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Increasing invasion debt through good intentions: the risk and responsibilities of greening initiatives in the Middle East

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1 Introduction

Alien invasive species pose a significant threat to biodiversity (Roy et al., 2023), particularly in arid desert environments, such as those in the Middle East, where alien species can have substantial ecological and economic repercussions. The arid desert ecosystem is highly adapted to extreme temperatures, low water availability, and nutrient-poor soils and is particularly vulnerable to the impacts of invasive species (Brooks, 2003; Underwood et al., 2019). These species often possess high reproductive capacity, rapid growth, and the ability to thrive under harsh conditions, enabling them to outcompete native flora and alter ecosystem functions (Gallardo et al., 2016; Milanović et al., 2020; Traveset and Richardson, 2006).

Their proliferation is primarily driven by human activities, including deliberate introductions, cultivation, and accidental spread through global trade (Kueffer, 2017; van Kleunen et al., 2015). These invasions threaten biodiversity in urban areas and encroach upon agricultural lands and natural landscapes (Thomas et al., 2016). Invasive species reduce crop yields and increase agricultural land management costs (Alvarez and Solís, 2019), thereby altering water availability, soil fertility, and fire regimes in arid environments, which stresses native ecosystems. These species impact agricultural productivity and management costs, threatening food security and environmental stability, as they contribute to 60% of global animal and plant extinctions, with 16% being the sole driver (Roy et al., 2023).

In parallel with the United Nations' Global Initiative on Reducing Land Degradation and Enhancing the Conservation of Terrestrial Habitats, and in response to climate challenges, the Middle East is increasingly focusing on environmental restoration and the development of green infrastructure (Alam and Azalie, 2023). The Middle East Green Initiative (MGI) and the Saudi Green Initiative (SGI), which aim to improve urban livability and promote sustainable development (Abbass et al., 2018), were founded in 2021. The Middle East Green Initiative seeks to plant 50 billion trees region-wide, enhance

regional cooperation to address climate change (Ghanem and Alamri, 2023), and initiate a transition to environmentally friendly economic activities, similar to the UAE's Green Agenda. While the MGI provides a framework, the Saudi Green Initiative ambitiously implements programs specifically designed to restore vegetation cover and reduce carbon emissions, aiming to generate 50% of the Kingdom's energy from renewable sources by 2030 and plant 10 billion trees (Khayat et al., 2023).

Amongst other countries, Saudi Arabian landscapes are, therefore, at risk of being exposed to an increasing land management efforts, particularly afforestation that may increase the number of invasive plant species threatening the native biodiversity and the ecological integrity of these habitats (Alharthi et al., 2023a; Assaeed et al., 2021; Hassan et al., 2023). The increased risk of introducing and dispersing alien species through greening initiatives demands urgent attention. This raises a critical question: Are well-intentioned greening efforts in the Middle East inadvertently increasing the number of invasive species and facilitating dispersal? This potentially intensifies invasion debt, which refers to the delayed ecological consequences of biological invasions, representing a time lag between the introduction of alien species and the manifestation of their full environmental, economic, and ecological impacts (Robeck et al., 2024). Invasion debt can become apparent across multiple temporal scales, linked to the introduction, establishment, spread, and impact of alien species (Rouget et al., 2016).

Despite growing awareness of invasive species, local research on the topic remains sparse, and policymaking and enforcement lag (Kumar Rai and Singh, 2020). Recent initiatives aim to consolidate research on biological invasions (Alfarhan et al., 2021; Thomas et al., 2016), but more substantial efforts are required to prevent the deliberate and accidental introduction of invasive alien plants into vulnerable ecosystems.

This article highlights these risks while advocating for the integration of stronger research, management, and policy as essential components of sustainable development, ensuring that greening initiatives contribute positively to long-term restoration targets. It serves as a call to action for a diverse range of stakeholders, including planning specialists (landscape and urban planners, and private developers), managing bodies (national parks, councils, botanical gardens, and development authorities), and implementation actors (landscape contractors, nurseries, growers, and private landowners). Still, it also addresses universities, field experts, ministry policymakers, national specialization centers, and those involved in drafting requests for proposals within government institutions.

2 Greening initiatives as plant invasion facilitators

Large-scale greening and restoration initiatives are promising, yet they also carry the unintended potential to introduce or spread invasive plants. Understanding both the risks embedded in such initiatives and the potential distribution dynamics of particular

plants that could become invasive is crucial for anticipating and managing future ecological impacts.

2.1 Potential risks of greening initiatives

The Middle East Green Initiative (MGI) was established in 2021 as a multinational framework led by the Kingdom of Saudi Arabia (KSA) and endorsed by 25 countries (Middle East Green Initiative, 2024; Saudi and Middle East Green Initiatives, 2024). This comprehensive program operates through a structured governance system comprising 32 components that define the organizational structure, project submission protocols, evaluation criteria, and financing mechanisms. Saudi Green Initiative, as a sister initiative has launched 86 programs spanning afforestation (Table 1), protected areas, agriculture, clean energy, climate action, policy, capacity and outreach, sport, tourism, urban greening and parks, waste and water management across 39 different private and public project owners (Albawardi et al., 2024; Saudi and Middle East Green Initiatives, 2024). A quarter of the announced programs are already underway, encompassing multiple strategic or site-based projects. During a recent steering meeting, the MGI announced plans to launch several qualifying projects in member countries by the end of 2025 (al-Abyad, 2024).

