might change according to the specific target of the scenario exercise. Therefore, regional or local scenarios might be more focused on specific vulnerable areas (e.g., invasion risk of conservation areas) or high-risk species (e.g., the Invasive Alien Species of Union Concern as defined by the European Union).

The recent establishments of comprehensive global databases on alien species distributions for different taxonomic groups (e.g., GloNAF for vascular plants, van Kleunen et al. 2015, Pyšek et al. 2017; GAVIA for birds, Dyer et al. 2017; the Alien Herptile Database for amphibians and reptiles, Capinha et al. 2017; GABI for ants, Janicki et al. 2016, Guenard et al. 2017) and the temporal dynamics of alien species accumulation during the last centuries (Alien Species First Records database, Seebens et al. 2017a) substantially improved our knowledge about the spatiotemporal dynamics of biological invasions at a global scale. These databases for the first time provide a robust baseline for quantifying future scenarios of biological invasions. On the contrary, robust and comparable data on the impacts of alien species in different regions are still largely lacking, and in many cases, uncertainties in impact assessments are large (Simberloff et al. 2013, Jeschke et al. 2014). However, more recently, standardized assessment schemes for impacts of biological invasions on the environment (Blackburn et al. 2014) and on human livelihoods (Bacher et al. 2018) have been proposed that might gather consistent data for future integration of impacts into scenarios. Given these constraints on the availability of alien species' impact data, we propose to concentrate, for the time being, on the change in number and abundance of alien species in regions as, so far, the most suitable and most coherent metrics for quantifying the ASNs.

Predictor variables. Many drivers of biological invasions, such as land use (Hurtt et al. 2011), human population development (Lutz et al. 2014), and climate change (IPCC 2014), and their historic states have been reconstructed and projected into the future under different scenarios (e.g., the representative concentration pathways, van Vuuren et al. 2011, or the shared socioeconomic pathways, O'Neill et al. 2017). Key challenges are the identification of the relationships of these drivers with future biological invasions and the availability of data that represent proxies for the underlying drivers—that is, the predictor variables. Ideally, such data have to fulfill several criteria: They have an appropriate spatial and temporal (i.e., historic and current) coverage, they capture the attributes of the drivers essential for biological invasions, they have ideally been used and tested by other environmental change models (which, of course, does not apply for novel proxies of specific importance to biological invasions), and projections on their future developments under different assumptions are available (table S1).

Although, for some drivers, all these criteria are met (e.g., for drivers of biophysical changes, such as climate or land use), for several others, this is not the case (e.g., political, technological, and societal responses to invasions), including some for which none of the criteria currently applies (a completeness assessment is included in the data set descriptions in table S1). Improving this situation will be highly challenging, because the indicators developed to capture socioeconomy, political governance, or societal developments often lack information particularly for historic times and projections of future development of these indicators are highly uncertain, if possible at all (e.g., because of high variability within and between countries and unpredictable future changes in society, politics, and technology).

Model. Analyzing response and predictor variables with different spatiotemporal resolution and quality requires a differentiated identification of their relationships and interactions using adequate methods. On the basis of data availability and the understanding of the processes, models to investigate these relationships might be constructed through equations that capture the mechanistic understanding of the relevant processes (e.g., as are used in global circulation models) or could be constructed using data driven approaches that establish statistical relationships on the basis of historic observations (e.g., regression models). For long-term scenarios, mechanistic models are preferable, because they can more adequately display long-term trends and are more flexible to integrate adaptation or mitigation strategies (IPBES 2016). Furthermore, mechanistic models can more flexibly capture systems dynamics, such that drivers or underlying mechanisms might likely change in the future, as is expected for biological invasions (e.g., Walther et al. 2009, Sitzia et al. 2018).

Drivers characterized mainly by qualitative or semiquantitative information (e.g., societal perception of alien species, beliefs and value systems) are often substituted by socioeconomic metrics resulting in a loss of valuable information (IPBES 2016). Therefore, developing conceptual models on the basis of expert elicitation (Krueger et al. 2012) or using approaches such as agent-based modeling (Kelly et al. 2013) or social network analysis (Burt et al. 2013) might improve the understanding of these indirect drivers on alien species richness and abundance. When this is not feasible (e.g., because of abrupt changes in human preferences, Swart et al. 2004, or unpredictable shifts in international relations such as emerging conflicts, Chadefaux 2017), comprehensive storylines need to be developed and refined on the basis of expert knowledge for an adequate assessment.

