A scenario-guided strategy for the future management of biological invasions

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Future dynamics of biological invasions are highly uncertain because they depend on multiple social–ecological drivers. We used a scenario-based approach to explore potential management options for invasive species in Europe. During two workshops involving a multidisciplinary team of experts, we developed a management strategy arranged into 19 goals relating to policy, research, public awareness, and biosecurity. We conceived solutions for achieving these goals under different plausible future scenarios, and identified four interrelated recommendations around which any long-term strategy for managing invasive species can be structured: (1) a European biosecurity regime, (2) a dedicated communication strategy, (3) data standardization and management tools, and (4) a monitoring and assessment system. Finally, we assessed the feasibility of the management strategy and found substantial differences among scenarios. Collectively, our results indicate that it is time for a new strategy for managing biological invasions in Europe, one that is based on a more integrative approach across socioeconomic sectors and countries.

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Invasive species are key drivers of global environmental change and strongly contribute to global biodiversity loss, exerting unsustainable economic losses through direct damage and management actions (Pyšek *et al.* 2020; Diagne *et al.* 2021). Despite ongoing efforts in policy, research, and management, the number of non-native species invading previously unoccupied areas and establishing populations around the world is still increasing, with no sign of saturation (Early *et al.* 2016; Seebens *et al.* 2017). The Convention on Biological Diversity (CBD) urges countries to develop early-warning and surveillance systems, action plans to address priority pathways of introduction, rapid eradication procedures to prevent establishment, and long-term mitigation and control measures (CBD 2022b). However, implementation of these management recommendations is challenging due to limited resources and capacity, a lack of legal frameworks (CBD 2020), and the uncertainties associated with future trajectories of societies and global change (Pyšek *et al.* 2020; Latombe *et al.* 2022).

The number of non-native species present in continental Europe, in both terrestrial and marine habitats, is projected to increase for most taxonomic groups by 2050 (Sardain *et al.* 2019; Seebens *et al.* 2021). These estimates, which are based either on observed past trends in the accumulation of non-native species or on a limited set of global socioeconomic factors (eg gross domestic product or regional trade), provide a baseline for exploring the future dynamics of biological invasions. However, future numbers and impacts of invasive species are expected to strongly depend on multiple environmental and socioeconomic drivers, which are highly uncertain and therefore difficult to anticipate (Essl *et al.* 2020). Quantitative models that incorporate these complexities are still lacking and, in any case, would be based on specific assumptions that

In a nutshell:

- A team of 35 experts from different countries and stakeholder groups developed a strategy for managing biological invasions in Europe in the coming decades
- The strategy considers a wide array of goals relating to policy, research, public awareness, and biosecurity
- Given the high degree of mutual dependence between these goals, management efforts should strive to address them jointly to better ensure success
- Participants assessed and refined the strategy under several future invasion scenarios to improve its overall feasibility
- Management of biological invasions in Europe requires a shift toward a more integrative approach across sectors and countries

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would likely limit the space of plausible and imaginable trajectories. In contrast, qualitative scenarios allow for a more open exploration of plausible futures (Lenzner *et al.* 2019), and consequently are instrumental in informing environmental policy and planning (Wiebe *et al.* 2018).

We explored qualitative scenarios about the future of biological invasions in all Europe (not restricted to continental Europe or the European Union) and developed a robust management strategy in the face of critical uncertainties using a participatory process. To do so, we (1) downscaled four global scenarios of biological invasions (Roura-Pascual *et al.* 2021) to the European level, (2) developed an overarching management strategy for biological invasions in Europe considering the challenges posed by each individual scenario, (3) examined the relationship between the different elements of the strategy, and (4) assessed its feasibility in the context of the downscaled scenarios. Due to COVID-19 travel restrictions and social distancing initiatives that discouraged or prevented in-person meetings, the process was conducted in two online workshops (1–2 Apr and 20 Sep–2 Oct 2020) with expert-based internal discussions (Appendix S1: Panel S1 and Figure S1). A total of 35 individuals representing 12 European countries and three distinct stakeholder groups—namely, public administration, nongovernmental organizations/interest groups, and academia (a full list of participants is provided in Appendix S1: Table S1)—participated in the process.