Both initiatives have led to the establishment of governmental management entities focused on plant production, land management, wildlife conservation, and ecological restoration (e.g., the National Centers for Vegetation Cover, Wildlife, Environmental Compliance, as well as Greening UAE Initiative, and many others). Their launch has also led to an increase in public environmental awareness and support for urban greening and conservation (Khayat et al., 2023).

Partially triggered by the MGI, seven states have released nationwide greening strategies, which are being implemented at regional and local levels through urban greening and natural restoration initiatives covering hundreds of thousands of square kilometers, with the target of planting billions of trees. In Saudi Arabia alone, seven urban greening initiatives are currently underway, comprising green infrastructure development, large-scale recreational park developments, and the restoration of semi-natural environments (Figure 1). Green Riyadh, for example, plans to plant 7.5 million trees over ~5,900 km² (Royal Commission for Riyadh City, 2023). At a different scale, Oman's Green Muscat Initiative targets 19,500 palms and more than 51,000 shade trees (Times of Oman, 2024). A review of grey literature and press releases has revealed that ecological restoration work has been ongoing in 22 protected areas across KSA, Yemen, and Oman since 2021. These efforts are complemented by ecotourism developments that are commonly coupled with rehabilitation and afforestation initiatives in both the terrestrial and marine environments.

The number and amplitude of these greening initiatives have increased business opportunities in landscape and environmental planning, landscape contracting, and plant production (Fernando et al., 2019; Rahman et al., 2023; Shah et al., 2025; Swaffield et al., 2019), while associated capacity-building efforts can also drive

TABLE 1 Summary of 79 of 86 announced initiatives for which data were available. Local projects are location-specific, whereas regional projects impact entire provinces or contiguous areas within a region.

Category	Local	National	Regional	Grand total
Afforestation, Protected areas, & Agriculture	21	17	10	48
Clean Energy & Climate Action	4	4	2	10
Policy, capacity & outreach		5		5
Sport & Tourism		2		2
Urban Greening & Parks	3	4	1	8
Waste Management		2	1	3
Water Resources Management	1		2	3
Grand Total	29	34	16	79

National-scale projects involve more than a single province or country.

biological invasions (Comte, 2024; Montaldi et al., 2024). In Saudi Arabia, for example, ongoing species trials aim to identify alien plants for their use in green infrastructure projects, supporting the Saudi Green Initiative (Alfarhan et al., 2021; Alharbi, 2024). These trials assess environmental suitability, resilience, growth rates, and usability in landscaping under local conditions (Alharthi et al., 2023a; Al-Sodany et al., 2016). Researchers and planners target plants that can thrive in urban areas while withstanding high temperatures, low water availability, and saline soils, thereby supporting greening efforts (Abbas et al., 2023; Alharthi et al., 2023b). Selected trials use acclimatized relocated plants to ensure

successful growth when transplanted from controlled environments (Bruce et al., 2007).

On another note, the highly adapted ecosystems of the Arabian Peninsula are severely understudied in the context of risk and impacts of invasive species on the local environment (Aljeddani et al., 2021; Thomas et al., 2016), with at most 33 publications on the topic of alien and invasive plants for the Kingdom of Saudi Arabia (Clarivate, 2024). This arid region harbors a surprisingly diverse range of flora and fauna. With 11% being endemic, the KSA’s flora (n = 2,250) is adapted to extreme conditions (Ansari et al., 2022; Basahi, 2018; Masood and Asiry, 2012) and is increasingly

