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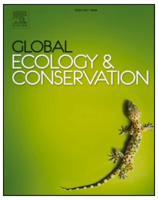

Original research article

# Spatialising the ecological impacts of alien species into risk maps

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## ARTICLE INFO

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## ABSTRACT

Spatial assessments of the ecological impacts of alien species are needed to integrate impacts into biodiversity conservation policies and management strategies. We developed standardised approaches for aggregating impact scores at both species and site levels, synthesising the ecological impacts of alien species into risk maps. We applied these approaches to 33 Australian *Acacia* species introduced in South Africa. Creating risk maps involves four main steps: (1) perform impact assessment per species; (2) combine impact categories into one score per species; (3) gather species occurrence data into standardised grid cells; and (4) combine impact scores across species per grid cell into a risk map. We proposed six risk maps based on different assumptions of impact aggregation. All risk maps revealed important variation in environmental impacts of alien *Acacia* species across South Africa. The only exception was the precautionary risk map, which indicated that nearly all the areas occupied by *Acacia* had high risk, whereas the other risk maps identified between 5 % and 14 % with high risk. Risk maps provide additional information compared to maps of alien species richness and can help identifying areas where greater ecological impacts are likely. The approaches for risk maps can be applied to any taxon with available data on their distribution and ecological impacts. Our approach can be used to identify and prioritise sites with potential high impact. Based on the future risk map, we suggest five management strategies to limit the expansion of impactful species, of for clearing impactful species.

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## 1. Introduction

The rate of introductions of alien species outside their natural range is rapidly increasing and represents one of the most important factors in the decline of native biodiversity (Johnson et al., 2017). Alien species can negatively modify the structure and functions of ecological communities and have direct and indirect impacts on economy and human health (Pyšek et al., 2020a; Roy et al., 2024). When these impacts occur, alien species are referred to as "invasive alien species" (IPBES et al., 2023). The recent global assessment report on biodiversity and ecosystem services, conducted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES et al., 2019), identified invasive alien species as the fifth direct driver of changes in biodiversity, with significant global impacts on natural ecosystems and ecological communities. The impacts on native species result from various mechanisms, such as competition for resources, change in habitat structure, hybridisation, transmission of disease, and predation (Levine et al., 2003; Pyšek et al., 2020a). Given the large and growing number of invasive alien species, signatories of the Convention on Biological Diversity (CBD) are committed to monitoring the status of biodiversity and improving the protection of natural resources under the Kunming-Montreal Global Biodiversity Framework (GBF) (Convention on Biological Diversity CBD, 2022). Target 1 aims at planning and managing all areas to reduce biodiversity loss while Target 6 aims at minimising the negative impacts of invasive alien species (Convention on Biological Diversity CBD, 2022). To achieve these targets, managers need to choose carefully where to concentrate their efforts (Forner et al., 2022).

Strategies to support decisions for the management of biological invasions include: (i) the prioritisation of alien species by identifying the most impactful species and/or the most abundant alien species; (ii) the prioritisation of sites by identifying the most impacted areas; sites of high conservation value and/or by identifying areas of potential future invasions; and (iii) the prioritisation of introduction pathways (e.g. Hulme et al., 2013; Leung et al., 2012; van Wilgen et al., 2011). Impact assessment tools, such as the Environmental Impact Classification for Alien Taxa (EICAT) or the Generic Impact Scoring System (GISS), play a crucial role in managing the impact of invasive alien species (Blackburn et al., 2014; IUCN, 2020a, 2020b; Nentwig et al., 2010). These tools aid in prioritising and/or ranking species according to their ecological impacts (Vilà et al., 2019).

Impact categories and ranking are not intrinsically quantitative, compared to e.g., invasion cost, which can be directly added and compared across taxa (Haubrock et al., 2021). Several ways of quantifying impact scores have been proposed to date (Table 1). Many studies have used the maximum score across all categories to represent the potential impact, which can be considered a precautionary measure (Blackburn et al., 2014; IUCN, 2020b; Kumschick et al., 2024). Other studies have used a range of metrics such as the arithmetic sum, the logarithmic sum, or the mean of impact scores (e.g., Hagen and Kumschick, 2018; Rumlerová et al., 2016; Sohrabi et al., 2021; Yazlik et al., 2018).

For site-based prioritisation, spatial assessments of ecological impacts are needed which require the aggregation of species impact data taking into account the species distribution. Although such spatial assessments are needed to effectively integrate impact data into biodiversity conservation policies and spatial management strategies (Dick et al., 2017; Katsanevakis et al., 2016), limited attention has been given to the methods for spatially aggregating ecological impacts. Different models and indicators were developed to track the impacts of alien species, and to support management efforts. For instance, a conservative additive model was developed to map the cumulative impacts of invasive alien species on marine ecosystems (Cumulative IMpacts of invasive ALien species (CIMPAL), Katsanevakis et al., 2016). Henriksen et al. (2024) developed potential and realised impact indicators, aiming at mapping the distribution of impacts on biodiversity, the mechanisms driving these impacts and the number of most impacting species (i.e., *harmful invaders* following EICAT terminology). Kumschick et al. (2025) modelled the potential distribution and potential impact under climate change scenarios of *Acacia* species alien to South Africa. However, there is no standardised approaches to quantify the impact of co-occurring species and to develop risk maps which can be used to prioritise sites.

In this study, we developed different approaches to generate reproducible risk maps. We propose several metrics to combine multiple impacts within and across species and explain the assumptions behind their calculations. Here, risk maps are defined as the spatial representation of potential ecological impacts of alien species in areas where they are currently present. Using EICAT, the IUCN standard for impact classification (IUCN 2020a, 2020b), we project the potential impacts of different alien species onto risk maps. As a case study, we examine Australian *Acacia* species introduced in South Africa to explore the different approaches assessed in this study (Botella et al., 2023; Jansen and Kumschick, 2022). Additionally, we generated a future risk map based on the potential distribution of *Acacia* species to identify areas that could be at risk if *Acacia* species were to expand beyond their current ranges, and proposed management strategies for selected areas of South Africa.

## 2. Materials and methods

### 2.1. General approach

Ecological impacts of alien species can be aggregated at two different scales: Firstly, "*within species*" refers to the species-level aggregation which combines all recorded impact mechanisms per species. This method is useful to compare impacts between different species. Secondly, "*across species*" refers to the site-level aggregation which combines the multiple impacts of all species co-occurring at a given site. This method is useful to compare and prioritise sites (McGeoch et al., 2016).

To generate risk maps, we developed a step-by-step approach where we integrate potential impacts of alien species with their distribution (Fig. 1 and Fig. 2). It consists of the following 4 steps: (1) perform impact assessment per species; (2) combine impact categories into one score per species; (3) gather species occurrence data into standardised grid cells; and (4) combine impact scores across species per grid cell into a risk map (Fig. 1).