Future scenarios of biological invasions

To the best of our knowledge, qualitative scenarios of biological invasions have not yet been applied in a continental context or used to inform policy. Recently, Roura-Pascual *et al.* (2021) developed the first global scenarios for biological invasions that explored plausible future trajectories of biological invasions in the coming decades. These global scenarios—16 in all—were clustered into four main contrasting sets of futures that ranged from high to low levels of biological invasions, accounted for uncertainties in social–ecological developments considered to be critical for invasive species on a global scale, and were more focused on biodiversity assets than other global change scenarios (eg shared socioeconomic pathways; O'Neill *et al.* 2017). Of the 16 global scenarios, four were selected as being representative of the four main contrasting clusters based on consensus voting among workshop participants. Selected scenarios were reframed and downscaled to the European level, resulting in the following four European scenarios: (1) Lost (in) Europe (cluster A), (2) Big Tech Rules Europe (cluster B), (3) Green Local Governance (cluster C), and (4) Technological (Pseudo-) Panacea (cluster D) (Figure 1; Appendix S1: Figure S2); note: all clusters were derived from Roura-Pascual *et al.* (2021). The exact procedure of downscaling the global scenarios to the European level and the relationships between these scenarios is described in greater detail elsewhere (Appendix S1: Panel S1; Pérez-Granados *et al.* 2024). Here, we present a general overview of the four selected scenarios and outline how they were used to develop the management strategy for invasive species and to assess the strategy's future feasibility.

Management strategy for invasive species

Workshop participants first formulated a number of general visions (objectives) for the future management of invasive species in Europe. These visions were collected and presented to all 35 participants, each of whom cast votes for the visions they deemed as the four most important. The four visions that obtained the most votes were then individually assigned to breakout groups, each of which was responsible for developing a preliminary management strategy for achieving the assigned vision. The resulting preliminary management visions and strategies were combined into a single management vision and strategy ("beta version") composed of multiple goals and actions. The goals referred to specific management aspects identified as important by the workshop participants, and the actions described the steps required to reach each goal. Participants then identified the strengths and weaknesses of the overall management strategy ("stress test") and assessed which actions (and consequently goals) would likely be feasible, partially feasible, or unfeasible under each scenario. On the basis of this assessment, participants revised the actions assessed as partially feasible or unfeasible to improve feasibility across all scenarios, with revisions subsequently integrated into the management strategy (Appendix S1: Panel S1 and Figure S1).

The general vision agreed upon by the participants was: "By 2050, the harmful impacts of invasive species in Europe (EU member states and non-EU states) are substantially reduced compared to today". This vision is in concordance with the Kunming-Montreal Global Biodiversity Framework, which includes a target to reduce the introduction and establishment of invasive species and their impacts (see Target 6 in CBD [2022b]). Participants identified 19 goals as relevant for achieving this general vision, which were grouped into four categories: Policy (goals P1–6), Research (goals R1–4), Public Awareness (goals A1–3), and Biosecurity (goals B1–6) (Figure 2; Appendix S1: Panel S2), highlighting the multifaceted nature of the management of invasive species and the importance of considering elements complementary to direct management actions. Several of these goals have already been identified as relevant for managing biological invasions (Piria *et al.* 2017) and are included in a framework to standardize management terminology (Robertson *et al.* 2020). To guide the long-term management of biological invasions, we organized the goals into a new framework that considers future uncertainties.

Managing invasive species efficiently requires harmonizing policy and biosecurity efforts across European countries (Keller *et al.* 2011) as well as globally (Hulme 2021). The implementation of EU regulation 1143/2014 on invasive species represents major progress in this regard, as it has helped

