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Overview Article

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Seeds of change: Global megatrends will shape the future trajectory of plant invasions

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Abstract

Global megatrends are large–scale, long–term shifts that shape environmental and societal change and provide a novel lens for anticipating future biological invasions. Using expert elicitation, we assessed how 15 megatrends may influence the arrival, establishment, spread, and impact of alien plant invasions by 2050. Most megatrends were expected to increase invasion risks, particularly by accelerating species arrival and spread. Megatrends clustered into four gigatrends: *Anthropocene*, *Digital*, *Societal*, and *Technology*. In the *Anthropocene,* invasion threats will escalate through increased global trade and climate–driven range shifts. *Digital* driven e-commerce and misinformation further elevate risks, whereas an aging society reduces the *Societal* capacity for managing invasive plants. Despite advances in *Technology* potentially abating plant invasions through improved detection and control tools, significant adoption barriers remain. Invasion scientists must urgently help policymakers recognize that, although future megatrends will amplify plant invasions, decisive engagement can still steer trajectories toward mitigating this growing global threat.

Keywords **climate change, forecasting, globalization, governance, incasting**

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In response to the growing threat of biological invasions worldwide (Roy et al. 2023, CBD 2024), many governments have set national strategies that include forecasting the magnitude of future risk arising from the arrival, establishment, spread, and impact of alien species (DENR-BMB 2020, ICIPE 2020, U.S. Department of the Interior 2021, DAFF 2022, MAyDS 2022, HM Government 2023). Forecasts involving extrapolations from current data have signaled increases in the numbers (Early et al. 2016, Seebens et al. 2021) and economic impacts (Henry et al. 2023) of alien species in many parts of the world by 2050. However, since these extrapolations rarely consider temporal changes in the drivers of biological invasions, the patterns seen today are unlikely to be representative of future dynamics (Hulme et al. 2023b). A more robust procedure is to apply quantitative approaches that incorporate projected trajectories of the drivers of biological invasions (e.g., climate change, land-use change etc.). To date, these approaches have largely focused on trajectories of climate change and point to both increased and decreased risks of biological invasions depending on the taxon and region concerned (Bellard et al. 2013, Allen and Bradley 2016, Bezeng et al. 2017, Yan et al. 2017).

More rarely, aspects of future economic trade have been incorporated into projections of biological invasions and appear to be more influential than climate change (Seebens et al. 2015, Liu et al. 2019, Sardain et al. 2019). Nevertheless, the future spatiotemporal dynamics of many drivers of biological invasions are uncertain and poorly quantified (Joppa et al. 2016), such that projections of biological invasions rely on qualitative assessments derived from expert elicitation (Hulme et al. 2023b, Essl et al. 2020, Lenzner et al. 2020). However, qualitative assessments of biological invasions are challenged by limited understanding of the additive or multiplicative interactions among different drivers (Hulme 2022, Isbell et al. 2023). There is therefore a growing awareness that drivers should not be examined in isolation but rather as complexes (Bowler et al. 2020, Langenbacher et al. 2026). There have been few attempts to forecast biological invasions in relation to multiple interacting drivers, and this remains a significant gap in national strategies to manage future risks from invasive alien species. A potentially innovative way to address this gap is to explore the role of megatrends in biological invasions.

A global trend can be defined as an ongoing, discernible, and observable phenomenon within a particular sector, industry, or region that has the potential to have a wider impact (Jackson 2003). Megatrends are clusters of interdependent global trends observed today that together have the potential to cause significant shifts in environmental, economic, and social conditions (Kuhn and Margellos 2022). Megatrends typically develop over a period of years or decades and occur at the intersection of multiple political, environmental, social, technological, legal, and/or economic trends (Naughtin et al. 2024). The defining features of megatrends include the convergence of the underlying global trends, the international scale of their impact, their transformative effect on entire societies, and their focus on a future time horizon of a decade or more (Pęciak 2016). Megatrends represent an important strategic foresight tool used by governments and multilateral organizations worldwide to assess future risks and opportunities to society and the economy (UNDESA 2020a, EEA 2015, USNIC 2021, Barry 2024, UK Ministry of Defence 2024, DFF 2025). It therefore makes sense to link these tools to national and international strategies addressing biological invasions. However, given the multitude of megatrend reports and articles published in recent years, where should the focus be?

Despite the burgeoning literature describing megatrends, most recent megatrends have been elaborated using half-a-dozen recurring issues: rapid technological development, environmental change, demographic change, globalization, urbanization, and global economic shifts (Artuso and Guijt 2020, Kuhn and Margellos 2022, Naughtin et al. 2024). Differences in emphasis depend on the target audience (e.g., government vs. industry), geographic region (e.g., global vs. national), and/or sector (e.g., health vs. defence). For the purposes of examining the potential future trajectories of biological invasions, the most instructive megatrends will be those that could deliver a negative or a positive outcome, are relevant to multiple sectors, and encompass issues of global importance that are relevant to both the Global North and South.

Although invasion scientists have previously developed future scenarios for biological invasions that cluster global trends into distinct groupings (Roura-Pascual et al. 2021), the choice and character of megatrends can be strongly shaped by the disciplinary and professional perspectives of those who develop them. To avoid any such bias toward biological invasions or environmental issues, we examined 15 global megatrends developed by the Copenhagen Institute of Future Studies (CIFS) to explore the future of biological invasions (box 1). The megatrends encompass a wide range of economic, environmental, social, and technological global trends that are forecast to have a marked impact on the world by 2050 (table 1). For each megatrend, we applied a novel incasting approach to address the possible future trajectories of alien plant invasions at a global scale (box 2, the full methods appear in the supplemental material online). Incasting is a technique designed to elaborate on megatrends by exploring the trajectory of events arising from broad, pre-defined future developments (Bishop et al. 2007), but to date has never been used to explore biological invasions. Compared to other futures thinking approaches, incasting encourages researchers to move beyond general descriptions and envision the concrete details of how a particular future might unfold. In this way, it is possible to uncover hidden opportunities, potential challenges, and unexpected consequences that might not be currently considered in forecasts of biological invasions (Hulme 2025). We sought answers to the following four key questions:

1. Which megatrends are most likely to influence invasion patterns and impacts?
2. Is the arrival, establishment, spread, or impact of alien species more responsive to some megatrends than to others?
3. What key global trends underlying the megatrends are linked to increased or decreased risk of invasions?
4. Do megatrends cluster together into distinct gigatrends (i.e., larger, longer-term forces shaping multiple domains) that better capture the suite of global trends most likely to influence the future risk of invasions?