Harnessing expert knowledge has been shown to offer novel and highly useful opportunities for classical ecological model development and can significantly account for model uncertainty and insufficient data (Krueger et al. 2012, Drescher et al. 2013), as is the case for developing scenarios and models of biological invasions. Especially, Bayesian modeling frameworks (e.g., Bayesian Network models) can account for highly heterogeneous sources of data and knowledge and significantly improve model accuracy (Ghazoul and McAllister 2003, Constantinou et al. 2016). Such models have already been applied in other fields such as climate change (Reside et al. 2018) and hydrology (Safavi et al. 2015) or for modeling socioeconomic (Dawkins et al. 2018) and cultural behavior (Shaw et al. 2016). A recurrent adaptation and refinement of the models in conjunction with the development of more balanced storylines will ensure a consistent advancement of either of the two and contribute to the successful implementation of the biological invasion scenarios (see the core element of figure 1).

More recently, models for predicting changes in alien species richness and abundance have been proposed that explore different facets of the invasion process and at different invasion stages (Seebens et al. 2015, 2016, Liebhold et al. 2017). These models already capture some dynamics for drivers discussed above and are valuable baseline models for further development and integration of other drivers into their conceptual structure. Nevertheless, model development in invasion sciences is still less advanced than that in other fields (e.g., climate change modeling). For example, current models still do not effectively include social, political, economic, or cultural factors relevant to the invasion process (Vaz et al. 2017). Furthermore, in many cases, we still lack a thorough understanding of the causal links between drivers and invasion success and how these might change in the future. For that matter, it would be highly beneficial to strengthen interdisplinary collaboration on ecological and socioeconomic modeling, as well as between different working groups on invasion modeling, model evaluation at different scales, and synthesis of existing approaches.

Consistency and synergies with other scenario frameworks

Different initiatives and frameworks exist that explicitly acknowledge the importance of biological invasions at various spatiotemporal scales and that call for measures to prevent the introduction and significantly reduce the impact of invasive alien species (box 2). The increasing attention biological invasions receive from different fields (i.e., science, policy, economy, civil society) stresses the necessity that emerging biological invasion scenarios are consistent with other qualitative and quantitative scenario frameworks. This can be achieved by linking the ASNs to already existing quantitative or semiquantitative frameworks (see box 2). Such a connection between already established frameworks is crucial to increase the applicability of the novel framework, to increase its acceptance by the relevant communities, and to ensure its ongoing adaptation and refinement.

To adequately capture the complexity of the ASNs, it is necessary to include information from a wide range of different fields (e.g., ecology, economy, sociology) and to integrate them into driver models of the ASN framework. Although some important drivers need to be quantified and modeled from scratch, others have already been investigated in other scenario frameworks (e.g., human population change, KC and Lutz 2014; land-use change, Hurtt et al. 2011; climate change, IPCC 2014). These scenarios follow the specific storylines of the respective scenario framework that might, however, be close to the new ASN storylines in terms of their internal logic and assumptions on how the world might change in the future. Identifying these synergies between the different scenario frameworks provides the opportunity to exchange information that can be integrated in either one.

The ASNs can be coupled with other scenario frameworks through a one-to-one mapping process (Zurek and Henrichs 2007) in which the similarities and assumptions of future developments within different socioeconomic and biophysical sectors of either storyline and how these match across scenarios are compared (van Vuuren and Carter 2014, van Vuuren et al. 2014). We illustrate such an approach in figure 3 for a fictitious mapping of the ASNs onto the widely used representative concentration pathways and shared socioeconomic pathways storylines. The connection of the storylines provides the justification to exchange quantitative data between the scenarios. Data exchange can be done through loose or tight coupling (IPBES 2016), such that output from the models of one framework can serve as input to the models of another one. Tight coupling includes feedback loops between the frameworks and therefore enables nonlinear dynamics of the system. Although making the model more realistic, it