**Table 1**

Metrics used in the literature to combine the impact score within species (Fig. 1 – Step 2). The calculation, assumptions, and potential issues are presented for each metric. In this study, four metrics were used: maximum, sum of the maximum scores per species, mean, and weighted mean (Fig. 2 – Step 2). The “References (e.g.)” column includes studies that propose or use the metric. See Table A2 for different ways of assigning numerical value to each impact category. Nb: number; Obs.: observation.

| Metrics and calculation | Assumptions | Issues | References (e.g.) |
|---|---|---|---|
| Maximum<br>= Max (all impact score) | Highest impact across all mechanisms as a precautionary measure. The species has (or had) this impact somewhere, so it could have it elsewhere, too. | The maximum could be an outlier or dependent on very specific conditions. There may be little variation between the species impacts as it is essentially one of five potential values. A significant portion of available information about the impact of an alien species, especially the variation in impact magnitudes, is ignored in this approach. | Blackburn et al. (2014); D’hondt et al. (2015); Hagen and Kumschick (2018); IUCN (2020b); Kesner and Kumschick (2018); Nentwig et al., (2018); Sohrabi et al. (2021) |
| Median<br>= Median (all impact score) | The median accounts for the range in impacts recorded. It represents the central tendency of the impact distribution, which assumes that the median provides a representative measure of the impact of the invasive alien species (Witte and Witte, 2017). | The median can underestimate the overall impact, potentially resulting in a lack of representativeness for observed impacts diversity. Additionally, the median is sensitive to sample size, where small variations in impact scores can cause a notable shift in the median score. | Kesner and Kumschick (2018) |
| Mean<br>= $\mu$ (all impact score) | Takes into account the number of times a certain impact level was recorded. For example, if a low impact level was recorded most of the time, but a high impact level a few times, this species has a lower probability of scoring a high impact than a species which consistently scored high impacts. | The mean can underestimate the overall impact as there are often a limited number of high impact records as it is costly to gather such data | D’hondt et al. (2015) |
| Frequency of the highest impact (maximal impact)<br>= Nb of regions where the species caused its *max* impact / Total nb of regions where the species is observed | Gives the frequency (as a proportion) at which a species’ introduced populations caused its highest impact. Allows to distinguish between alien species that systematically cause their highest impact magnitude when introduced to a novel environment from alien species that only occasionally cause their highest impact magnitude. | The frequency does not account for differences in ‘sampling effort’ between species. For example, a species widely introduced and having caused harmful impacts every time it has been introduced would not be differentiated from a species introduced once and having caused harmful impacts. Furthermore, regions will have to be defined consistently for this approach to work across taxa. | Volery et al. (2021) |
| Frequency of the highest impact level *i* for a species<br>= Number of impact categories in which the species has impact level *i* | A species with several high level of impact (e.g., a score of 4) in different impact categories could be considered more problematic than a species with only moderate scores.<br>If a species frequently has a high level of impact (e.g., a score of 4) in different categories, this suggests that its impact is systematically harmful. | Species that have been studied more often may be more likely to have high scores documented in several categories, creating a bias towards species that are already well known, while less-studied or more recently introduced species could be underestimated. | Nentwig et al. (2018) |
| Sum of the maximum scores per mechanism *j*<br>$= \sum (\max(\text{score of mechanism } j))$ | The sum takes into account the number of different impact mechanisms a species can cause impacts through. Species with a greater variety of impact types (mechanisms) have a higher potential to cause impacts elsewhere, resulting in a higher sum. | Equal weighting for all mechanisms is assumed when summing up the maximum impacts. However, not all impact mechanisms may be equally important ecologically. Assigning equal weight to each mechanism may not accurately reflect their relative significance. Furthermore, it assumes that impacts across categories are additive, and that for example 2 times a MN impact (1) equals a MO impact (2). | Kumschick et al. (2015a); Nentwig et al. (2010) |
| Logarithmic sum of the maximum score per mechanism *j*<br>$= \log_{10}(\sum (10\hat{\ }\max(\text{score of mechanism } j)))$ | Logarithmic sum can be used to reflect the exponential nature of the gradual increase in the categories, when individual levels of impact are of different orders of magnitude | Equal weighting is assumed when summing up the maximum impacts. However, not all impact mechanisms may be equally important ecologically. Assigning equal weight to each mechanism may not accurately reflect their relative significance. | Rumlerová et al. (2016); Yazlik et al. (2018) |

Step 1 first involves the collation of impact information for each species into standardised categories (Fig. 1). Different scoring systems can be used, such as EICAT (IUCN, 2020a, 2020b) or GISS (Nentwig et al., 2016). These systems rely on potential impact scores based on observed impacts recorded somewhere in the world. Then, impact categories need to be converted into numerical values (Fig. 2). Several approaches have been used for this purpose in the literature, as the linear, and the exponential approach (e.g., Copp et al., 2009; Kumschick et al., 2015a; Jansen and Kumschick, 2022; Ricciardi and Cohen, 2007; Rumlerová et al., 2016; Laverty et al., 2015).

Step 2 combines impact score at the species level (aggregation within species; Fig. 1) based on four existing metrics used in previous studies: the maximum impact score across all impact categories (Blackburn et al., 2014; IUCN, 2020a, 2020b), the sum across the maximum impact score per mechanisms (Kumschick et al., 2015; Nentwig et al., 2010), the mean impact score across all impact categories, and the weighted mean (D'hondt et al., 2015; Katsanevakis et al., 2016; Fig. 2). Other metrics have been used in the literature to combine impact scores within species, each with their own assumptions (Kesner and Kumschick, 2018; Volery et al., 2021; Nentwig et al., 2018; Rumlerová et al., 2016; Yazlik et al., 2018). For a comprehensive description of the assumptions and issues of each metrics, refer to Table 1.

Step 3 gathers species occurrence data into standardised grid cells (Fig. 1). For risk maps, these could consist of occurrence data representing the current species distribution which can be obtained from international databases (e.g., the Global Biodiversity Information Facility (GBIF) and iNaturalist), herbarium data, or field studies. For future risk maps, potential distribution data (obtained from species distribution models) can be used. Finally, the study area is divided into standardised grid cells, and each species occurrence is linked to a unique cell ID corresponding to the grid cell where it was recorded.

Step 4 combines impact scores across species per grid cell into a risk map (aggregation across species; Fig. 1). The resulting risk map refers to potential, not realised, impacts within the study area. We assigned each grid cell occupied by an alien species its respective impact score. If several species were present in the same grid cell, the overall impact score is calculated (Fig. 2). Different metrics can be used to combine impact across species, such as the maximum, the sum, or the mean. For a comprehensive description of the assumptions and issues of each metrics, refer to Table 2.