Rather than attempt to explore implications for all forms of biological invasions, we focus on the problem of invasive alien plants in terrestrial and freshwater ecosystems. The processes leading to their arrival, establishment, spread, and impact of alien plants are among the best documented biological invasions worldwide (Pyšek et al. 2017 , Weber 2017, Clements et al. 2022, Gioria et al. 2023). A focus on alien plant invasions thus facilitates a better-defined synthesis. Nevertheless, many of the issues addressed by examining plant invasions will also be relevant to other taxonomic groups.

Box 1. Identifying the most important global megatrends shaping the world by 2050.

The Copenhagen Institute for Future Studies (CIFS) is a politically and commercially independent non-profit think tank dedicated to developing global foresight across the public, private, academic, and civic sectors since 1969 (www.cifs.dk). Although a single source of megatrends cannot capture all possible futures, the CIFS megatrends have wider coverage than other recently published megatrend reports but also show significant overlap (Krys et al. 2023, PMI 2024, PwC 2024). Three separate steps were used by senior researchers at CIFS to generate megatrends that each have a clear trajectory toward 2050 (Martin Kruse, personal communication). First, interviews with experts were used to identify several hundred global trends observed over recent time. Second, a trend hierarchy was derived that ranked global trends in terms of how broad reaching and long-term their effects were likely to be in the future. Finally, approximately one hundred of the top ranked global trends were then subject to a lengthy iterative process of clustering, discussion, and further regrouping to derive 15 distinct megatrends. Details of the 15 megatrends (and their abbreviations used in this article) are summarized in table 1. Each megatrend was presented as a ~500-word narrative and associated with three to eight key global trends that all point in the same general (though not necessarily parallel) direction to provide an additional level of detail (CIFS 2023).

Table 1 Brief summaries of the 15 megatrends examined to interpret the potential future outlook for plant invasions. Descriptions are drawn from several sources (Artuso and Guijt 2020, USNIC 2021, CIFS 2023, Krys et al. 2023). The abbreviations are those used throughout the manuscript.

Megatrend	Abbreviation	Single sentence description
An Aging World	Aging	Aging societies slow down economic growth in developed economies, put pressure on welfare systems and require increased participation in the labor force from the elderly as well as reliance on immigration to sustain the workforce
AI & Automation	Automated	Automation in the workforce challenges governments and businesses to reinvent job markets and welfare systems with negative impacts particularly on young people in emerging economies and rural regions in developed economies
Biotech Revolution	Biotech	Biotech and bioengineering enable genetic manipulation to create synthetic life, giving rise to significant opportunities in a range of areas from health to food security but increase biosafety risks and opportunities for malicious use
Engineering Advances	Engineering	New materials and mechanical engineering designs expand the use of robotics and automated devices (e.g., drones), improve the efficiency of transport and energy systems and help combat climate change and environmental damage
Environmental Change & Sustainability	Environment	Climate-related disasters, droughts and chronic crop failures cause impoverishment and migration forcing states to make hard choices and trade-offs that may only be partially offset by a drive toward environmental sustainability
Globalization	Globalized	Greater worldwide connectivity (digital and geographic) results in changing working, consumption, and trade patterns but the increased reach of multinationals means regional issues quickly become global in scope
Economic Growth	Growth	Global economic power shifts to emerging countries in Asia, but future economic development will increasingly include climate change considerations requiring massive public and private investment to achieve net zero emissions
Focus on Health	Health	A growing understanding of how genetics and lifestyle influence health, coupled with new technologies enables a more preventive rather than reactive approach and a greater personalization of health
Individualization and Empowerment	Individualized	Rising human empowerment, driven by increasing access to information, gives rise to a pluralization of ways of living and working boosting the potential for public mobilization
Greater Interconnectedness	Interconnected	Digital technology enables governments to prepare and respond to crises, leverage data to inform decision-making, and communicate effectively to large audiences but also allows the spread of fake news and mass manipulation
Network Economy	Networked	The ongoing digitalization of society gives rise to new peer-to-peer processes and the creation of value in decentralized networks that rely on flat hierarchies and collaboration, and which operate both on local and global scales
Population Growth	Population	The projected increase in the global population acts as a positive stimulus for the global economy, with more innovators, consumers, and researchers but also increases pressure on biodiversity, food security, and natural resources
Service Economy	Serviced	The service economy gives rise to the platform business model where products and services are no longer separate but part of a service-product continuum, where "solutions" that combine the two are on offer to businesses and consumers
Urbanization	Urbanised	Increasing urbanization and the development of new megacities increases economic growth but also result in increased inequality and exclusion putting pressure on local governments to provide better infrastructure and services
Concentration of Wealth	Wealth	Greater inequality in wealth discourages skill accumulation and social mobility whereas super wealthy individuals will seek to use the power they hold because of their wealth to lobby governments on issues they consider important

Although these megatrends include a few topics that have been previously explored in the context of biological invasions, for example, Globalization (Hulme 2021b, Bonnamour et al. 2021), Urbanization (Heringer et al. 2022, Richardson et al. 2025), Environmental Change (Hulme 2017, Robinson et al. 2020), Economic Growth (Ding et al. 2008, Essl et al. 2019), most megatrends have never been considered from this point of view. Integrating potential influences of these underexplored megatrends on biological invasions requires invasion scientists to think "outside of the box" and into areas

with which they have less familiarity, and it is in these areas that innovative ideas and insights will most likely emerge. Although we are using megatrends identified by a single source, all of the 15 megatrends have also been recognized by one or more organizations around the world (UNDESA 2020a, Artuso and Guijt 2020, USNIC 2021, Krys et al. 2023, PMI 2024, DFF 2025). Because most megatrend reports address similar issues but in different formats, the choice of report matters less than the process of examining their relevance to biological invasions.

Despite different sources, recent depictions of global megatrends appear to be similar and highlight risks from environmental change, technological disruption, demographic shifts, and social instability as likely to shape the world over the next decades. This provides some assurance that the 15 megatrends are well recognized issues that many organizations consider will shape the world in forthcoming decades. Furthermore, the issue of biological invasions was never considered when developing the 15 CIFS megatrends ensuring that there is independence between the choice of megatrends and their likely role in the arrival, establishment, spread, and impact of invasive alien species. This should ensure a more interdisciplinary perspective of the future outlook for biological invasions. Some megatrends will drive major environmental, economic, and social changes sooner than others, but all are expected to have an impact by 2050 (CIFS 2023). We therefore set 2050 as our target date and assessed future change against a 2025 baseline representing current conditions.

Box 2. Applying an incasting approach to futures thinking in biological invasions.