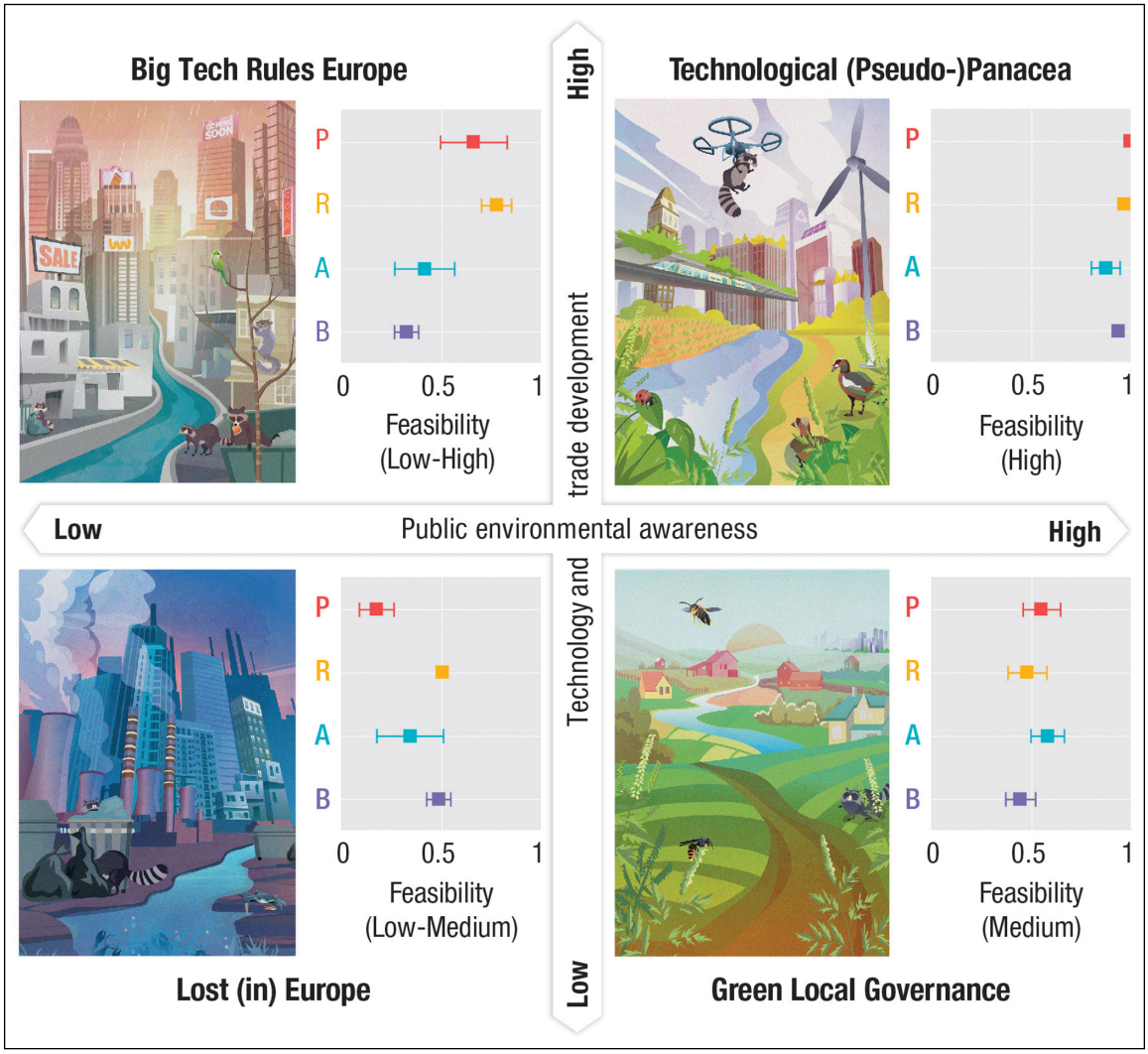

Figure 1. Illustrations of the four future scenarios for biological invasions in Europe, and associated charts depicting the feasibility of the management strategy under each scenario as assessed by the workshop participants. Means (colored squares) and standard errors (error bars) indicate the average feasibility of the goals included in the strategy (1 = feasible, 0.5 = partially feasible, 0 = unfeasible) as grouped into four categories: Policy (P), Research (R), Public Awareness (A), and Biosecurity (B) (Figure 2; Appendix S1: Panel S2). See Appendix S1: Table S2 for the feasibility of each individual goal under the different scenario assumptions. Scenario illustrations created by K Tsenova (Paidia Consulting Ltd).