For each of the calculations within and across species (Tables 1 and 2), the different basic assumptions on the individual categories can be made, which changes the final numbers.

### *2.2. Case study*

We selected the Australian *Acacia* species belonging to the Family Fabaceae, which were introduced into South Africa (Magona et al., 2018). This selection included 33 *Acacia* species whose ecological impacts have been assessed using EICAT (Jansen and Kumschick, 2022; Table A1) and whose distribution within South Africa has been well documented (Botella et al., 2023).

#### *2.2.1. Step 1: perform EICAT assessment for each alien Acacia species*

EICAT is a standardised method adopted by the IUCN (IUCN, 2020b) for ranking alien taxa based on their environmental impact (Blackburn et al., 2014; Hawkins et al., 2015; IUCN, 2020a, 2020b; Volery et al., 2021). Alien taxa are classified into different impact categories based on reports of impact in the literature, from Minimal Concern (MC) to Massive (MV), depending on the magnitude of impact. Additionally, the mechanisms by which impact occurs are noted. EICAT has defined 12 different impact mechanisms such as competition, structural change to the ecosystem, and predation (IUCN, 2020a, 2020b). Species with no impact (MC) are distinguished from those for which there is insufficient evidence to assess impact, the latter being classified as Data Deficient (DD). EICAT uses a confidence rating system to quantify the probability of the assessment being correct, assigning a confidence level of low, medium, or high based on the reliability of the source, the scale of the study, and other factors (Probert et al., 2020; IUCN, 2020a, 2020b). A high confidence level signifies that the assessor is confident the assigned magnitude is the true one, a medium confidence level indicates that the actual magnitude may differ from the assigned category, while a low confidence level indicates that it is likely that the true magnitude is different from the assigned one (the magnitude of impact could be higher or lower than the assigned category).

Among the 33 *Acacia* species assessed, 22 were classified as Data Deficient (DD), meaning no impact data was found in the literature search [see Jansen and Kumschick (2022) for further explanation]. For each individual impact observation found in the literature (i.e., each record describing a specific impact caused by a species), we recorded each mechanism as a separate entry in our database, even if several mechanisms are possible for the same impact record.

We used non-aggregated data as a starting point, which consists of separate impact categories for each record with associated mechanisms and confidence scores. With this approach, each species can have multiple impact scores, as each impact record was separately scored according to the type of impact mechanisms and the region in which the impact occurs (Fig. 2 – Step 1; Kumschick et al., 2020).

We transformed the impact categories into linear values as follows: Minimal Concern (MC) = 0, Minor (MN) = 1, Moderate (MO) = 2, Major (MR) = 3, Massive (MV) = 4; Data Deficient (DD) entries were assigned as NA and were excluded from the analysis. Although different ways of transforming impacts into numerical values exist (Table A2), we chose the linear approach as this is the most commonly-used one (e.g., Jansen and Kumschick, 2022; Kumschick et al., 2017; Laverty et al., 2015; Ricciardi and Cohen, 2007; van der Veer & Nentwig, 2015). We set the value for Minimal Concern (MC) to 0, as it best fits the definition of this category in EICAT; i.e., "no impact on native species performance was found" (IUCN, 2020a, 2020b).

#### *2.2.2. Step 2: combine impact score within species*

For each *Acacia* species, we calculated the global impact score by using four existing metrics: the maximum score, the sum of maximum score per mechanism, the mean score and the weighted mean score (Fig. 2 – Step 2; Tables 1 and 2). To calculate the weighted mean, we weighted the impact based on the assigned confidence representing the probability that the assigned category was the correct one, as suggested by IUCN guidelines (IUCN, 2020a). For example, for a record with an impact category of Minor (MN = 1) with a confidence level of Medium, the probabilities were as follows: 0.66 for MN, 0.15 for MC, 0.18 for MO and 0.01 for MR. Therefore, the weighted impact score for this record would be 1.05 (see Table A3 for details of each impact category and confidence level).

The maximum score across all categories is a precautionary measure which aims to not under-estimate the potential impact (Laverty et al., 2015). This metric represents the highest recorded potential impact of a species in an invaded area - the overall species impact is assumed to be equivalent to the highest impact score recorded for that species across all mechanisms and all sites (Blackburn et al., 2014; IUCN, 2020b; Kumschick et al., 2024; Table 1). Summing up the maximum impact across all mechanisms assumes that impacts are additive between mechanisms, i.e., a high impact in several mechanisms is more severe than a high impact caused through only one mechanism. It represents a higher impact potential if a species can cause impacts through different mechanisms (Hagen and Kumschick, 2018; Kumschick and Nentwig, 2010; Nentwig et al., 2010). The mean score considers the frequency at which each impact level is recorded (D'hondt et al., 2015). For instance, if a low impact level is recorded most often, with only a few high impacts, the species is less likely to have a high overall impact compared to a species consistently recorded with high impacts. The weighted mean score considers the uncertainty in the impact category assigned to each species, based on the probability that the assessment is correct.

### 2.2.3. *Step 3: gather species occurrence data into standardised grid cells*

To produce actual distribution maps of each *Acacia* species alien in South Africa, we used the distribution data of Botella et al. (2023); (2022). We kept all records which had complete coordinates, which were tagged as "presence", and were located outside the native ranges of the species. Then, we filtered the occurrences to keep only *Acacia* present in South Africa. We divided South Africa into standardised quarter degree squares (QDS) grid cells.

In addition to these actual distribution maps, we also used the potential distribution of 30 *Acacia* species from Kumschick et al. (2025). The species distributions were modelled using global occurrence data from GBIF and four climatic variables (mean annual temperature, mean diurnal air temperature range, annual precipitation, and precipitation seasonality). Models were fitted using random forest classification and evaluated through spatial cross-validation (see Kumschick et al., 2025 for further information on the model). Three species (*A. crassiuscula, A. acuminata* and *A. koa)* were not modelled due to insufficient occurrence information (Kumschick et al., 2025). We divided South Africa into standardised grid cells of 4 km x 4 km, corresponding to the resolution of the potential distribution model. The potential species richness based on the predicted distributions was generated.

### 2.2.4. *Step 4: combine species impact score across species into a risk map*

We used the current distribution of *Acacia* species alien to South Africa to develop the different approaches for aggregating impact scores across species into risk maps. We used one of these approaches to generate a risk map with the potential distribution of *Acacia* species, referred to as the 'future risk map'.