Incasting involves elaborating a megatrend by describing what one or more possible futures might look like from a particular perspective (Hulme 2025). It is an exploratory method that aims to make those futures concrete and internally coherent generating questions that are relevant to decision-making (Bishop et al. 2007). Because incasting is qualitative, reliability is assessed in terms of the credibility, coherence, and usefulness of the interpretations rather than probabilistic outputs. This is often judged by the consistency and rigor of the participants' thinking process as judged by the consensus. The usefulness of incasting depends on the imagination, biases, and expertise of participants. Thus, participants must represent a diversity of viewpoints without any vested interests in outcomes.

The project brought together 14 plant-invasion researchers to consider how global megatrends may shape the future of biological invasions. Because anticipating global invasion trajectories requires multiple viewpoints, the team was intentionally diverse ensuring gender-balance, a wide span of career stages, and including strong representation from the Global South as well as both island and continental regions. All participants met for a two-day workshop at Lincoln University, New Zealand, in September 2025, after completing extensive preparation tasks.

Before the workshop, each participant was assigned one of the 15 megatrends and asked to produce a ~250-word, referenced summary describing its potential implications for plant invasions. These summaries were compiled and shared two weeks prior to the workshop. Participants evaluated how each megatrend might influence four stages of the invasion continuum:

1. Arrival—likelihood that alien species are transported to a new region.
2. Establishment—likelihood of alien species forming self-sustaining populations.
3. Spread—rate of natural or human-mediated dispersal within the new region.
4. Impact—economic or environmental consequences.

Influence was scored relative to the present using a five-point scale ranging from major reduction (–2) to major increase (+2) in likelihood, rate, or cost, with a value of 0 indicating no change in the status quo. Each participant scored all four stages for all 15 megatrends, yielding 60 scores per person.

Because megatrends represent broad, multifaceted drivers, participants also examined the key global trends underlying each megatrend. The CIFS report lists 87 such key global trends across the 15 megatrends. Participants evaluated these in two ways:

1. Within-megatrend ranking: identifying the key global trend most influential for invasions.
2. Across-megatrend ranking: selecting the top 10 most important key global trends overall.

This enabled researchers to pinpoint the mechanisms within the broad megatrends most responsible for shaping biological invasions. The importance of each megatrend was then estimated by averaging scores across its key global trends, allowing comparisons despite unequal numbers of key global trends.

Recognizing that megatrends do not operate independently, participants examined pairwise interactions among all 15 megatrends, identifying which pairs were likely synergistic. They could select any number of pairs. These associations were analyzed using a network approach, revealing clusters of related megatrends. These clusters referred to as "gigatrends" represent higher-level groupings of drivers that may collectively shape invasion futures.

During the workshop, participant scores were aggregated and presented for discussion. Each participant reviewed their assigned megatrend considering group scoring patterns, focusing on influential key global trends, sensitive invasion stages, outlier scores, and emerging insights. After discussion, participants could revise their scores, which then formed the final dataset. On the second day, participants identified up to three key global trends per megatrend that could increase plant invasions, and up to three that could decrease them. Working within gigatrend clusters, groups synthesized these insights to develop an integrated understanding of how combinations of megatrends may shape the future of global plant invasions. Further details of the methodology appear in the supplemental material online.

Most global megatrends are expected to increase plant invasions by 2050

Although a small number of the global megatrends might potentially lead to a reduction (Automated, Biotech) or no change (Serviced, Health) in future plant invasions, most megatrends will increase the threat (figure 1). Three megatrends (Globalized, Population, and Environment) stand out as having the greatest role in increasing the threat of future plant invasions. Many of the most important key global trends were associated with these three megatrends (table 2). The top key global trends for the Globalized megatrend included the growth of developing economies, growing migration, improved global infrastructure, and the erosion of national boundaries, all of which will increase the risk of plant invasions. Similarly, the growing human population and especially the growing urban population were key global trends underpinning the importance of the Population megatrend in plant invasions. Several key global trends for the Environment megatrend will accelerate plant invasions, particularly shifting climate zones, extreme weather, and biodiversity decline. In contrast, none of the key global trends underlying the Aging, Engineering, Health, or Serviced megatrends were thought to be highly important for future plant invasions (see table S1 in supplementary materials).

The invasion stages expected to contribute most to this increased threat of plant invasions are a high likelihood of species arrival and spread, with impact playing a lesser role (figure 1). These expectations were similar across most megatrends apart from Aging, Health, Environment, Population, and Wealth where the strongest effects were found for impact. Increased risk of species arrival will stem from deliberate or accidental global movement of plants due to improved global transportation infrastructure, a growing online marketplace for everything, and growing migration. In addition to these key global trends, species spread will also be helped by shifting climate zones, more extreme weather, and growing urban and inter-urban infrastructure. Impacts of plant invasions will be exacerbated by declining biodiversity and decreasing wealth at the disposal of governments to manage the threat.

But some key global trends provide hope that the future may provide solutions to counter the threat of plant invasions. Increased environmental consciousness combined with the growth of knowledge regarding the threat of plant invasions might motivate people to prevent invasions. This awareness could be supported by big data analysis to forecast and manage such threats possibly combined with novel control tools arising from genetic technologies. Nevertheless, the most important megatrends tended to be those that would result in a greater threat of plant invasions (figure 2). There were, however, two exceptions to this tendency; the Automated and Biotech megatrends were expected to potentially reduce future plant invasions but were deemed to be quite important for this very reason.

Identifying the global gigatrends arising from interacting megatrends

Although the boundaries between megatrends are rarely clear-cut (CIFS 2023) attempts to map how megatrends might be interconnected are rare (Önnered et al. 2026). Closely related key global trends are often associated with more than one megatrend (table 2). For example, improved infrastructure is a common theme in the following megatrends: Interconnected (improved global transportation infrastructure), Urbanized (growing urban and inter-urban infrastructure), and Globalized (improved global infrastructure). Network analysis highlighted the strong interdependence of all 15 megatrends (figure 3) and identified four overarching gigatrends we have termed: Anthropocene, Digital, Technology, and Societal. These four gigatrends span multiple megatrends and are expected to have multidecadal impacts at a planetary scale leading to fundamental shifts that will shape the trajectory of human society.

The Anthropocene gigatrend

The Anthropocene gigatrend brings together five of the megatrends that are most likely to result in increasing biological invasions (table 2): Environment, Globalized, Growth, Population, and Urbanized. All five megatrends encompass the major drivers of biological invasion worldwide (Hulme et al. 2023b). However, these megatrends are often discussed in isolation when they should really be seen as an ensemble. For example, the projected increase in the human population worldwide, especially in the Global South, will accelerate urbanization, expand the labor force, and drive economic growth and market globalization, but also cause environmental degradation through land-use change, resource extraction, and pollution (Balvanera et al. 2019, Jayadevan et al. 2025). Although climate change and sustainability are often treated separately from economic growth and globalization, these megatrends are likely to interact and jointly influence biological invasions.