EU member states to develop and implement management measures for invasive species included on the so-called Union list (a list of invasive species of Union concern), following a common framework that includes risk assessment, surveillance, and reporting. However, coordination between EU and non-EU countries remains lacking, and the effectiveness of management actions is influenced by limited funding and conflicting views among managers (eg whether removal of established invasive species is warranted; Blaalid *et al.* 2021), scientists (Shackleton *et al.* 2022), and the general public (eg regarding the killing of invasive animals; Novoa *et al.* 2017). Although an impressive amount of knowledge and technical information has accumulated through years of research and management practices (Scalera *et al.* 2017; Dana *et al.* 2019), practical knowledge on managing invasive species is still largely disconnected from academic knowledge (Bayliss *et al.* 2013; Muñoz-Mas *et al.* 2021). More research on how to facilitate responses to management needs and how to improve the availability and accessibility of data for biological invasions is needed (Gatto *et al.* 2013). To better align scientific research with management needs and resolve conflicting ethical views, it is crucial to improve communication between scientists and stakeholders, and to promote public engagement and awareness to facilitate knowledge transfer across Europe.

Strategy associations and key recommendations

In addition to developing the management strategy, we analyzed the relationships between the strategy's goals. We first characterized the essence of each goal and then reviewed all other goals to identify any associations between them. An association was loosely defined as any direct relationship between two goals, without necessarily implying causality (see Appendix S1: Panel S1 for details). Overall, we found high

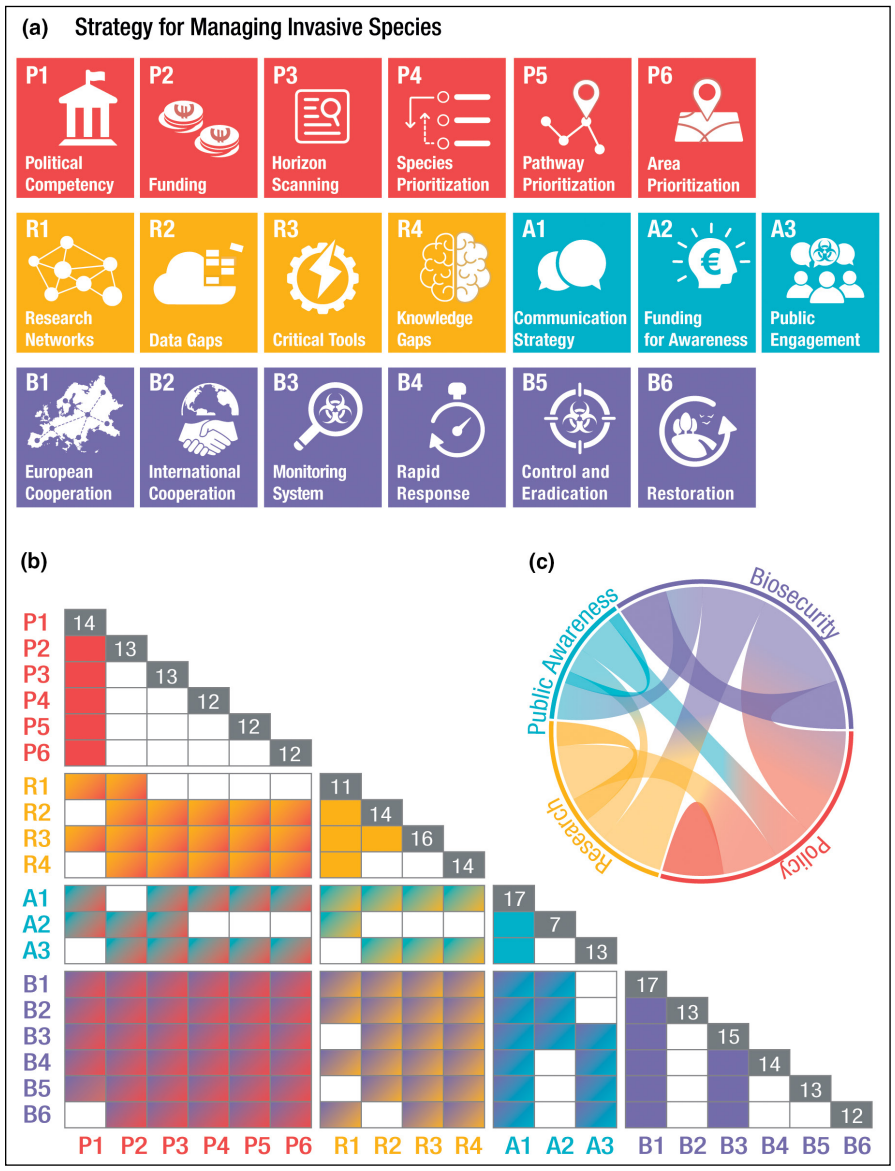

Figure 2. (a) Visual summary of the management strategy for invasive species in Europe, consisting of 19 goals grouped into four categories: Policy (P), Research (R), Public Awareness (A), and Biosecurity (B) (Appendix S1: Panel S2). (b and c) Visual representation of the associations between goals and categories of goals. In (b), colored cells signify an association between two goals, and diagonal numbers indicate the total number of associations each goal has with other goals. In (c), the arch's width that connects two parts of the circle denotes the number of associations between goals of two connected categories (or within the same category).