We created risk maps with the current distribution of *Acacia* in South Africa based on six different combinations of aggregation (Table 2, and Fig. 2 – Step 4): (1) the precautionary risk map represents the highest impact score that a grid cell can have, it is the worst-case scenario; (2) the precautionary cumulative risk map also represent the highest impact score possible at a grid cell, but it consider the number of co-occurring species; (3) the cumulative risk map summarises the cumulative risk across species, offering a comprehensive view of the overall risk by considering the combined impact of multiple species. If one species had several impact scores per mechanism, we calculated the maximum (Nentwig et al., 2010); (4) the mean cumulative risk map balances the cumulative impact by considering the mean impact score across species, providing a nuanced perspective compared to the cumulative risk map; (5) the mean risk map takes into account the variability of the impact score within and across species; and (6) the weighted mean risk map takes into account the uncertainty of the impact category assigned to each species. Additionally, we generated a map of species richness of the genus *Acacia* (i.e., the number of *Acacia* species occurring in each grid cell) for comparison with the risk maps generated. The species richness was considered as the null approach since it did not include any measure of impact.

We used a correlation matrix to assess how similar the risk maps are between the different metrics used. We calculated the proportion (Prop) of grid cells having the two highest categories of impacts per risk map.

As an example of a potential application for management, we generated a mean cumulative future risk map (Table 2) with the potential distribution of the 30 *Acacia* in South Africa (Table A1).

All statistical analyses were performed using R version 4.3.1 software (R Core Team., 2023) and spatial analysis using QGIS version 3.34.2 (QGIS.org, 2024).

## 3. Results

### 3.1. *Current distribution*

The species richness maps showed three areas with the greatest number of *Acacia* species: the coastal strip of the Western Cape province (WC), Garden route – in the south coast of Western Cape (WC) and Eastern Cape (EC) provinces, and Gauteng province (GP) (Fig. 3).

All the risk maps, except for the precautionary one, showed important variation in *Acacia* impact throughout South Africa (Fig. 4). When mapping the impact with the precautionary approach, no variation in impact was observed due to the consistently high impact scores of most *Acacia* species (Fig. 4A, and Table A1 and A4). Concerning the other risk maps, three areas of South Africa emerged with the highest risk of *Acacia* species: two areas in the Western Cape province (WC) and one area in the east of Gauteng Province (GP) (Fig. 4). The cumulative map had the highest proportion of areas with the two highest impact categories (14 %), with areas located along the South coast (Fig. 4C). Mean and weighted mean risk maps highlighted different high-risk areas (Fig. 4E–F).

The cumulative, mean cumulative, and precautionary cumulative risk maps were highly correlated (Fig. 5). The weighted mean risk map showed the least correlation with the other risk maps, except with the mean risk maps. The species richness map, considered here as the null approach, was highly correlated to half of the risk maps: cumulative, mean cumulative, and precautionary cumulative risks maps (Fig. 5).

### 3.2. *Potential distribution*

The future mean cumulative risk map showed a higher overall impact compared to the current cumulative risk map (18.9 % vs 5.6 % of areas with the two highest impact categories) (Fig. 6A). We identified five possible management situations for either limiting the expansion or clearing impactful species (Fig. 6A): (1) areas where species with moderate impact are currently present, and which are suitable for highly impactful *Acacia* species; (2) areas where highly impactful species are already present; (3) areas where only a few species with low impact are currently present and which are suitable for highly impactful *Acacia* species; (4) areas where only a few species with low impact are currently present and which are suitable for moderately impactful *Acacia* species; and (5) areas not suitable for impactful or highly impactful species.

## 4. Discussion

Our results present different approaches to quantify the environmental impacts of alien *Acacia* species in South Africa and to estimate the spatial variation in their impacts, illustrated through risk maps. Our approach can be used to prioritise sites for management actions and mitigation measures. By aggregating the impacts of co-occurring species at the same location, it identifies areas having potential for the highest impact or climatically-suitable areas for species with high impact. This is particularly important as practitioners need to prioritise sites to concentrate efforts and resources to achieve the greatest ecological benefits. Our approach can also be used to prioritise species according to the importance of their impacts, by aggregating all recorded impacts at the species level.

Our approach aggregated impact scores per species, based on the global impact of alien species rather than their local impact. However, the impact of invasive alien species depends on the environments in which they occur (Hulme et al., 2013; Pyšek and Richardson, 2010) and EICAT assessments consider impact from any location within the global alien range (IUCN, 2020a, 2020b). For example, some impact mechanisms are context-specific, such as hybridisation, which generally depends on the native species co-occurring in the alien range (Hirsch et al., 2017; Pyšek et al., 2020b). Therefore, the maps produced reflect the potential impact due the aggregated impact rather than the realised impact.

Few published studies have explored how to spatially quantify alien species impact. Nentwig et al. (2010) have prioritised sites having the most species with the highest potential impact. Katsanevakis et al. (2016) have prioritised sites having the most species with the highest sum of impacts. While these previous studies focused on simple aggregation methods, we developed several approaches to combine the impact of alien species into risk maps, namely precautionary, cumulative and mean (Figs. 2 and 4; Table 2). The precautionary approach can prioritise sites with at least one species having a high impact. However, depending on the taxa studied and the context, the precautionary approach may not always be the most appropriate for site prioritisation. In our case study, the precautionary risk map did not show much variation throughout South Africa, as predominantly high ecological impact was recorded for *Acacia* species (Jansen and Kumschick, 2022; Fig. 4A). Therefore, this approach is not optimal to differentiate high-risk sites. The cumulative approach emphasises the different impact mechanisms of a species, as well as the respective magnitude of each impact. The cumulative approach allows capturing the combined impact across multiple mechanisms, which amplifies the overall magnitude of the impact compared to the maximum value of impact following EICAT protocols (i.e., value ranging from 0 to 4 – minimal concern to massive impact). Under this approach, the initial quantitative impact values (0−4) from the EICAT protocol no longer directly correspond to the impact category (Minimal Concern to Massive). Consequently, the resulting risk maps become decoupled from the standardised EICAT framework and can only be interpreted within the context of the case study. Furthermore, identifying the precise mechanisms causing an impact can be challenging (Clarke et al., 2021), resulting in ambiguity and possible double-counting of some impact reports. These limitations must be considered when using the cumulative approach to create risk maps, as not all impact mechanisms are equal or additive (Kuebbing et al., 2013). The mean approaches (mean cumulative, and weighted mean approach) consider the impact variability of a species. Each within species approach can be biased due to inherent difficulties in demonstrating impact of large magnitude (Measey et al., 2020), and limited data could lead to underestimation of the magnitude of impact (Kumschick et al., 2024).