The Anthropocene gigatrend appears to be particularly associated with a higher likelihood of alien species arriving in a region, reflecting the importance of globalization that facilitates social and economic integration driven by cross-border flows in goods and people (figure 4). But although globalization may increase species arrival, greater disturbance due to accelerated rates of urbanization and population growth will provide multiple new opportunities for alien plant establishment (Pauleit et al. 2021). Warmer temperatures and lower rainfall may help alien plants spread by making regions more suitable for frost-intolerant and drought-adapted species (Turbelin and Catford 2021), and also exacerbate their impacts, especially in terms of fire risks (Kelly et al. 2023).

The more positive aspects of the Anthropocene gigatrend, for instance, the increase in environmental consciousness (WWF 2021) or the growth in non-monetary assets such as private conservation land (Lewis et al. 2023) are unlikely to provide much of a brake on biological invasions. This is because in the future, there is an expectation that the national and international governance of environmental issues will likely be less effective. Globalization is increasingly eroding national boundaries as multinationals become more powerful than governments (Kapeller et al. 2024). Even within nations, the growing power of megacities challenges the balance of power between the state and cities (Pejic and Acuto 2022). Rivalrous multi-polarity, where major powers and blocs compete more intensely and cooperate less on the global stage is progressively weakening the influence of multinational institutions responsible for environmental governance (Kim and Bridgewater 2025). Deteriorating national and global governance of the environment will exacerbate problems associated with biological invasions through a lessened emphasis on biosecurity and quarantine at international borders, limited legislative and regulatory instruments to prevent the movement of alien species within a coun-

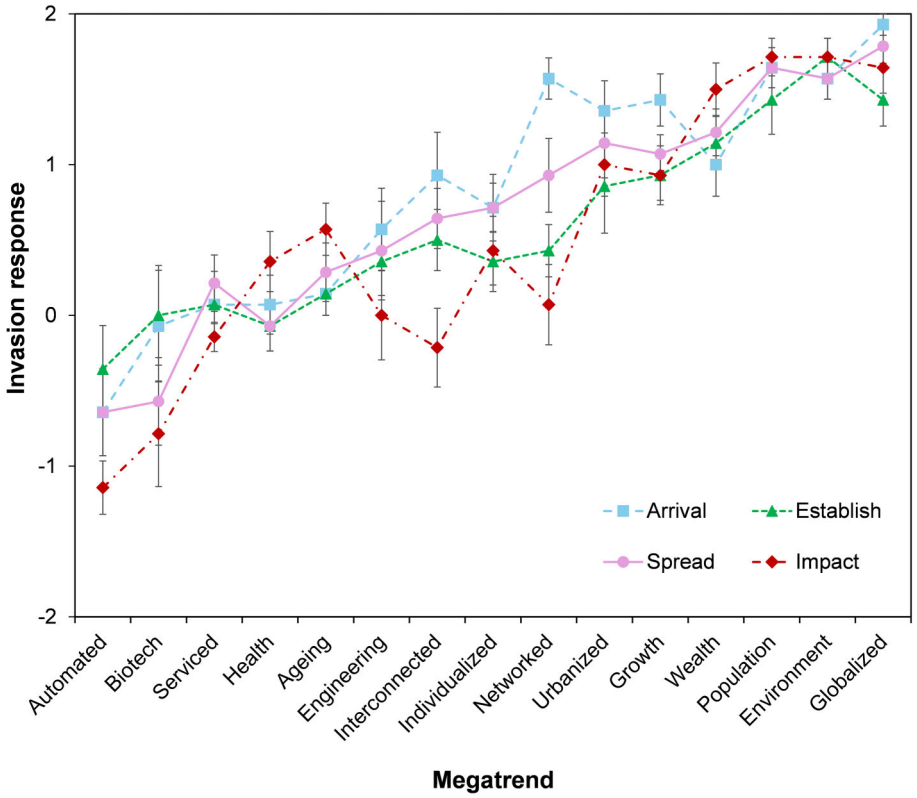

Figure 1 Expected effect of 15 megatrends on the future global threat of alien plant species in relation to the arrival, establishment, spread, and impact of alien plants. Data are the mean (and standard error) of participant scores that ranged from 2 (major increase) to −2 (major reduction) in the likelihood, rate, or cost of invasion. The graph is ordered by the mean invasion response over the four stages. A repeated measures ANOVA revealed significant variation in participant scores that was explained by the main effects of megatrend ($F_{(14, 192)} = 23.13$, $p < .001$), stage of invasion ($F_{(3, 39)} = 8.52$, $p < .001$), and an interaction between the two ($F_{(42, 546)} = 3.29$, $p < .001$). The differences among the megatrends had a large effect size ($\omega^2 = 0.55$) compared to the more modest effect sizes of either invasion stage ($\omega^2 = 0.10$) or the two-way interaction ($\omega^2 = 0.11$).

Table 2 The top 20 key global trends ranked in order of decreasing perceived importance based on the frequency with which they were selected among the top ten most important by workshop participants.

Gigatrend	Megatrend	Key Global Trend
Anthropocene	Environment	Shifting climate zones
Anthropocene	Globalized	Growth of developing countries
Anthropocene	Population	Growing global population
Anthropocene	Environment	More extreme weather
Anthropocene	Growth	Growing global economy
Digital	Interconnected	Improved global transportation infrastructure
Digital	Networked	Growing online marketplaces for everything
Anthropocene	Globalized	Growing migration
Technology	Biotech	Genetic technology
Anthropocene	Environment	Declining biodiversity
Digital	Individualized	Social media
Anthropocene	Urbanized	Growing urban and inter-urban infrastructure
Anthropocene	Globalized	Erosion of national boundaries
Anthropocene	Population	Growing urban population
Anthropocene	Environment	Growing environmental consciousness
Technology	Biotech	Synthetic biology
Anthropocene	Globalized	Improved global infrastructure
Technology	Automated	Big data analysis
Technology	Automated	Growth of knowledge
Societal	Wealth	Decreasing wealth at the disposal of governments

Although 87 key global trends were available for scoring the top 20 accounted for the majority (83%) of participant scores with most (57%) key global trends never being scored as important (table S1). Information is presented on the specific key global trend and both the overarching megatrend and gigatrend to which it belongs.