connectivity among the four categories of goals (Figure 2c) and among the 19 goals of the management strategy (Figure 2b), with each goal associated with 13 of the other 18 goals (72%) on average. This highlights the integrative nature of the strategy and the mutual dependency of its components to ensure its effectiveness. The goals with the highest numbers of associations were: European Cooperation (B1) and Communication Strategy (A1), followed by Critical Tools (R3) and Monitoring System (B3) (Figure 2b; for goal descriptions and designations, see also Appendix S1: Panel S2). These goals are key elements for the implementation of the overall management strategy, as reaching them is also conducive to the achievement of many associated goals. Therefore, they deserve particular attention. On the basis of these four "keystone" goals and further crosscutting aspects emerging from the management strategy, we identified four key recommendations for managing biological invasions in Europe. They represent general fundamental principles that lie at the core of the strategy and should guide its implementation.

Recommendation 1: European cooperation for a common and effective biosecurity regime

Establishing a dedicated European agency or an intergovernmental agreement furnished with a mandate and resources to regulate and oversee activities related to the management of invasive species in Europe will strengthen cooperation between states and stakeholders across Europe (see keystone goal B1; Appendix S1: Panel S2). It will also positively affect most other goals, improving the efficacy of monitoring and managing invasive species. Such an institution should liaise with European and global international organizations (eg Centre for Agriculture and Bioscience International [CABI], CBD, European Alien Species Information Network [EASIN], European and Mediterranean Plant Protection Organization [EPPO]) for guidance on invasive species policy, prioritization, best practice, and management harmonization between European countries (and including non-EU states). It should foster interactions and synergies across sectors, stakeholders, and biosecurity regimes; consider regional particularities (eg regarding differences in management priorities); and integrate local knowledge and cultures. Shared governance and participatory decision making shall strengthen the legitimacy of agreed-upon actions.

Recommendation 2: cross-sectoral communication and outreach strategy

Establishing a cross-sectoral communication strategy about invasive species (including a dedicated education curriculum for schools) and a centralized, multilingual communication platform at the European level (see keystone goal A1; Appendix S1: Panel S2) will help increase awareness of causes and impacts of invasive species and their management, as well as facilitate knowledge transfer and collaboration. Goals in all categories of the management strategy benefit from principles of good and transparent communication, leading to an increased understanding among stakeholders and the general public, which is required for sustained support of management actions.

Recommendation 3: data standardization and management tools

Routinely identifying and addressing critical gaps in tools for impact/risk assessment and management of invasive species (see keystone goal R3; Appendix S1: Panel S2) will improve proactive and reactive capacity to manage (new) invaders. This includes creating and/or improving standard protocols for assessing pathways, impacts, and vulnerability of priority areas; conceiving adaptive approaches to guide management decisions; and developing novel management techniques. These tools should be adopted at the country and European level (and if feasible at the global level as well). For example, the International Union for Conservation of Nature (IUCN) recently adopted the Environmental Impact Classification for Alien Taxa (EICAT) as a tool to collect standardized impact data (IUCN 2020). Several goals (eg R2 and R4; Appendix S1: Panel S2) also call for the establishment of a Europe-focused centralized open-data portal that facilitates efficient recording, storing, standardization, updating, peer-reviewing, and accessibility of all information related to invasive species and their management in Europe. EASIN may provide a useful foundation for this platform. Novel automated approaches are needed for managing and analyzing big datasets resulting from such data aggregation. Many aspects of this recommendation are echoed in the CBD COP15 Decision regarding invasive species (see Annex 5 in CBD [2022a]), which was recently adopted in connection with the Kunming-Montreal Global Biodiversity Framework (CBD 2022b).