Given the considerations outlined above, we suggest using the mean cumulative approach or the cumulative approach for alien *Acacia* species in South Africa. However, other approaches might be best suited elsewhere or for different taxa. Selecting a method depends on what assumptions are most appropriate for the situation at hand, but it is important to outline and specify the assumptions made in every case. To determine the strengths of the different approaches and ensure their robustness, it is crucial to test them on other case studies with diverse datasets or on simulated datasets (Weber et al., 2019). Our approach to map alien species impact is easily reproducible and can be applied to a wide range of taxa. Here we used EICAT categories as a measure of the ecological impact of species, but other measures of impact can be used, for example as assessed with different frameworks (Vilà et al., 2019). It is however important that impact assessment meet several criteria: transparency, clarity, user-friendliness, appropriate scope, scaling,

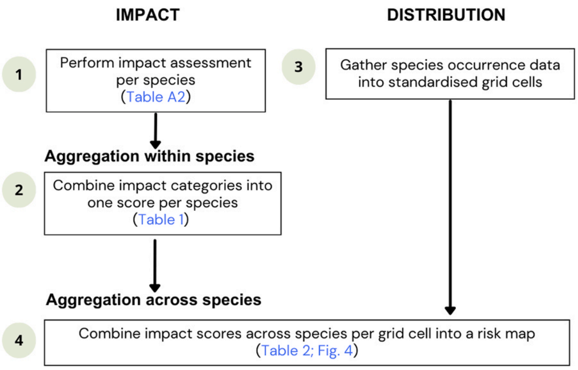
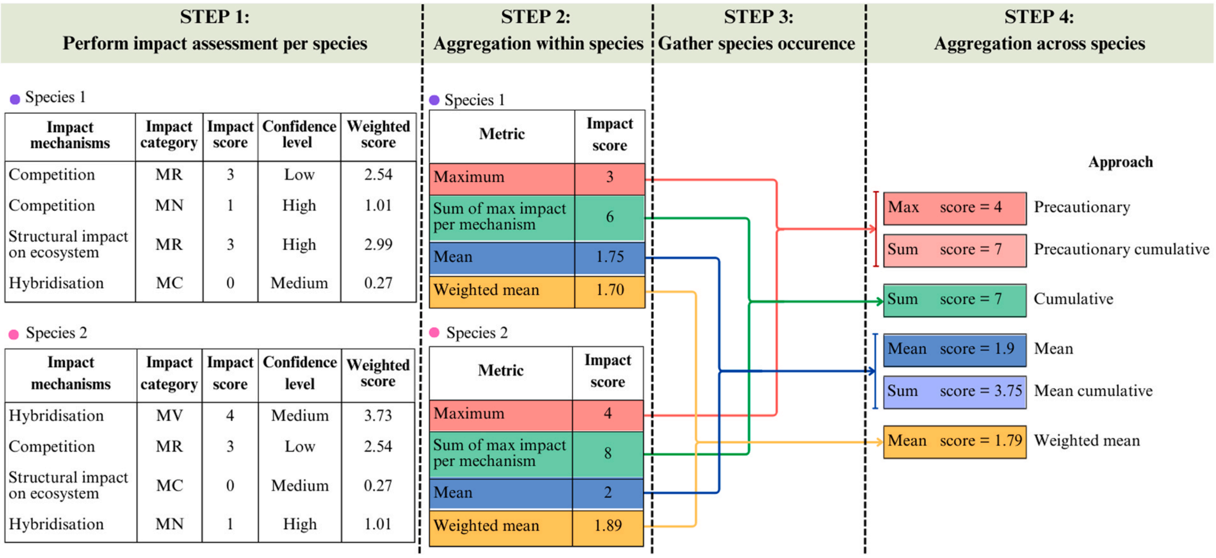


**Fig. 1.** Conceptual diagram of the development of risk maps for alien species.



Species 1

| Impact mechanisms | Impact category | Impact score | Confidence level | Weighted score |
|---|---|---|---|---|
| Competition | MR | 3 | Low | 2.54 |
| Competition | MN | 1 | High | 1.01 |
| Structural impact on ecosystem | MR | 3 | High | 2.99 |
| Hybridisation | MC | 0 | Medium | 0.27 |

Species 2

| Impact mechanisms | Impact category | Impact score | Confidence level | Weighted score |
|---|---|---|---|---|
| Hybridisation | MV | 4 | Medium | 3.73 |
| Competition | MR | 3 | Low | 2.54 |
| Structural impact on ecosystem | MC | 0 | Medium | 0.27 |
| Hybridisation | MN | 1 | High | 1.01 |

Species 1

| Metric | Impact score |
|---|---|
| Maximum | 3 |
| Sum of max impact per mechanism | 6 |
| Mean | 1.75 |
| Weighted mean | 1.70 |

Species 2

| Metric | Impact score |
|---|---|
| Maximum | 4 |
| Sum of max impact per mechanism | 8 |
| Mean | 2 |
| Weighted mean | 1.89 |

| | | Approach |
|---|---|---|
| Max | score = 4 | Precautionary |
| Sum | score = 7 | Precautionary cumulative |
| Sum | score = 7 | Cumulative |
| Mean | score = 1.9 | Mean |
| Sum | score = 3.75 | Mean cumulative |
| Mean | score = 1.79 | Weighted mean |

**Fig. 2.** Explanation of the four steps used to generate risk maps (Fig. 1). Here we showed an example of two co-occurring species with four different impact categories, based on the EICAT assessment (Blackburn et al., 2011). In step 1, a numerical value is assigned to each impact category: Minimal Concern (MC) = 0, Minor (MN) = 1, Moderate (MO) = 2, Major (MR) = 3, Massive (MV) = 4. In step 2, we used four metrics to calculate the impact score for each species. The weighted mean takes into account the probabilities that the assigned category is correct (see weighted score of step 1) as proposed by IUCN (2020a). In step 3, the occurrences of both co-occurring species are gathered into standardised grid cells. In step 4, the overall impact score for both co-occurring species is calculated according to three different metrics (maximum, sum, or mean). According to the metric used to aggregate impact scores within and across species, six different approaches are possible to generate risk maps (See Table 2 for a more detailed description of the metrics used for each approach).

reproducibility and flexibility (Vilà et al., 2019). Currently, standardised global impact assessments (e.g., EICAT) remain lacking for most taxa, and similarly, at country level, systematic assessments and reporting of impact mechanisms and impact categories are generally limited. Due to this data limitation, scores could be derived by expert opinion. However, regardless of the measure used, it should be made transparent how the data was derived and which calculations were selected. In our case study we used the current and potential distributions of the alien species to produce the maps, but the potential distribution of alien species under different scenarios of climate change can be used to produce the risk maps (Kumschick et al., 2025), as climate change can affect the invasion of alien species and their distribution (Bellard et al., 2013; Walther et al., 2009).