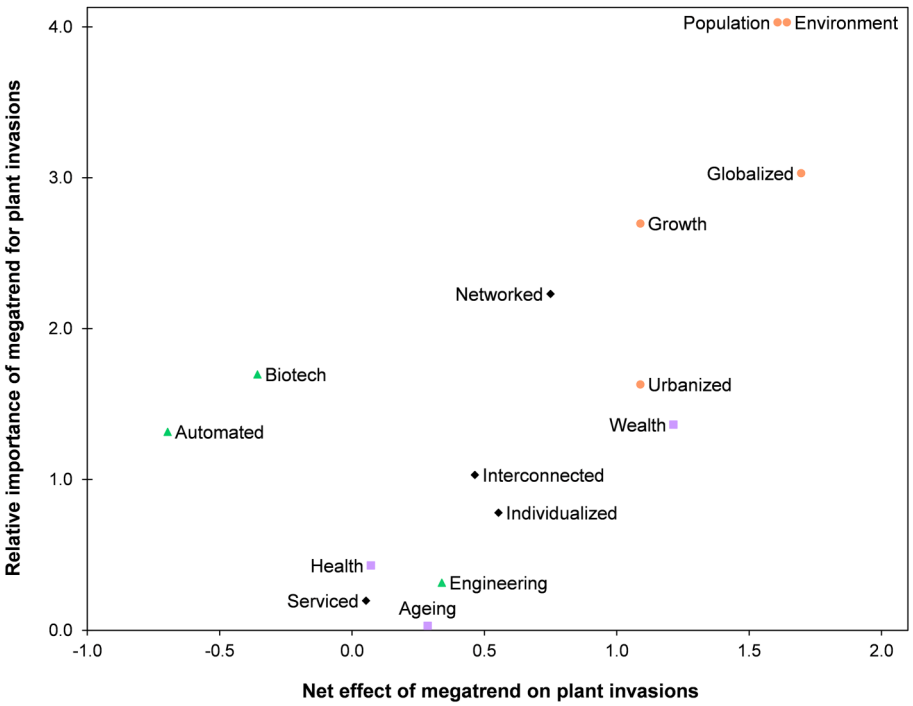

Figure 2 Positive relationship between the mean expected effect (positive or negative) of 15 megatrends on future plant invasions and their perceived importance in shaping future plant invasions. A positive net effect means the megatrends are expected to exacerbate plant invasions whereas a negative net effect indicates that they will reduce plant invasions. In general, megatrends perceived as more likely to increase plant invasions were generally rated by participants as more important (Pearson $r = 0.72$, $p = .003$). Megatrend symbols reflect their associated gigatrend: Anthropocene (circle), Digital (diamond), Societal (square), and Technology (triangle).

try and greater difficulties in coordinating management once an alien species has become widely established in a new region.

The Digital gigatrend

The Digital gigatrend is closely aligned to economic growth and globalization through its incorporation of the Individualized, Interconnected, Networked, and Serviced megatrends. The dominant aspect of this gigatrend is the growth and extended reach of digital networks into every aspect of society where information, connectivity, and collaboration are key drivers of economic activity and innovation. The increased economic activity facilitated by digital platforms that connect multiple parties (platform economy) will result in decentralised governance which may complicate the enforcement of any biosecurity regulations (Girard 2024). Regulatory gaps in digital marketplaces, such as the online trade in live plants and seeds, can allow high-risk species to slip through unnoticed. Digital platforms streamline just-in-time delivery, increasing the volume and speed of goods crossing borders (Gomez-Alvarez and Morales-Sánchez 2023) and heightening the risk of unintentional species introductions through packaging, shipping containers, and supply chains.

The Digital megatrend will increase the risk of plant invasions primarily by streamlining international and national e-commerce that will influence arrival and spread, respectively (figure 4). Nevertheless, the digitalization of society has the potential to deliver real-time surveillance of alien species by connecting digital sensors, drones, and satellite imagery, as well as data from citizen science platforms. This would require the establishment of formal agreements regarding the sharing of both public and commercial data and tools to safeguard data security and privacy (di Vimercati et al. 2013). A more likely outcome is that peer-to-peer networks empower communities to share information useful to the management of alien species and mobilize local action to prevent invasions. Such decentralization may allow communities to adapt management to local environmental and social conditions and be more effective than a one-size-fits-all national program. Although the internet and mobile communication technology are universal in the Global North, the mobile broadband usage rate is only 29% in the least developed countries, and access to fixed broadband is only 1% (Di et al. 2025). Thus, expectations arising from the Digital gigatrend must be mindful of this digital divide. Technological solutions may help resolve the digital divide, especially the launch of mega satellite constellations in low earth orbit that can deliver broadband Internet services in underserved regions without the time and investment required for terrestrial infrastructure (Akcali Gur and Kulesza 2024).

The Technology gigatrend

Technological solutions (e.g., drones, environmental DNA, gene drives) have often been proposed as the best opportunity to stem the tide of biological invasions (Hulme et al. 2023a, Ricciardi et al. 2017, Dehnen-Schmutz et al. 2018, Roura-Pascual et al. 2021). Thus, the Technology gigatrend is expected to broadly reduce the likelihood of plant invasions in the future (figure 4). The Automated, Biotech and Engineering megatrends that form the Technology gigatrend are closely interrelated and linked to the Digital gigatrend. For plant invasions, it appears the benefits of these technological developments will be obtained most immediately through limiting the spread and

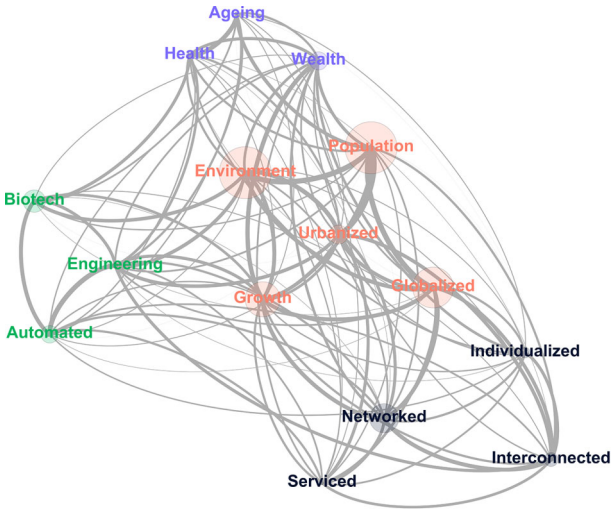

Figure 3 Network plot of the associations among 15 megatrends where the size of nodes reflects the perceived importance of the megatrend and the width of the links is determined by the frequency with which each bilateral association was scored by participants. A fast and efficient force-directed layout algorithm, ForceAtlas2, as implemented in Gephi version 0.9 (Bastian et al. 2009) was used to visualize the network in order to reveal structural clusters and relationships among megatrends (Jacomy et al. 2014). The Louvain algorithm was implemented to detect modularity in the network and assign megatrends to clusters in which the constituent megatrends are more similar to each other than to megatrends in other clusters (Blondel et al. 2008). The megatrend network was fully connected (graph density 0.98), forming a giant component in which there were associations between all pairs of megatrends. Indeed, the average degree was 13.6, close to the maximum of 14, confirming most megatrends were associated with every other megatrend. When data were filtered to only include links that had been scored by at least five participants (edge weight ≥ 5), four distinct modules could be discerned (modularity 0.15). The analysis highlights four distinct gigatrends: the Anthropocene gigatrend (comprising the Environment, Globalized, Growth, Population, and Urbanized megatrends), the Digital gigatrend (Individualized, Interconnected, Networked, and Serviced), the Technology gigatrend (Automated, Biotech, and Engineering), and the Societal gigatrend (Aging, Health, and Wealth).