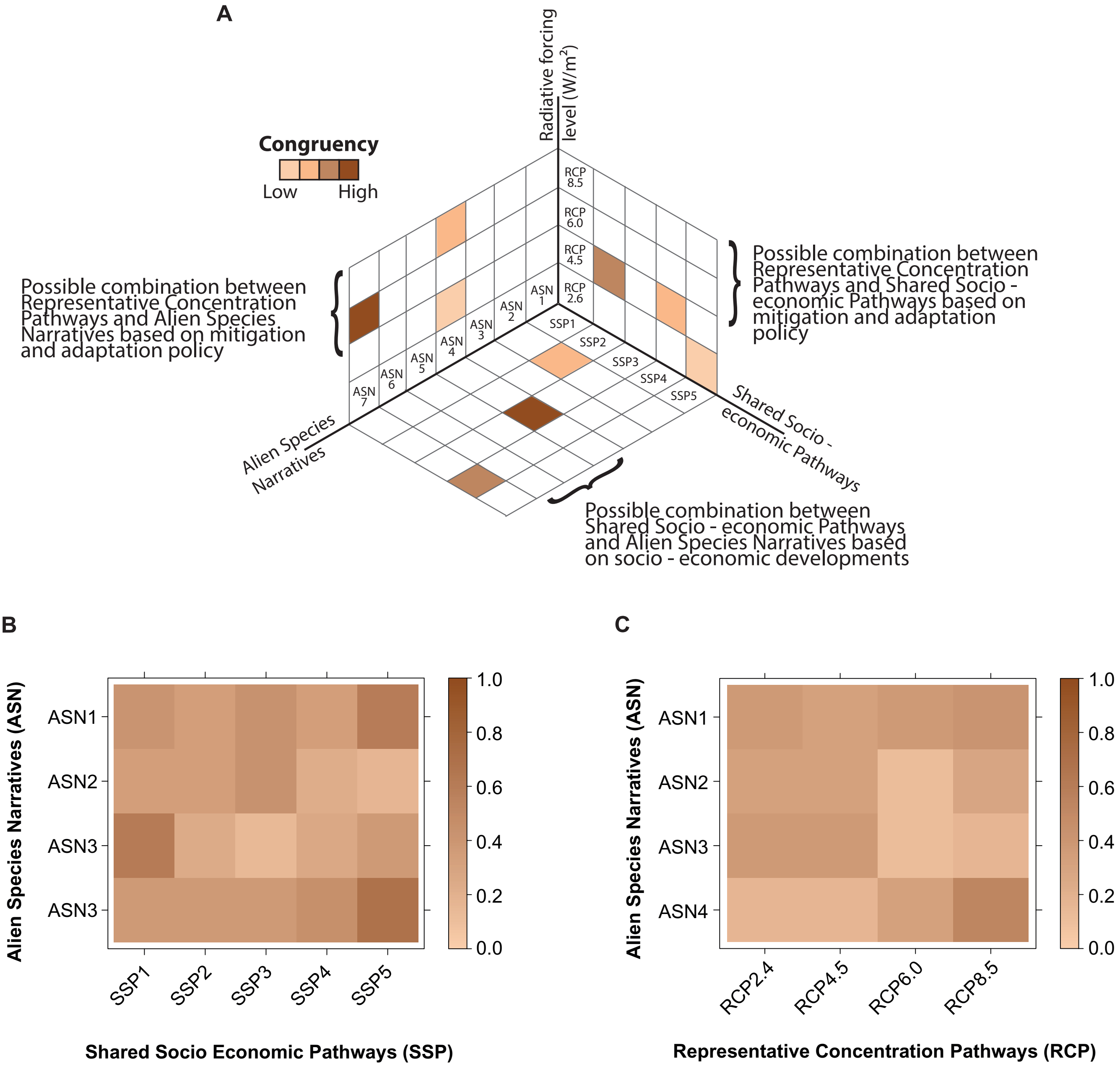

Figure 3. The one-by-one mapping approach to establish the relationships among different sets of environmental scenarios. (a) The different axes represent three different sets of global environmental change scenarios (x-axis: shared socioeconomic pathways [SSP], O'Neill et al. 2017; y-axis: radiative forcing or representative concentration pathways [RCP], van Vuuren et al. 2011; z-axis: alien species scenario narratives [ASN]). The scenarios can be combined using reference assumptions described in the individual storylines. The mapping of different sets of scenarios provides information on their similarity and, therefore, how results from one framework can be linked to another. (b) A narrative comparison between the four hypothetical ASNs and the SSPs and (c) a comparison between the four hypothetical ASNs and the RCPs. The congruency between scenarios is bound between 0 (no relationship) and 1 (a perfect relationship), with darker colors indicating higher congruency between the narratives.

dramatically increases the complexity and the number of uncertain parameters and processes, which makes model behavior intractable and often reduces robustness ("integronsters," Voinov 2010). Loose coupling is more robust and the implementation is more straightforward as different models can be run sequentially, but they are limited in their explanatory power of nonlinear dynamics.

Independent of the coupling procedure chosen, all models need to be harmonized (IPBES 2016). This means that all inputs have to be standardized and output metrics need to follow a consistent format. This is also necessary for model benchmarking to evaluate model performance and the validity of the derived predictions (McCarthy et al. 2012). For the development of the ASNs, this means that the biological invasion models need to be designed in a way that output variables from models of other frameworks can readily be integrated and vice versa.

Key actors and their roles within the scenario building process

The establishment of biological invasion scenarios is a highly complex task that strongly depends on the engagement of different key actors who adopt different functions. These stakeholders necessarily have different backgrounds, including governmental and nongovernmental bodies (i.e., IPBES, IPCC, IUCN, and CBD), the scientific community, and other research institutes and stakeholder groups (e.g., Future Earth, *www.futureearth.org*; the Great Transition Initiative, *www.greattransition.org*). All these groups might contribute to different stages and challenges of the scenario building process (see supplemental table S2).