The approaches developed in this study could also be used as indicators to track progress of actions towards reducing alien species impacts. Target 6 of the Kunming-Montreal GBF aims to minimise, reduce, eliminate or mitigate the impact of alien species on biodiversity and ecosystem services, and to track progress within a Theory of Change framework (Convention on Biological Diversity CBD, 2022). However, few indicators are available in the literature. The indicators proposed so far focus on rate of spread of alien species, and their impact risk (Henriksen et al., 2024; McGeoch et al., 2021). The impact risk indicator prioritises impacts and sites to eliminate or reduce these impacts (Henriksen et al., 2024; McGeoch et al., 2021). The overall impact of co-occurring species at the site level determines the consequence of invasion for local biodiversity (Lenda et al., 2019; McGrannachan and McGeoch, 2019). Henriksen et al. (2024) proposed a multi-species and spatially explicit approach to monitor alien species impact over time. Similarly, here we suggest combining quantitatively multiple impacts across species in a spatially-explicit manner, specifically outlining assumptions for each approach. Our measures capture information on both taxonomic and geographic variability in environmental impacts and can be recalculated over time to support the monitoring of change relevant to alien species and their impacts. Our proposed approaches fulfil seven of the eight criteria for scientific validity and policy relevance of indicators according to Vicente et al. (2022): 1. providing information that can be linked to a specific spatial location ("spatially explicit"); 2. the indicator can be scaled up (e.g., international level) or down (e.g. site-level) ("scalable"); 3. including a temporal dimension ("temporal"); 4. reporting at least one measure of uncertainty regarding alien species information ("uncertainty appraising"); 5. the indicator can be applied to any taxa ("taxonomically representative"); 6. the indicator has been calculated using specific data on alien species, rather than proxy data ("alien species specific"); and 7. data for the indicator is publicly available and accessible, along with calculation indications ("reproducible"). The only remaining criterion relates to the indicator being established, in other words tested and implemented in a wide range of context (Vicente et al., 2022).

The approaches developed here can be used to inform management in two ways: (i) at the species level (aggregation within species), measuring the overall impact of a single species can be used to prioritise management of species with high impact (Zavaleta et al., 2001; Wilson et al., 2018); and (ii) at a site level (aggregation across species), we measured the overall impact of co-occurring species at a given site, which can be used to identify and prioritise sites with high risk of impact (McGeoch et al., 2021). Together with other criteria, such as protection status, biodiversity importance, or introduction pathways, this approach can help prioritising management in protected or high-level biodiversity sites with high risk of environmental impact (Katsanevakis et al., 2016; McGeoch et al., 2016). Sensitive sites may include areas with high conservation status, functional importance, or the presence of threatened or vulnerable taxa (Keith et al., 2013; Tu, 2009; McGeoch et al., 2016). As such assessments are based on updated distribution records and species impact assessment, we recommend increasing efforts towards assessment of alien species distribution and spread, and

**Table 2**

Presentation of the metrics to combine impact score within (Fig. 1 – Step 2) and across species to create risk maps (Fig. 1 – Step 4) with the hypothesis and calculation for each metric combination. Here we give only the assumption and the issues for the metrics across species. For the metrics within species, refer to Table 1. $i$ refers to one species; $j$, one mechanism; $c$, one impact category; $n$ is the total number of species; $m$ is the total number of mechanisms; $ti$ is the total number of impact categories for species $i$; $Pic$ refer to the probability that the assigned impact category is correct, considering the confidence level (Table A3), for impact category $c$ and species $I$ (give the weighted score per record, Table A3); and $score(ic)$ refers to the numerical score of impact category $c$ of species $i$.

| **Scores** | | **Approach names** | **Formula** | **Assumption across species** | **Issues across species** |
|---|---|---|---|---|---|
| **Within species** | **Across species** | | | | |
| Max | Max | Precautionary | $= ((score_{ic})\quad)$ | The maximum gives the highest impact score among species. Regardless of the number of high impact records or highly impacting species, if there is at least one high impact, this will show as high impact. | The precautionary approach does not consider any variability of impact among species. |
| Max | Sum | Precautionary cumulative | $= \sum_{i=1}^{n} \max_{c=1}^{t_i} (score_{ic})$ | Summing the impact across species assumes that the presence of more species leads to a higher overall impact. Additionally, if more species with significant impacts are present, the likelihood of any of these impacts occurring at the site increases. | The impacts of alien species are not necessarily additive. For example, it might not matter if one or more species with a high impact is present, the resulting impact could be the same. |
| Sum of max impact score across mechanism | Sum | Cumulative | $= \sum_{i=1}^{n} \sum_{j=1}^{m} \max_{c=1}^{t_i} (score_{ijc})$ | Considers the number of impact mechanisms a species can have. The more different impact mechanisms the species has, the higher the impact score will be. | Same as above |
| Mean | Sum | Mean cumulative | $= \sum_{i=1}^{n} \left( \frac{1}{t_i} \sum_{c=1}^{t_i} score_{ic} \right)$ | Assumes that the presence of a greater number of species results in a higher overall impact, while considering the impact variability of each species. | Same as above |
| Mean | Mean | Mean | $= \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{n} \sum score_{ic} \right)$ | The mean across and within species allows to balance between the number of species and the impact level. This reflects the potential variability of impact at a species and site level. | Impacts across species could be additive and the mean value could underestimate the overall impact. |
| Weighted mean | Mean | Weighted mean | $= \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{t_i} \sum_{c=1}^{t_i} (score_{ic} \cdot P_{ic}) \right)$ | The weighted mean has the same assumption as the mean approach but highlights records with a high confidence level. | Higher confidence levels do not necessarily represent higher impacts. |