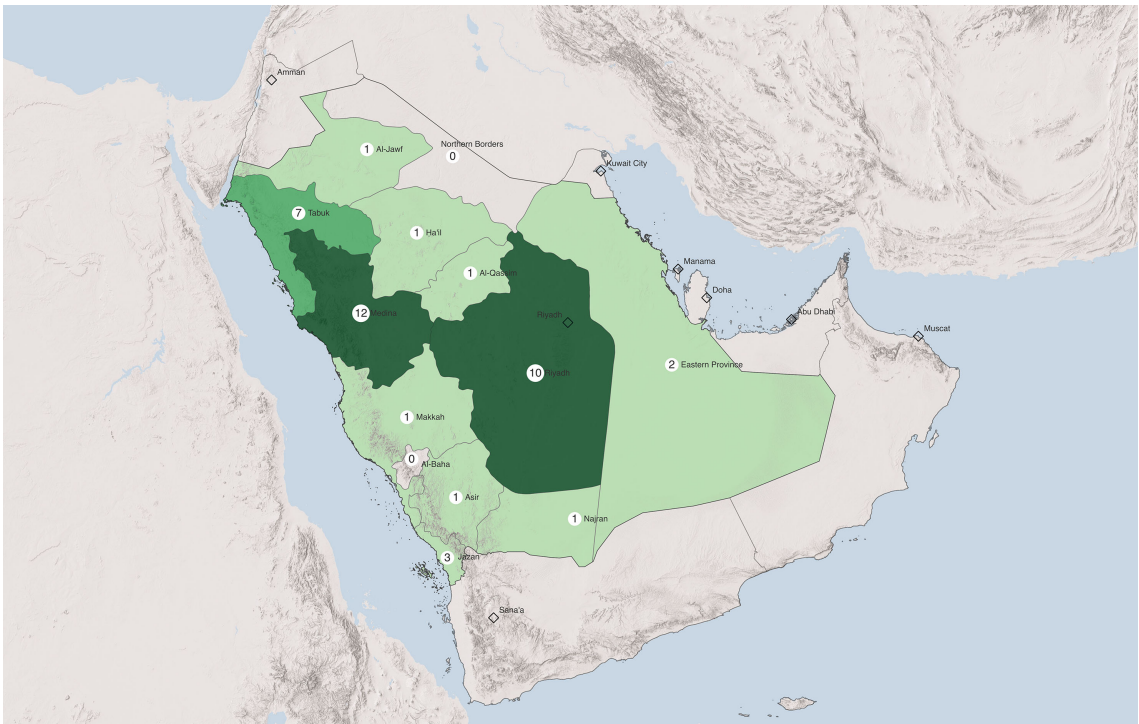


FIGURE 1 Number of Saudi green initiatives announced per province shown in circular white labels. 45 SGI initiatives are national or not location-specific and cannot be shown on the map. Capital cities are shown for reference.

threatened by invasive species introduced through trade, travel, or agriculture (Alfarhan et al., 2021). Introduced plants with broad environmental tolerances suitable for diverse habitat types have the potential to outcompete highly adapted native plants, disrupt the ecological equilibrium, and lead to declines in native biodiversity (Aljeddani et al., 2021; Hassan et al., 2023). Invasive plants and pests can significantly impact crop yields (Paini et al., 2016), thereby threatening the productivity of cereal and fruit production. This impact may contribute to an increased reliance on food imports.

2.2 Potential distribution

To demonstrate the practical application of data-driven approaches in understanding species distribution patterns and underscore the risk of alien invasive plants, we conducted an exploratory analysis using species distribution modelling (SDM).

We selected eight countries with a representative range of environmental conditions, from hyper-arid deserts to more temperate and mountainous climates. These countries also vary in size, biogeography, and data availability, allowing for a balanced assessment of species establishment potential. We modelled the potential distribution of 63 terrestrial invasive plant species using MAXENT (Elith et al., 2011), a presence–pseudoabsence niche modelling algorithm, and predicted their distribution on the Arabian Peninsula. We compiled global occurrence records for the target species from GBIF (GBIF.org, 2024), eliminating duplicates, absence records, and entries with missing or erroneous locations, which resulted in 1,188,272 presence points. We further thinned the dataset to one occurrence per 1 km² grid cell to address spatial sampling bias. Environmental predictors included four soil parameters (bulk density, clay content, pH CaCl₂, and organic carbon) and five climatic variables (annual mean temperature, warmest month's maximum temperature, annual precipitation, precipitation of the warmest and coldest quarters) (Fick and

Hijmans, 2017; Hageer et al., 2017; Hengl et al., 2017). For details see the SI.

The results reveal the varying potential of unique species to inhabit and cover substantial portions of the surface area across the studied countries. 46 of the 63 assessed species have suitable habitats in 1% or more of the six countries. Yemen has the highest number of species (41), followed by Oman and Jordan (24) (Figure 2). More dramatically, 22 species could cover 10% of the eight assessed countries. Yemen (15 species), Oman (6 species), and Jordan (9 species) remain the most suitable areas for these species. On a high level, these results demonstrate that more than 94% of species regulated in KSA may establish in any of the assessed countries.

This preliminary investigation reveals the potential risks associated with invasive alien plants. It further confirms that data and technology are publicly available for data-driven policymaking and to support communication and outreach efforts to build public awareness.

Evidence-based outreach of invasion risks has become increasingly important as Saudi Arabia's ambitious afforestation and biodiversity goals have significantly boosted economic activity in the nursery and soil products sectors, driven by park, landscape, and nature park development projects. Horticulture, recognized as a significant pathway for introducing invasive alien plants (Reichard and White, 2001), is critical in this expansion. The Saudi landscaping and ornamental plants market is projected to grow at an annual rate of 8.1% (Techsciresearch, 2024), driven by urbanization, rising disposable incomes, and supportive government policies for landscaping (6Wresearch, 2023). This growth is driven by Vision 2030 initiatives, alongside significant infrastructure and urban development projects in regional capitals such as Riyadh, Jeddah, and Dammam (Alharbi, 2024).

However, before the surge in urban development and government programs, millions of globally recognized invasive species were introduced in Saudi Arabia through greening and urbanization projects (Al-Frayh et al., 1999). Limited data on failed