improving the management of alien plant species so as to reduce impact. Generative AI could be used to optimize management decisions by integrating environmental data, expert opinion, and stakeholder surveys to model different management strategies and prioritize outcomes based on the social acceptability of each strategy as well as to forecast economic and environmental cost-benefits.

The integration of AI with future engineering advances in sensor technology, advanced autonomy, and high-speed connectivity (Butt et al. 2022) promises the cost-effective application of autonomous ground-based cameras, unmanned aerial, terrestrial, or aquatic vehicles (drones) and satellites to rapidly detect and map plant invasions across large spatial scales and in inaccessible regions (Singh et al. 2024, Fenollosa and Salguero-Gómez 2025). Surveillance will be further improved through the development of sensors capable of detecting and identifying environmental DNA and RNA (Hulme et al. 2023a). Engineering advances will also be key to extending the use of autonomous robots in precision weed management beyond agricultural environments to address invasive alien plants (Zhang et al. 2022). Similarly, advances in both gene drive and gene silencing technologies have been proposed as more targeted and environmentally sustainable control options for invasive alien plants (Kumaran et al. 2020). Taken together, these developments herald a future where AI-informed autonomous devices detect, map and then control invasive alien plants, thereby improving the cost effectiveness of management across large areas. But is this realistic?

Although there has clearly been progress in the application of robotics and drones to precision weed management in the relatively simple ecosystems of agricultural crops (Vijayakumar et al. 2025), caution should be applied when extrapolating this success to the management of alien plants in more complex landscapes. Digital sensors mounted on drones have been used to map alien plant species for over a decade. However, this technology remains a minor component of the management toolkit; it is currently restricted to applications at small spatial scales and classification accuracy remains limited by radiometric anomalies due to atmospheric impedance, sensor calibration errors and environmental noise (Singh et al. 2024). Although it might be expected that in the future longer battery life and improved sensor and software design might overcome these limitations, a more significant constraint for large-scale mapping is privacy. Privacy regulations that have requirements for data minimization, purpose limitation, and explicit consent pose unique challenges for drone-based data collection and in some jurisdictions piloting a drone on or over private property is considered trespassing (Cordill et al. 2025). The high initial and operation costs, requirement for skilled operators and strong regulatory constraints suggest that the Global North will be the primary beneficiary of these technological solutions. Many countries in the Global South have shown slower adoption of robotics, drones, and sensors in weed management (Vijayakumar et al. 2025). Furthermore, genomic data, genetic engineering, and gene editing tools are increasingly being used to manipulate stress resistance, plasticity, and adaptation in ornamental plants (Partap et al. 2023) potentially resulting in commercially available plants being inadvertently selected for traits that increase invasiveness.

The Societal gigatrend

The growth in new technology fuels innovation but has led to increasing concentration of wealth, particularly among tech billionaires. Since 2015, the number of billionaires has risen by more than half and their combined wealth has more than doubled to US$14 trillion, with new tech billionaires contributing substantially to this growth (UBS 2024). At a country level, the wealthiest 1% derive a disproportionate share of national income (Roine and Waldenström 2015). The concentration of wealth in relatively few individuals results in the concentration of influence and power. The outlook of the super wealthy can shape policy priorities and their philanthropic activities can influence research agendas. Billionaires may want to benefit society but are drawn to causes to which they feel personally connected, often the arts, museums, education, and health (UBS 2024). Biodiversity conservation does attract philanthropic support, but such funding often targets specific regions, ecosystems, species, and threats that have a high media profile. For example, the Protecting Our Planet Challenge is the largest-ever private funding commitment ($5 billion) to biodiversity conservation and will support projects around the globe to help protect the 30% of ecosystems most important for biodiversity by 2030 (www.protectingourplanetchallenge.org). Some of these funds will likely go to managing plant invasions. Philanthropic initiatives that target biodiversity are comparatively rare, and it seems unlikely that addressing plant invasions will be among the priorities of most billionaires except where they target management on their own, of-

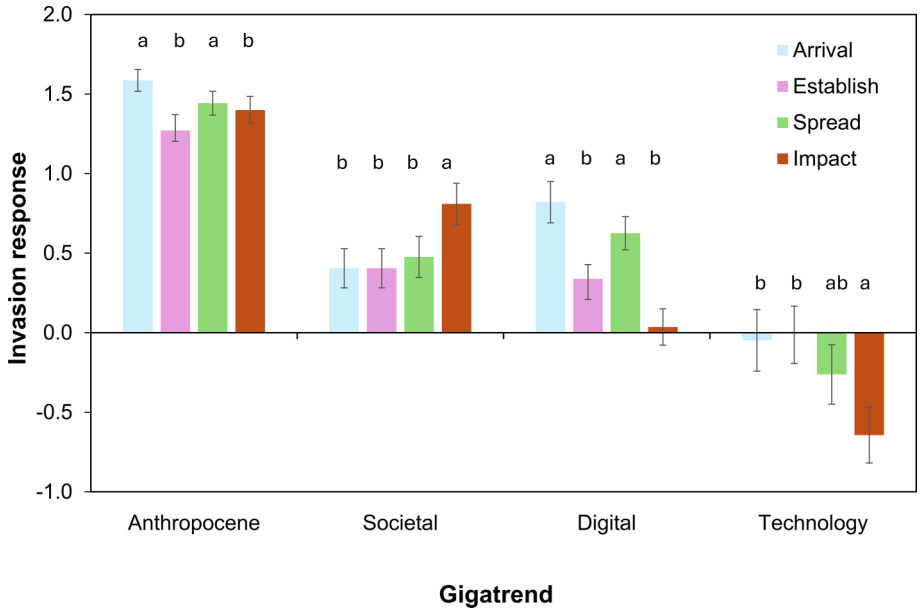

Figure 4 Expected effect of four gigatrends on the future global threat of alien plant species arrival, establishment, spread, and impact. Data are the mean (and standard error) of participant scores that ranged from 2 (major increase) to −2 (major reduction) in the likelihood, rate, or cost of invasions. A repeated measures ANOVA was used to examine within each gigatrend whether there were statistically significant differences in the participants' expectations as to the relative effect of each invasion stage on future plant invasions. All four gigatrends exhibited significant variation across the four invasion stages in terms of their likely role in future plant invasions (all $p < .002$). Within each gigatrend, differences among the four invasion stages are depicted by the columns having a different letter and these contrasts are based on Bonferroni adjusted post-hoc tests.