Recommendation 4: monitoring, assessment, and management priorities

Establishing a comprehensive regime for monitoring and assessing invasive species at the European and country levels (see keystone goal B3; Appendix S1: Panel S2) will improve the capacity for early detection and rapid response. Sound and comprehensive knowledge of the past, current, and future circumstances of the introduction, establishment, and spread of invasive species, as well as their (actual and potential) impacts and success of past management attempts, is a prerequisite for effective management and for establishing management priorities at different levels (ie species, sites, and pathways). Policy regulations (eg the Union list of invasive species in Regulation 1143/2014) are useful for defining legally binding priorities (eg goals P4–P6; Appendix S1: Panel S2), but priorities should also be flexible and updatable based on, for instance, new data obtained by managers (eg goals B4–B6; Appendix S1: Panel S2), to facilitate rapid adaptation to changing conditions.

Strategy feasibility

The suggestions generated from the stress-testing process under the four different scenarios for biological invasions were incorporated into the goals and actions of the management strategy. In an online exercise after the workshops, participants revisited the feasibility assessment given during the stress test and repeated the assessment process for the revisited, final actions. For graphical purposes, we converted the assessments assigned to each action of the strategy into a numerical value (feasible action = 1; partially feasible action = 0.5; unfeasible action = 0) and averaged these values at the goal level (Appendix S1: Panel S1). To visualize divergences among scenarios, we displayed the means of the goals' averaged values at the category level (Figure 1).

The results indicated that some future scenarios are more challenging than others for the management of invasive species (Figure 1; Appendix S1: Figure S2). Scenarios with high levels of technological development, public environmental awareness, and effectiveness of policies on invasive species that encourage research and biosecurity (eg Technological [Pseudo-]Panacea) offer favorable conditions for implementing the management strategy across all goals (Appendix S1: Table S2), whereas disruptive scenarios, such as those conceiving an isolationist Europe (eg Lost [in] Europe), are more problematic for management strategy implementation. In particular, goals that require coordination across Europe, such as policy-related goals and the establishment of a European biosecurity regime (B1, European Cooperation) and a Communication Strategy (A1), will be extremely difficult to achieve under this scenario (Appendix S1: Table S2).

Between these two extremes, there are scenarios with an intermediate feasibility of the management goals (and categories of goals). Some of these scenarios include prominent levels of economic power and technology that stimulate research and policy development on invasive species but have poor public awareness and biosecurity measures (eg Big Tech Rules Europe). The feasibility of other scenarios is more balanced across management goals and their categories, with technological deficiencies being offset (at least to some extent) by greater public awareness (eg Green Local Governance). For these intermediate scenarios, most goals within the biosecurity category (goals B3–6) had a medium level of feasibility, suggesting that our vision would only be partially achievable (Appendix S1: Table S2).

Conclusions

Effectively reducing the impacts of biological invasions over the long term will require consideration of the range of social–ecological developments that influence them. Our strategy for managing invasive species in Europe consists of 19 closely interconnected goals relating to policy, research, public awareness, and biosecurity. Given the uncertainties of the future, it is crucial to assess the feasibility of these goals and their associated actions under different future scenarios covering a broad range of social, economic, and ecological trajectories. Our research reveals how the feasibility of specific management goals varies under different scenarios. For example, scenarios

with low technological development, weak public environmental awareness, and ineffective policies will reduce the feasibility of the management strategy, thereby making it less likely that the impacts of invasive species will be substantially reduced by 2050.

Furthermore, our results highlight four interrelated key recommendations that any strategy aimed to prevent and mitigate the impacts of invasive species in Europe should prioritize. These include (1) promoting cooperation between countries and stakeholders at the European level, (2) fostering communication and outreach across sectors, (3) standardizing data and developing tools in support of management, and (4) monitoring invasive species efficiently and prioritizing management accordingly. Although none of these recommendations alone will suffice, they represent key elements that can structure a long-term strategy for managing biological invasions at the European level. In short, it is time to shift the focus of biological invasion management in Europe and elsewhere toward a more integrated perspective that takes into account different sectors and countries, and explicitly accounts for plausible future scenarios.

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Data Availability Statement

Data are already published and publicly available, with those items properly cited in this article.

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Supporting Information

Additional material can be found online at http://onlinelibrary.wiley.com/doi/10.1002/fee.2725/suppinfo

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