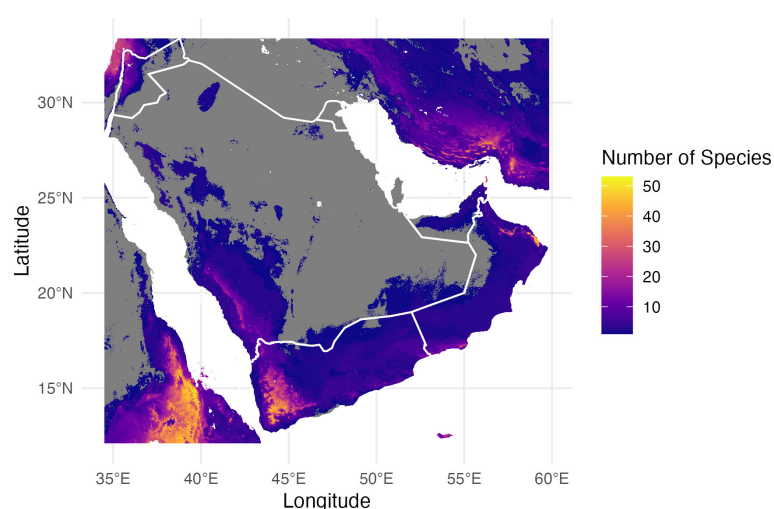


FIGURE 2

Potential distribution of invasive plant species across the Arabian Peninsula. Unsuitable areas are shown in grey. The absence of soil data in urban areas results in the absence of predictions, which are shown in white.

introductions and establishment events highlight the risks of species trials and unintentional or accidental introductions becoming invasive. While Saudi Arabia's hyper-arid climate may suggest that globally impactful invasive species are unlikely to establish, the potential for their unintentional dispersal into more suitable regions with higher rainfall and temperate climates remains a significant concern.

The tools and methods used in restoration and conservation initiatives can sometimes lead to unintended negative consequences. For example, building infrastructure to support conservation areas may fragment habitats (O'Brien, 2006), isolate wildlife populations (Torres et al., 2016), or even create corridors that facilitate the spread of alien species. For example, the increasing demand for ornamental palms in landscaping projects across Gulf cities drove substantial imports from infested regions. This trade in adult palms and offshoots became the primary vector for long-distance dispersal (Abdel-Banat and El-Shafie, 2023). Solely the eradication of the Red Palm Weevil affecting date palms is estimated to cost \$25.92 million at a 5% infestation rate across the member states of the Gulf Cooperation Council (GCC) (El-Sabea et al., 2009), while indirect costs (i.e. reduced yields, loss of market value, negative impacts on related industries) are estimated to represent a 3–5 fold of the direct financial consequences.

In the Middle East, Mesquite (*Prosopis juliflora*) has become a major invasive tree expanding the area covered in the UAE alone by an 80-fold over the last three decades (Howari et al., 2022), imposing substantial economic costs through groundwater depletion, infrastructure strain, and management requirements, translating to USD 11–22 million per year in energy and infrastructure expenses (Shiferaw et al., 2024; Tundia et al., 2025). While the negative impacts have not been quantified economically yet, Mesquite invasions have led to loss of productive land, health impacts (Al-Frayh et al., 1999), and increased land management expenses in environmentally similar regions such as eastern Africa and Jordan. For perspective, potential future costs could reach USD 375 million annually across similar regions if suitable habitats become fully invaded (Hundessa and Fufa, 2016). Further examples include multiple pear cactus species (*Opuntia* spp.) that have established significant populations across the Arabian Peninsula (Alharthi et al., 2023a). In Saudi Arabia's Al-Baha and Asir regions, the introduced pear cactus has been abandoned by farmers. It has invaded forests and rangelands, infesting arable fields and pastures, reducing crop yields and livestock carrying capacity to unquantifiable dimensions (Alwadai, 2019). Globally, species such as Mesquite (*Prosopis juliflora* (Sw.) DC.), Common Lantana (*Lantana camara* L.), and Prickly Pear Cactus (*Opuntia* spp.) have been studied for their economic impacts; however, GCC-specific financial assessments are lacking.

3 Ongoing regulatory efforts

Across the Gulf, the prevention and control of invasive species primarily rely on plant health, quarantine, and seed/seedling regulations, which are guided by GCC-level agreements and

heterogeneously implemented through national legislation. The GCC's unified Plant Quarantine Law (Plant Quarantine Law, Gulf Cooperation Council, 2001) and Seed, Seedlings, and Saplings Law (Seed, Seedlings, and Saplings Law for the Gulf Cooperation Council Countries, Gulf Cooperation Council, 2008) provide a legal framework for declaring quarantine pests, regulating the trade of plants and plant products, and prescribing inspection, treatment, and eradication measures. Recent efforts include regulations that ban the planting of invasive species and impose fines. For example, Saudi Arabia introduced specific regulations with penalties in two forms. The first ranges from ~5300 to 106,000 USD (20,000 to 400,000 SAR) per tree for planting invasive species in or around protected areas. And the second ranging between ~260, 1060, and 2600 USD (1000, 4000, and 10,000 SAR) for cultivating invasive plants (per tree or shrub).

To address marine vectors, GCC states are parties to the IMO Ballast Water Management Convention, which provides a defense against the spread of aquatic invasive species. At the regional level, broader environmental agreements under the GCC Convention on the Conservation of Wildlife and Natural Habitats (2001) (Gulf Cooperation Council, 2001) and national strategies (e.g., the UAE National Invasive Species Strategy & Action Plan (Ministry of Climate and Environment, 2022) complement these measures, while individual national plant-quarantine laws (e.g., Oman's Agricultural Quarantine Law of 2004) (Agricultural Quarantine Law - Oman, GCC, 2001) provide additional statutory tools.