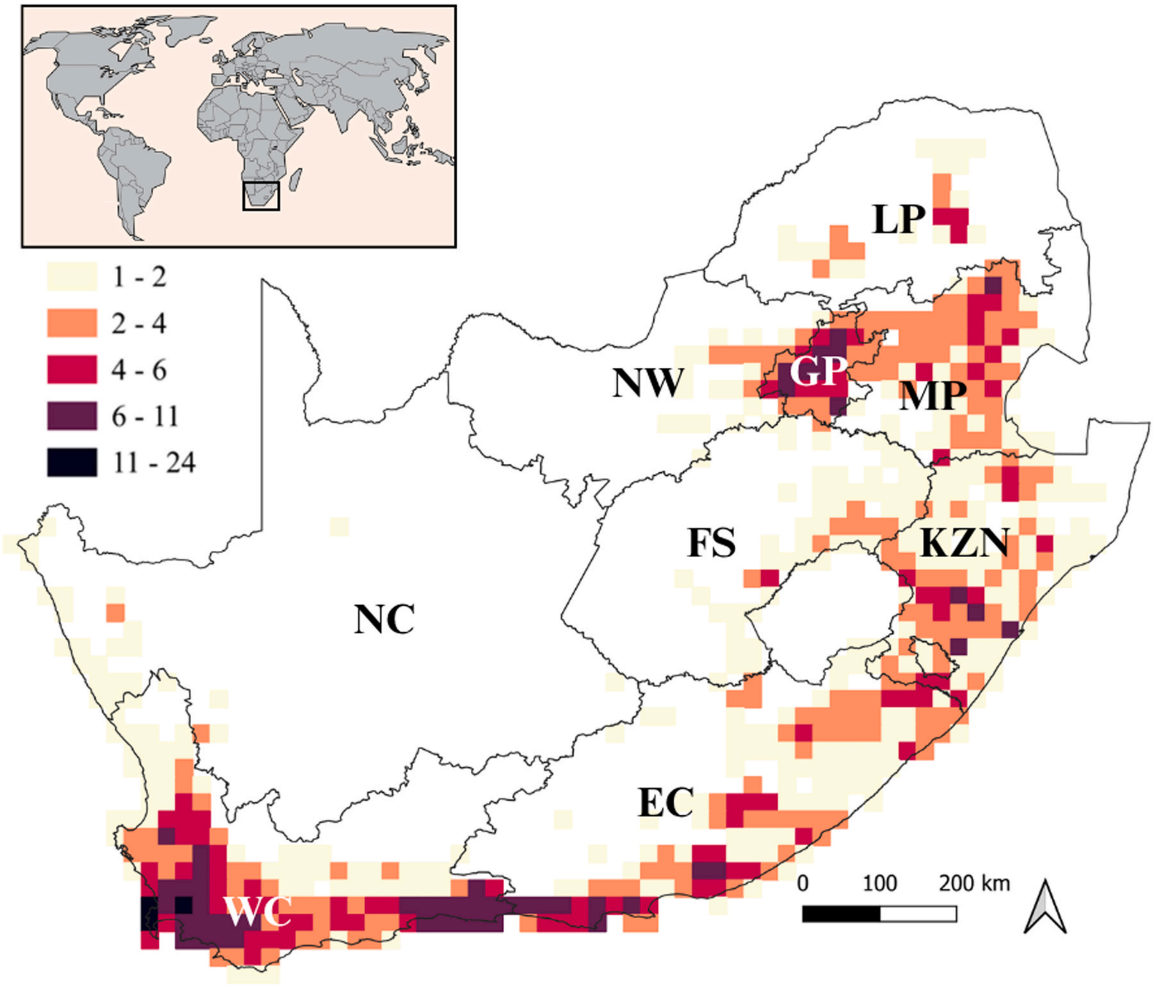


**Fig. 3.** Localisation of South Africa and map of the species richness of alien *Acacia* species at the country scale; the colour gradient represents the number of *Acacia* species present per quarter degree square (QDS); the acronyms represent the provinces: Limpopo (LP), North-West Province (NW), Gauteng (GP), Mpumalanga (MP), Northern Cape (NC), Free State (FS), Kwazulu-Natal (KZN), Western Cape (WC), and Eastern Cape (EC).