As a coordinating umbrella organization, IPBES appears to be most promising, in the sense that it can provide necessary infrastructure, resources, and visibility across the scientific and political domains and might contribute to further capacity building. Especially objective 3: "Thematic and methodological issues," with its deliverables; 3(b)(ii): "Thematic assessment on invasive alien species and their control"; and 3(c): "Policy support tools and methodologies for scenario analysis and modeling of biodiversity and ecosystem services on the basis of a fast track assessment and a guide" would be highly suitable for coordinating the scenario building process. In addition, the IUCN and CBD, global institutions with a vast network, existing working groups (e.g., the IUCN's Invasive Species Specialist Group), and widely accepted agendas (e.g., the CBD Aichi targets), should engage strongly in the scenario development process. All three institutions—IPBES, IUCN, and CDB—are crucial players that align the scientific world with the political sphere and are therefore perfectly suited to host and support such an undertaking through their infrastructure and the provision of targeted funding for scenario and model development for biological invasions.

Subsequently, we suggest that the translation of the scenarios to models and the model implementation and parameterization should be realized through a self-organizing scientific community approach similar to the one adopted for other environmental topics (e.g., climate or land-use change). Therefore, the establishment of novel structures, such as specialized working groups on different aspects of the biological invasions scenarios (comparable to the IPCC working groups) or the establishment of a model intercomparison project (MIP) as in other environmental scenario modeling communities (e.g., AgMIP for agriculture systems modeling (Rosenzweig et al. 2013) or ISI-MIP for climate change impact modeling (Warszawski et al. 2014), can be a valuable tool to steer and efficiently organize this process.

Recently, the path has been paved to start and develop an open scientific community approach through a joint funding call by the Belmont Forum and BiodivERsA, which is targeted at the development application of scenarios of biodiversity and ecosystem services (*www.biodiversa.org/1400*). Among the 21 funded projects are two, "InvasiBES" and "AlienScenarios," focused solely on alien species scenarios; the authors of the present article are involved in the latter. In addition, other working groups, such as the GEO BON working group on using an essential biodiversity variable approach to invasion monitoring (GEO BON 2015) or the German Centre for Integrative Biodiversity Research working group sTWIST: Theory and Workflows for Alien and Invasive Species Tracking (*www.idiv.de/sdiv/working_groups/wg_pool/stwist.html*), have been established and provide a valuable baseline for the biological invasions scenario development.

We can not stress enough that such an undertaking will only be successful in a joint effort with high degrees of collaboration and knowledge exchange between researchers, legislators, and the general public. Given the already existing and emerging structures we are, however, confident that this will be the case and invite other groups to engage in this endeavor.

Conclusions

Developing scenarios and models of biological invasions for the twenty-first century is an urgently needed but highly challenging task. The recent advances in data availability and the formulation of mechanistic models for individual drivers of biological invasions allow addressing this task appropriately for the first time. In the present article, we provide the conceptual foundation and a roadmap for the development of scenarios and models of biological invasions. This framework has to be tested, applied, and refined in future studies with the long-term goal to develop comprehensive integrated assessment models of biological invasions. Several challenges and key actions have to be solved on the way (figure 1, table S2). First, more data needs to be gathered (e.g., through field work or modeling of historic driver trajectories), especially for model validation, and a comprehensive assessment of data availability, quality, and consistency is crucial. Furthermore, expert based quality assessment, evaluation, and refinement of the ASNs and the resulting models is vital. This can be achieved by establishing an ASN working group, including experts from various fields, that coordinates these tasks. Models need to be subsequently developed and improved to integrate crucial steps (i.e., integration of different stages of the invasion process) and identify underlying processes and mechanisms between alien species richness and impacts for the development of more mechanistic models. Finally, the ASNs need to be communicated to the relevant communities to build and increase the awareness regarding the necessity of integrating biological invasion models into existing models of socioeconomic and natural systems.

At the same time, we note that a number of different ways for advancing the ASN concept will be possible, including a range of different solutions in terms of complexity, models, and scenario framework specifications used. We believe that the ASN concept presented in the present article provides an important contribution for understanding—and proactively managing—the future of biological invasions. We simultaneously call for further work on each step along the process (data mobilization, storyline development and refinement, model construction, and initiative connection) to make it a fully operational approach that captures all relevant drivers of biological invasions. This will allow an assessment of the potential long-term consequences of human mediated species movements on the same basis as done for other features of global environmental change.

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Supplemental material

Supplemental data are available at *BIOSCI* online.

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