In 2023, the National Centre for Vegetation Cover expanded its regulation to include 207 species, including 63 plants (Ministry of Environment, Water and Agriculture, 2020), based on earlier studies (Thomas et al., 2016). According to the Executive List for the Development of Vegetation Cover and Combating Desertification (Ministry of Environment, Water and Agriculture, 2020), individuals found planting or cultivating invasive species face substantial fines, starting at USD 130 per tree or shrub for the first offence, increasing four to ten times for subsequent violations. This policy underscores the government's commitment to preserving ecological balance and cautions against the unregulated introduction of invasive plants. This represents significant national awareness and enforcement progress—steps neighboring countries have yet to undertake.

However, despite these recent regulations, enforcement gaps remain. Twenty-seven per cent (n=17) of the 64 regulated plants are still available for import to Saudi Arabia via the Amazon Marketplace. Through local online retailers such as bastanastore.com and bostan.com.sa, 6% (n=4) of the targeted species are commercialized. *Lantana camara*, classified as one of the world's worst alien invasive species (Invasive Species Specialist Group, 2013), is commercialized alongside other cosmopolitan weeds, such as *Amaranthus hybridus*, *Bidens aurea*, *Opuntia ficus-indica*, and *Senna occidentalis*. These findings were uncovered through a web-scraping search using botanical names and common names in English and Arabic, revealing the continued availability of these invasive species despite legal restrictions (See method in SI). The actual number may be much higher, due to the many local common names and spelling variations commonly found in online marketplaces.

Moreover, retail points for plant products and nurseries represent another mechanism for the spread of alien species. The

transportation between production points and approximately 430 retail points (Google Maps, 2024) in KSA provides additional opportunities for pests, seeds, and plant material to escape. In addition, preliminary findings indicate that 8 out of 38 inspected nurseries cultivate at least one of the 64 regulated invasive species, representing a cumulative 10% of all regulated plants (unpublished data). This highlights the lack of awareness and the fact that they actively contribute to spreading invasive species. In summary, while recent regulatory efforts in Saudi Arabia demonstrate a commitment to addressing the risks associated with invasive species, significant challenges remain in enforcement and public awareness, particularly on a regional scale.

4 Pathways forward

To effectively bridge science with policy and planning, it is crucial to consider several factors to prevent the introduction, establishment, and spread of invasive species. We highlight the need for science-driven regulations that transcend administrative boundaries and are sufficiently nuanced to account for local environmental conditions. Similarly, enforcement efforts require a coordinated approach considering anthropogenic and natural dispersal pathways. Effective communication and outreach, along with fundamental advancements in regional research in biological invasion and agricultural science and technology, would further raise awareness.

4.1 Nuanced regulations

Traditionally, environmental regulations operate within administrative boundaries, overlooking ecological realities such as species dispersal and establishment (Török et al., 2018). Habitat-specific risk assessments are crucial for developing detailed species lists that enable policymakers to evaluate the likelihood of species establishment under specific climatic conditions (Marchioro and Krechmer, 2021; Vilizzi et al., 2021). For example, species struggling in hyper-arid environments may thrive in wetter regions, posing unforeseen risks to local ecosystems once dispersed. Furthermore, urban environments often represent climatic and edaphic combinations that do not exist in the natural environment and require regulatory efforts to consider ecological variables over administrative borders. Overarching species lists may not accurately reflect the dynamic nature of biological invasions, which can evolve rapidly in response to environmental changes and human alterations to the natural environment. Therefore, iterative policy review processes are required to create nuanced lists and regulations.

4.2 Invasion-sensitive planning and design

Leveraging greening initiatives and the associated economic upswing can support the creation of standardized design and

planting pallets and guidelines, urban greening codes, and species suitability lists that align with economic opportunities (Du and Zhang, 2020; Radhakrishnan et al., 2019; Threlfall et al., 2016).

While species lists and design guidelines are commonly available for selected districts or projects (Balmford and Gaston, 1999; Tingstad et al., 2020), they often aim to advise species selection based on aesthetic and functional aspects of vegetation, ignoring the risk of adverse effects of plants, the combination of plants, and the transport of live plant material. Riyadh's authoritative planting guide (High Commission for the Development of Arriyadh, 2014), for example, includes five recently regulated invasive species without distinguishing native from alien or classifying invasiveness. Collaboration between regional governments and public actors in urban, environmental, and agricultural realms is necessary to establish robust assessment protocols for ornamental, farming, and soil products, ensuring a thorough evaluation of suitability and potential invasiveness. Those design and planning guides should not be the responsibility of commercial landscape planners and designers. Still, they should be based on science and data-driven tools authored and approved by qualified public entities.

4.3 Managing dispersal pathways

The movement of invasive plants from, to, and within Saudi Arabia is not solely a result of deliberate introductions but also stems from socio-economic activities and natural dispersal mechanisms. Anthropogenic drivers, including trade, tourism, and infrastructure development, contribute to the introduction and dispersal of species. The region's extensive road networks, shipping routes, and air travel hubs facilitate the accidental transport of propagules, while livestock movements, bird migrations, and marine currents contribute to natural dispersal.

In addition to nuanced, ecosystem-specific species lists, introduction-dispersal risk assessment is a foundational tool for regulatory frameworks (Brenton-Rule et al., 2016; Essl et al., 2011), as well as for defining regulations and enforcement. Those spatially explicit assessments consider species traits, dispersal mechanisms, environmental suitability, and population demographics, as well as invasion contexts such as the intent of introduction and other anthropogenic factors.