ten extensive, private estates. At the same time, the neo-luxury trend among the super wealthy that seeks experiential, serene estates creates a demand for private botanical landscapes often comprised of "exotic" alien plant species that may subsequently jump the garden fence. Similarly, the desire among the super wealthy for exclusive, remote, and untouched travel destinations increases human traffic to fragile or isolated ecosystems and risks the inadvertent introduction of alien plants.

The concentration of wealth is tied to aging. In developed economies, personal wealth tends to increase as individuals reach late middle age as they systematically reduce debt, build real estate equity, then accumulate financial assets (World Bank 2021). This concentration of wealth will continue as populations age. Over the next three decades, all regions of the world will see an increase in the share of their population aged 65 years or older and globally the number of older persons is expected to double to 1.5 billion people by 2050 (UNDESA 2020b). It is estimated that about 80% of adults aged 60 and above will reside in the Global South by 2050 and the effects of population aging will be more notable in these countries as existing services and infrastructure are less prepared for an aging society. Do older people play a distinct role in the future trajectory of plant invasions?

Ornamental garden plants, and especially those that are easy to grow, are often the primary source of invasive alien plants (Hulme et al. 2018). In developed countries, people over the age of 65 garden more than those in other age groups (Ashton-Shaeffer and Constant 2006, Wiles et al. 2021), and retirement marks a significant rise in older people's levels of interest and attachment to gardens (Milligan and Bingley 2015). There is a higher proportion of alien plants in urban parks located in cities with inhabitants of higher median age (Bayón et al. 2021). Furthermore, second-home ownership, that potentially provides opportunities for gardens to be established in rural and remote areas, is linked to retirement and affluence in both the Global North and South (Norris and Winston 2010, Visser and Hoogendoorn 2015). Thus, a shift toward more gardening could result in a higher propagule pressure into neighboring environments should alien plants become more widely planted by a growing population of elderly gardeners. Nevertheless, middle-aged individuals are also more likely than other age groups to volunteer for managing alien plant infestations or restoring invaded ecosystems (Tidwell and Brunson 2008, Jubase et al. 2021) potentially helping mitigate the possible shift toward more gardens filled with alien plants.

People over 65 generally account for a disproportionately high level of health expenditure compared to younger cohorts and aging populations will place increased stress on public health systems (Morgan and Mueller 2023). In aging societies, care for those over 65 is projected to account for a significant portion of total health expenditure and this will result in reduced public spending on issues that are low on most political agendas such as the management of alien plant invasions. Countering this possibility will require reframing of the problem of plant invasions as an issue of relevance to wellbeing, specifically targeting species that have impacts on human health (Hulme et al. 2025). National governments will need to implement measures to reduce the burden of medical costs on the older population (Chen et al. 2023). In later life, gardening has a strong relationship to health and wellbeing and such activities may be further encouraged in the future for health reasons (Milligan and Bingley 2015, Wiles et al. 2021) and might spur a new wave of gardening among the elderly with an increased risk of higher propagule pressure from ornamental plants.

Overall, the Societal gigatrend points to an increased threat of plant invasions as public spending on managing plant invasions is reduced

due to the increasing health burden in aging societies and as powerful philanthropists shape political and research priorities toward causes that are more charismatic than invasive alien plants (figure 4). Ornamental horticulture is expected to significantly expand and transform as a consequence of multiple megatrends including globalization, climate change, urbanization, digitalization, an aging society as well as neo-luxury, sustainability, and wellbeing-oriented consumption patterns (Gabellini and Scaramuzzi 2022)

Addressing plant invasions in an uncertain future

Despite the breadth of megatrends examined, most pointed to a future world where the threat and impact of plant invasions are likely to increase. By 2050, we can expect more invasive alien plant species, additional areas invaded, a greater magnitude of economic and environmental impacts, and increased conflicts of interest when there are economic benefits arising from the cultivation of alien plant species. But how confident can we be of these prognoses? Although the megatrends reflect a global consensus they could all be offset before 2050 by isolated, unanticipated shocks to the system such as a major geopolitical armed conflict, a worldwide zoonotic pandemic, collapse of the global finance system, an energy/oil crisis or malicious artificial superintelligence. Furthermore, the complex interactions and feedback loops among multiple global megatrends can lead to emergent, often unforeseeable, system-level properties and outcomes that cannot be forecast by examining the individual megatrends in isolation. Although it is impossible to assess precisely how rare system shocks or emergent phenomena might influence biological invasions, it seems improbable that they would make the management of invasive alien species any easier (e.g., the rising fuel prices resulting from the 2026 closure of the Strait of Hormuz have increased costs for managing plant invasions). Given this uncertainty, we have been cautious not to suggest that our analyses deliver predictions, rather they indicate probable outcomes that should be borne in mind when planning future investment, policy changes, or new legislative instruments (Hulme 2025). For example, we highlight that the gigatrends are likely to have an effect on not only the arrival and establishment of new alien species but also the further spread and increased impact of established species underscoring that a whole of system approach to biosecurity is essential (Hulme et al. 2025).