They also enable the early detection of emerging threats, such as "sleeper" species (Osunkoya et al., 2021) that remain dormant for years before proliferating under favorable conditions (Robeck et al., 2024). Moreover, risk assessments can facilitate targeted surveys and management, such as eradicating impactful species in sensitive natural environments and restricting high-risk species in landscaping projects while permitting controlled cultivation in less sensitive areas (e.g., urban).

Effective policy responses must account for these diverse pathways, integrating socio-economic data with ecological insights. For instance, predictive modelling can identify high-risk introduction routes and inform pre-emptive measures, such as enhanced biosecurity protocols at ports of entry and along

transportation corridors. Such an integrated approach is vital for a region like Saudi Arabia, where human activity and natural processes often overlap, amplifying the risks of invasive species spread.

4.4 Communication and outreach

Communication and collaboration are crucial for enhancing regulatory awareness among planners, growers, and the public (Smith et al., 2019). Actions should include equipping species lists with accessible identification keys and detailed descriptions to improve usability and encourage compliance. Leveraging greening initiatives can support the creation and standardization of design guidelines, urban planning codes, and species suitability lists that align with economic opportunities (Coffey et al., 2020; Du and Zhang, 2020).

National collaboration is necessary to establish robust assessment protocols for ornamental, agricultural, indoor, aquatic, and soil-associated species, evaluating their suitability and potential invasiveness (Roman and Mauerhofer, 2019; Roy et al., 2018). Educational initiatives should address gaps in local landscape planning expertise, empowering stakeholders to make better decisions. Clear, risk-based guidance on managing invasive species will streamline local decision-making and resource allocation, ultimately enhancing the effectiveness of invasive species management.

4.5 Data and technology

In addition to data-driven risk assessments, exemplified by the distribution model, user-friendly identification tools can be further developed, adapted to local languages and environmental contexts, and made publicly available (Bilyk et al., 2021). These tools can foster awareness, empower citizen science initiatives, and contribute valuable data for biodiversity research and risk assessments.

Traditional distributional risk assessments used at local scales should be made publicly available, enabling their integration into strategic planning and policy frameworks to support data-driven decision-making and enhance regulatory effectiveness. Mobilizing and sharing often unstructured and siloed biodiversity data further enables decision-making as a foundational basis for science and policy (Güntsch et al., 2025).

Enforcement can be strengthened through screening technologies driven by machine learning approaches to flag and limit the trade of prohibited species in online marketplaces. Warning banners for key search terms can further deter illegal activity. Offline measures include implementing nursery certification systems and digital self-reporting tools to track stock movements. Mechanisms to monitor interstate sales and exchanges of plant materials will also ensure compliance with regulations, creating a robust framework for managing invasive species risks.

5 Navigating risks and unlocking opportunities

Efforts to regulate invasive species are unfolding at the intersection of conservation priorities, economic realities, and governance capacity. It involves barriers that can slow or undermine implementation, as well as opportunities that, if leveraged, can accelerate sustainable change. The current momentum in green infrastructure development, awareness around climate change mitigation, and public recognition of natural asset values provide an opportunity to recognize and balance these dimensions (Colombari and Battisti, 2023; Epanchin-Niell, 2017), which is essential for building effective and durable management strategies (Beaury et al., 2020).

Locally adapted but internationally coordinated regulations also provide opportunities to optimize the ecosystem benefits of alien plants in controlled settings, such as urban and roadside greening. By balancing ecological risks with urban development needs, this approach can contribute to sustainable urban planning while minimizing the potential for invasive species to escape into natural habitats (Hazarika et al., 2024; Moya, 2025).

The science-policy interface for invasive species management presents opportunities for strengthening connections between research and policy implementation. Current planning and land management efforts could benefit from linkages to research entities to obtain comprehensive evidence-based decision-making input. Enhanced collaboration between research institutions and policy-making bodies would facilitate improved knowledge translation and dissemination (Graham et al., 2019). Greater coordination of inter-institutional and international protocols would help harmonize regulatory approaches across the region. Promoting knowledge exchange between research and policy communities and integrating scientific evidence into practical implementation strategies would accommodate regional characteristics and answer cross-border coordination needs (Shackleton et al., 2019; Wallace et al., 2020).

Building on existing foundations (Plant Quarantine Law, Gulf Cooperation Council, 2001), adaptive management frameworks incorporating biannual policy review cycles could enable more responsive regulatory systems. The development of a regional invasive species database and early warning system, drawing inspiration from Europe's successful EASIN network (European Commission, 2025), would establish valuable infrastructure for evidence-based policy development. Additionally, regionally coordinated risk assessment tools and protocols, as well as standardized screening procedures for plant trade, would support regulatory effectiveness. For instance, with the democratization of AI, probabilistic approaches that utilize machine learning frameworks offer opportunities to enhance risk assessment, detection, and prioritization of management efforts.

Regional cooperation on invasive species management may face significant obstacles that can undermine the effectiveness of policy and enforcement measures. Limited transparency regarding natural assets, policies, and trade (invasion pathways) may hinder collaboration. Additionally, differing governance structures and regulatory frameworks across countries create challenges in

harmonizing standards and enforcement mechanisms. Beyond the policy level, lack of commitment to environmental enforcement and the absence of strong enforcement mechanisms in international agreements may hinder execution, monitoring, and control.