It is important to emphasize that every megatrend has some potential to either reduce or increase the likelihood of the arrival, establishment, spread, or impact of biological invasions. Four examples drawn from each of the four gigatrends illustrate this issue more clearly:

1. Economic growth is an important driver of biological invasions (Hulme 2021b) but weaker economies struggle to manage invasive alien species (Early et al. 2016). Although wealthier nations are more susceptible to biological invasions due to their exposure to international trade and the scale of their national infrastructure development, they also have a greater response capacity to reduce the overall burden (Bradshaw et al. 2024). Thus, economic growth may help limit biological invasions if governments balance economic growth with investment in more effective border biosecurity, post-border pest management, and citizen awareness to mitigate these threats.
2. When it comes to technology, low-cost methods of gene manipulation can be used to reduce reproductive success or promote complete sterility, allowing the generation of cultivated plants that pose a lower risk of invasion (Dehnen-Schmutz and Novoa 2022). However, there is considerably more interest and financial support to use these tools to increase the drought, frost, salt, and pest resistance of plant species with little consideration for the potential risk of increased invasiveness (Chachar et al. 2025, Li et al. 2025). Invasion scientists should be at the heart of the genome modification debate arguing for the risks of biological invasions to be explicitly considered in all future plant breeding.
3. Digital networks will lead to stronger interconnections among individuals, which could empower them to be agents of change. As communities become more interconnected, there will be ever greater opportunities to employ social media more effectively to mobilize action on plant invasions, share management techniques that are tailormade to specific species and ecosystems, and celebrate success stories. Such digital interconnection and empowerment should reduce plant invasions. On the other hand, digital channels are ideally suited to spreading misinformation, whether that be exaggerating the human health risks arising from herbicides (Jun et al. 2023) or accusing stakeholders of perpetuating nativist worldviews (Hobman et al. 2025). It is imperative that invasion scientists engage with multiple social media platforms and associated networks to ensure evidence-based information on alien plant management and impacts is distributed widely from trusted sources.
4. Societal changes such as the concentration of wealth will provide multinational corporations with a strong platform to significantly influence foreign policy, trade agreements and transnational economic governance (Ballor and Yildirim 2020). Such power imbalance could limit the effectiveness of international multilateral treaties such as the Convention on Biological Diversity and challenge national biosecurity regulations that restrict trade. A weakening of these agreements would increase the threat of biological invasions. At the same time, there is strong emerging interest from forward-looking multinational firms to finance nature protection through biodiversity credits as part of nature-positive investment strategies (WEF 2023). Multinationals have the financial capital and influence to markedly scale-up nature-based solutions if consumer pressure is sufficient to drive such a step-change. To achieve wins for biological invasions, investment has to go beyond supporting the initial costs of restoration but also include longer-term operational costs such as the management of alien plants (Arjaliès et al. 2025).

These subtleties in which the same megatrend could lead to markedly different results are often lost in prognoses regarding the future of biological invasions since the outcomes are contingent on the decisions society makes when addressing the megatrends. Unfortunately, discussions relating to economic growth, technology development, or demographic change rarely address the consequences for biological invasions. With the exception of pandemic communicable diseases of humans, biological invasions do not feature as a consequence, concern, or opportunity in any of the megatrend reports to date (USNIC 2021, Kuhn and Margellos 2022, CIFS 2023, Krys et al. 2023, Barry 2024, PMI 2024, PwC 2024, UK Ministry of Defence 2024). The greater the engagement of invasion scientists with these megatrend analyses, especially by adopting an incasting approach, would be one way to raise the profile of this issue to an audience for whom, at present, it may not even be on the radar.

Conclusions

The widespread and recurrent production of global forecasts describing future megatrends (USNIC 2021, Kuhn and Margellos 2022, CIFS 2023, Krys et al. 2023, Barry 2024, PMI 2024, PwC 2024, UK Ministry of Defence 2024) represents an underutilized resource for the assessment of future risks from biological invasions. By building on the detailed work of economists, technologists, entrepreneurs, and futurists in published megatrend reports, our incasting approach broadens the context for the examination of biological invasions encouraging thinking outside of the norm. Our work describes a structured, repeatable, and easily implemented approach to incasting which although focused on terrestrial plant invasions could be adapted to deliver insights relevant to other taxa.

Our assessment points to several future social, technological, economic and environmental megatrends as likely having a net effect of increasing the likelihood of the arrival, establishment, spread, and impact of invasive alien plants in the future. Despite some optimism that technological solutions may prevail to reduce this threat, there are significant barriers to technological uptake. Although this finding is expected to be true worldwide, it is especially the case for nations in the Global South. Continuing population growth and rapid urbanization combined with a progressively aging society will place increasing demands on infrastructure, particularly in the Global South. As a result, many developing economies are likely to experience insufficient investment in surveillance and rapid response technologies to counter the increased biosecurity threats at national borders arising from greater globalized trade. Although many of these countries currently face a lesser burden from plant invasions than other parts of the world (Pyšek et al. 2017) this is expected to change and result in negative consequences for the economy and human wellbeing. Purely pointing the finger of blame at traditional targets such as globalization or economic growth is simplistic and unhelpful. Multiple megatrends will drive an increase in future plant invasions unless invasion scientists can engage with policymakers to steer them toward more positive outcomes that will mitigate the threat of biological invasions.

The intersection of multiple megatrends as described by our four gigatrends emphasizes that managing the risk of biological invasions is beyond the reach of single-sector policies. Mitigating future plant invasions requires a unified One-Biosecurity approach that integrates trade, environmental, technological, and social policy domains (Hulme 2021a). This must involve the strengthening of international cooperation on biological invasions, regulating high-risk pathways such as online plant trade, investing in scalable detection and rapid-response systems, and embedding invasion risks into broader policy agendas such as climate adaptation, urban planning, and economic development. Ultimately, the trajectory of plant invasions will depend less on the megatrends themselves than on how effectively policymakers respond. A key message is that proactive, coordinated governance has the potential to redirect these powerful global forces toward mitigating biological invasions rather than exacerbating them.

Supplemental material

Supplemental data are available at *BIOSCI* online.

Data availability

The data that support the findings of this study are openly available in figshare at: https://doi.org/10.6084/m9.figshare.30929738.

Author contributions

Phil E. Hulme (Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing), Jacob N. Barney (Conceptualization, Investigation, Validation, Writing – review & editing), Jennifer L. Bufford (Conceptualization, Investigation, Validation, Writing – review & editing), Jane A. Catford (Conceptualization, Investigation, Validation, Writing – review & editing), Julie Coetzee (Conceptualization, Investigation, Validation, Writing – review & editing), Curtis C. Daehler (Conceptualization, Investigation, Validation, Writing – review & editing), Michele de Sá Dechoum (Conceptualization, Investigation, Validation, Writing – review & editing), Heinke Jäger (Conceptualization, Investigation, Validation, Writing – review & editing), Aníbal Pauchard (Conceptualization, Investigation, Validation, Writing – review & editing), Petr Pyšek (Conceptualization, Investigation, Validation, Writing – review & editing), David M. Richardson (Conceptualization, Investigation, Validation, Writing – review & editing), Montserrat Vilà (Conceptualization, Investigation, Validation, Writing – review & editing), Elizabeth M. Wandrag (Conceptualization, Investigation, Validation, Writing – review & editing), John Wilson (Conceptualization, Investigation, Validation, Writing – review & editing)

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Conflict of interest

The authors declare no conflict of interest.

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