Outreach efforts in the region can address distinct challenges while capitalizing on the growing momentum for greening initiatives among government planners, managers, and the public. Resource constraints can lead to generic messaging that fails to resonate with diverse cultural contexts, reducing campaign quality and reach. Significant and sustained financial investment is often required to develop research-based materials, multilingual media campaigns, educational programs, and ongoing evaluation—needs that many governments currently struggle to meet. To overcome these hurdles, targeted support for government planners and managers should include funded training workshops, customized guidance on invasion-sensitive planning, and clear protocols for integrating native species into large-scale restoration and development projects. For the public, engaging multilingual community planting events, interactive digital platforms, and partnerships with schools and nonprofits can foster broader awareness of the ecological and aesthetic benefits of native plants. By combining strategic investment in professional outreach resources with inclusive, culturally tailored public engagement, programs can strengthen stakeholder commitment, ensure more effective communication, and sustain interest and participation in regional greening efforts over the long term.

Outreach and regulatory strategies targeting market drivers in the GCC region must acknowledge several key challenges before leveraging potential opportunities. The ornamental horticulture industry, a significant economic force, often finds invasive species regulations economically burdensome, with research indicating that up to 47% of stakeholders resist measures that affect valuable species (Shackleton et al., 2019). The industry's extensive plant propagation, transportation, and sales channels further amplify invasion risks over time. Online marketplaces present additional complexity, as unregulated trade can rapidly spread alien plants across borders.

Nonetheless, promising market-based solutions can align economic incentives with conservation goals. Certification systems for invasive-free nurseries and preferential procurement policies in government projects can reward compliance rather than relying solely on penalties. Supporting the industry's transition to non-invasive alternatives through compensation schemes, technical assistance for identifying native species, and marketing support can reduce resistance and foster collaboration. Finally, integrating oversight of plant production processes with targeted public outreach—such as labelling native-only plant kits or online awareness tools—can strengthen market transparency and engage consumers in the conservation effort. By balancing economic support with policy incentives, these measures can transform commercial motivations into drivers of sustainable greening and biodiversity protection.

6 Conclusion

The Middle East region, particularly KSA, is witnessing increased environmental, landscaping, and greening initiatives.

While planting efforts are generally well-received, they also increase the risk of introducing, establishing, and spreading invasive species.

This article advocates for detailed cross-boundary research, policy-making, and invasive species management, especially across the Arabian Peninsula. While we use alien invasive plant species in KSA as an example, we recommend that future discussions include invasive animal species, which often exacerbate plant invasions and threaten native ecosystems. Secondary invasions, where one invasive species facilitates the establishment of others, highlight the interconnected challenges. Addressing these dynamics through an interdisciplinary, sustainability-driven approach will ensure comprehensive solutions that leverage research and technology to protect biodiversity, agricultural capacity, and long-term ecological resilience.

Addressing biological invasions has become more pressing in the face of escalating climate challenges. Mitigation and proactive measures today can prevent the compounding impacts of these invasions on ecosystems, economies, and communities tomorrow.

Species Distribution Modelling.

We assessed the potential distribution of 63 terrestrial invasive plants in Saudi Arabia using the presence/pseudoabsence model MAXENT (Elith et al., 2011). MAXENT, or Maximum Entropy modelling, assumes that presence data accurately represent the species' ecological niche and that the chosen environmental variables are suitable for species distribution (Phillips et al., 2006). It also assumes that the background points represent the environmental conditions across the study area. A key caveat is that MAXENT does not explicitly model species absences, which can lead to overestimating suitable habitats if presence records are biased or incomplete (Elith et al., 2011). Additionally, the model's performance is highly dependent on the quality and resolution of input data and may be sensitive to sample size and geographic extent (Merow et al., 2013). Potential issues such as spatial autocorrelation and sampling bias must be carefully addressed to ensure robust predictions.

For this study, we acquired global occurrence records for the 63 invasive species, totaling 2,393,411 records, from GBIF (GBIF.org, 2024). After removing synonyms, duplicate entries, absence records, and records with missing or erroneous location data, 1,188,272 records remained. We further refined the data by thinning it to include only one record per 1 km² grid cell ($n = 702,762$).

Environmental variables used in our model included soil parameters and climatic factors. Soil data (bulk soil density in g/cm³, clay content percentage, pH CaCl₂, and organic carbon percentage) were obtained from SoilGrids250m (Hengl et al., 2017), a global gridded soil information system providing predictions at 250-m spatial resolution for seven standard depths. Climatic variables (annual mean temperature, maximum temperature of the warmest month, mean annual precipitation, precipitation of the warmest quarter, precipitation of the coldest quarter) were derived from WorldClim Version 2 (Fick and Hijmans, 2017), which provides spatially interpolated monthly climate data at approximately 1-km resolution for the period 1970–2000. Bioclim variables that are reflective of the average

(annual mean temperature and precipitation), extreme (mean temperature of the warmest and coldest quarter, precipitation of the wettest and driest quarter), and variability (temperature and precipitation seasonality) of hydrothermal conditions. These climate variables are considered relevant to the ecology of plant species and have been widely used in modelling their distributions (Hijmans and Graham, 2006; Nuñez and Medley, 2011; Webber et al., 2011). We reserved 20% of the records as testing data and generated 10,000 background records for the modelling process. The species distribution model utilized native and invaded range occurrence data to predict potential distributions within the region of interest. We determined the highest threshold at which the sum of the sensitivity (true positive rate) and specificity (true negative rate) was highest to convert the generated probability maps into binary distribution maps. Additionally, we reported the Area Under the Curve (AUC) values, variable correlations, and relative coverage within Saudi Arabia.

While the generic risk analysis conducted in this study provides valuable insights into the potential distribution of invasive plants in Saudi Arabia, several limitations and areas for improvement should be noted:

This analysis used the same set of environmental variables across ecologically diverse taxa. Although this approach provides a broad overview, it may not capture the specific habitat requirements of each species. Tailoring the selection of environmental variables to the individual species' ecological requirements could significantly enhance the accuracy of the models.

The quality of the species distribution model is highly dependent on the accuracy and completeness of the occurrence data. In our study, we sourced global occurrence records from GBIF, but these records may not fully represent the current distribution within Saudi Arabia. Reviewing and validating these data, as well as mobilizing additional data sources specific to observations within Saudi Arabia, could improve model performance. Local datasets, herbarium records, and citizen science contributions could provide more precise and up-to-date information. Furthermore, the sensitivity of MAXENT to sample size and geographic extent is another critical factor. Small sample sizes or restricted geographic ranges can lead to overfitting or underprediction of suitable habitats.

The presence records used in MAXENT models can be subject to spatial autocorrelation and sampling bias, which can affect the predictions. Spatial autocorrelation occurs when presence records are not independent, leading to overestimation of suitable habitats. Similarly, sampling bias, where certain areas are more heavily sampled than others, can skew the results. Implementing methods to address these issues, such as spatial thinning of records or incorporating bias correction techniques, would enhance the robustness of the predictions.

The conversion of probability maps into binary distribution maps is a crucial step that involves selecting a threshold value. The chosen threshold can significantly impact the reported distribution of suitable habitats. Although we used the highest threshold at

which the sum of sensitivity and specificity is maximized, exploring alternative thresholding methods and validating them with independent datasets would provide more robust results.

By addressing these caveats, future studies targeting single species based on their ecology will improve the precision and reliability of species distribution models. This would involve a more nuanced approach to variable selection, enhanced data quality from local sources, and the application of advanced statistical methods to correct for biases and improve model validation. Such improvements will contribute to more effective management and conservation strategies for invasive species in Saudi Arabia.

Species occurrence data.

Below is a summary of the global species occurrence data used on the exemplary species distribution model (GBIF.org, 2024).

Online Availability Analysis Method.

These findings were uncovered through a comprehensive web-scraping exercise designed to assess the online availability of invasive plant species in Saudi Arabia. The methodology employed automated data collection techniques using Python-based web scraping tools to systematically search e-commerce platforms for species regulated in Saudi Arabia. Before web scraping, the species list was first matched to the GBIF backbone taxonomy to produce consistent naming conventions and obtain standardized common names, ensuring taxonomic accuracy and comprehensive coverage of alternative nomenclature. The approach utilized Selenium WebDriver with Chrome browser automation to navigate Amazon's Saudi Arabian domain (amazon.sa) and extract product availability data, ensuring that results reflected actual accessibility to Saudi consumers rather than international shipping limitations.

For each species, the script executed targeted searches using botanical nomenclature (genus and species names), common English names, Arabic common names, and hybrid species designations, employing regex pattern matching with the expression `'([A-Za-z]+(?:\s|x)?[A-Za-z]+)'` to accurately identify species names. Search terms were systematically formatted and URL-encoded for Amazon's search interface using the pattern `'https://www.amazon.sa/s?k={species_name}&language=en'`, ensuring comprehensive coverage of potential product listings.

The data extraction framework employed multiple CSS selectors and XPath expressions to capture product titles, descriptions, URLs, availability status, pricing information, seller details, and delivery options. To ensure reliable data collection and avoid detection by anti-bot systems, the methodology incorporated randomized delay intervals between requests, headless browser operation, user-agent rotation, browser fingerprint masking, automated captcha solving capabilities, and robust error handling with retry mechanisms for failed requests. The approach also included comprehensive data validation and quality control measures, such as duplicate detection and removal based on URL and product characteristics, manual verification of random samples, and exclusion of non-plant products (e.g., books or medical items) through keyword filtering.

The web scraping was conducted over multiple sampling rounds to account for seasonal variations in product availability and to capture the dynamic nature of online marketplaces. The

methodology adhered to Amazon's robots.txt guidelines and implemented rate limiting to minimize server load, with all data collection conducted for academic research purposes, focusing solely on publicly available product information. While acknowledging limitations such as potential gaps in search algorithm coverage, rapidly changing product availability, alternative species naming conventions, and inability to verify actual compliance with Saudi Arabian import regulations at the point of sale, this systematic approach revealed the continued availability of invasive species through online channels despite existing legal restrictions, highlighting potential gaps in enforcement of invasive species regulations in the digital marketplace.

Author contributions

PR: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. GA-K: Investigation, Methodology, Resources, Writing – review & editing. YR: Supervision, Validation, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fevo.2025.1621445/full#supplementary-material>

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