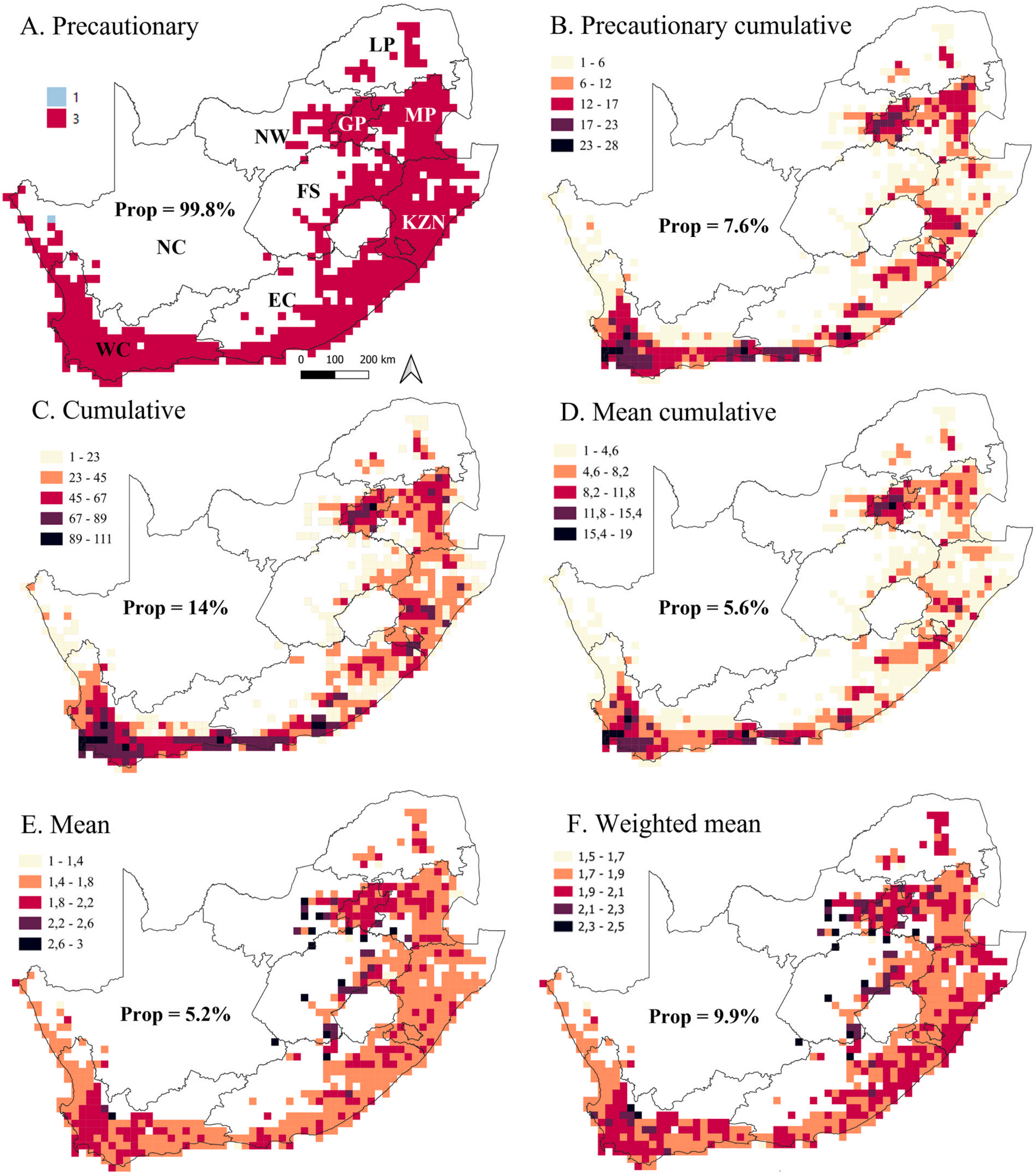


**Fig. 4.** Risk maps of 11 assessed alien *Acacia* species in South Africa according to the metrics chosen (22 species are Data Deficient and were excluded from the analysis). A. The precautionary risk map, which represents the highest impact score that a site can have. The acronyms represent the provinces: Limpopo (LP), North-West Province (NW), Gauteng (GP), Mpumalanga (MP), Northern Cape (NC), Free State (FS), Kwazulu-Natal (KZN), Western Cape (WC), and Eastern Cape (EC); B. The precautionary cumulative risk map, which represents the highest impact score possible at a site, considering the number of co-occurring species at the site level; C. The cumulative risk map, which considers the number of mechanisms a species can have and the number of co-occurring species. D. The mean cumulative risk map, which considers the variation of impact scores within species and the number of co-occurring species at the species level; E. The mean risk map, which considers the variability of the impact score within species and the number of species co-occurring at a site level, F. The weighted mean risk map, which is an uncertainty-averse approach to highlight impact scores with low uncertainty. In the panel, 'Prop' is the proportion of grid cells having the two highest impact classes. The colour gradient represents the aggregated impact scores according to the metrics chosen, per quarter degree square (QDS) (see Table 2).

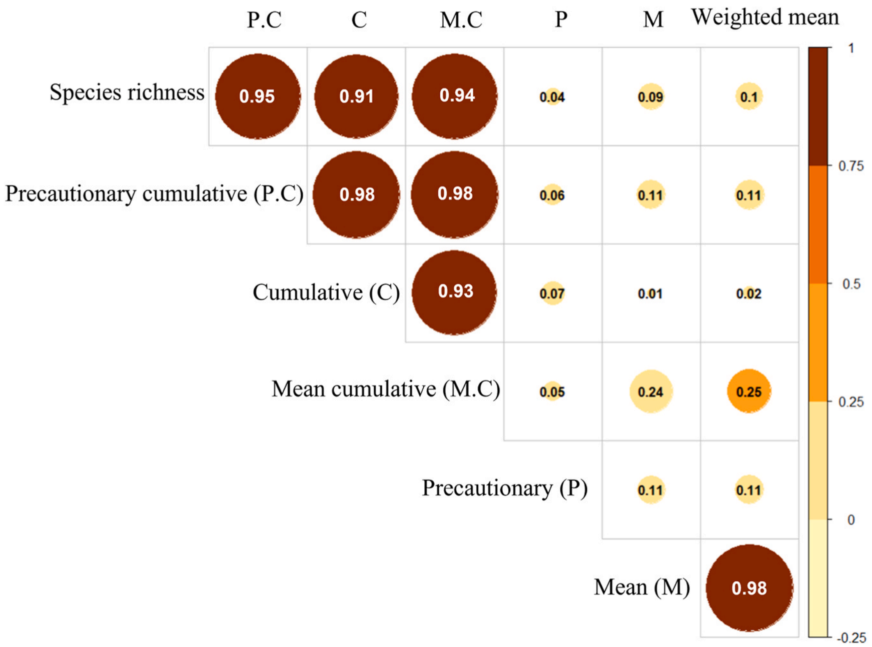


**Fig. 5.** Correlation matrix for the different risk maps based on the current distribution of invasive *Acacia* species in South Africa. The precautionary risk map represents the highest impact score that a site can have; The precautionary cumulative risk map represents the highest impact score possible at a site, considering the number of co-occurring species at the site level; The cumulative risk map considers the number of mechanisms a species can have and the number of co-occurring species; The mean cumulative risk map considers the variation of impact score within species, and the number of co-occurring species at a species level; The mean risk map considers the variability of the impact score within species and the number of species co-occurring at a site level; The weighted mean risk map is an uncertainty-averse approach to highlight impact scores with low uncertainty.

standardised impact assessment.

Future risk maps where impactful species could occur can be used as tool to prioritise sites for management actions, e.g., to limit the expansion of impactful species, or for clearing impactful species expected to remain present (Blanchard and Holmes, 2008; Cheney et al., 2019; Hulme, 2006; Moyano et al., 2025; van Wilgen et al., 2011). For *Acacia* species introduced to South Africa, we propose to combine areas into five prioritisation categories according to their current and potential impacts.

Compared to a study looking at the potential species richness and impact of 12 alien *Acacia* species in South Africa (van Wilgen et al., 2011), we found more areas suitable for impactful *Acacia* species in the Free State province (FS) but less in Northern province (NP). Kumschick et al. (2024) showed that suitable areas under three different climatic scenarios were reduced by half across South Africa. Therefore, we recommend focusing management actions on areas suitable for impactful alien species, by including both actual and potential climate.

Priority for management actions should be guided by both the current presence of impactful species and the potential risk of future invasions. We adapted the management decision support tool of Ehrensperger et al. (2025) to include risk for setting management priorities. First, areas where moderately impactful species are already present, and which are suitable for highly impactful *Acacia* species should be prioritised for immediate control with density reduction, and early detection and rapid response (EDRR) with local eradication where feasible (see 1 in Fig. 6A). Second, areas where highly impactful species are already present should be prioritised for immediate control with density reduction (see 2 in Fig. 6A). Third, areas that are currently occupied by a few low-impact species, and which are suitable for highly impactful *Acacia* species (see 3 in Fig. 6) should be prioritised for EDRR with local eradication, and prevention. Fourth, areas that are currently occupied by a few low-impact species, and which are suitable for moderately impactful *Acacia* species (see 4 in Fig. 6) should be priorised for EDRR with local eradication, and prevention. Finally, areas unsuitable for future invasion should be assigned lower priority, but should still benefit from awareness raising, prevention, and EDRR with local eradication (see 5 in Fig. 6A). Management actions within areas should be implemented at finer spatial scales, such as regional, local, or site-specific levels, to ensure targeted and efficient responses (van Wilgen et al., 2011).

While the future risk maps developed in this study provide valuable spatial assessment of potential impacts of invasive alien plant species, several sources of uncertainty must be acknowledged. Uncertainties exist regarding how individual alien species, or assemblages of co-occurring species, will shift their distribution in response to specific environmental changes (Hui and Richardson, 2019). These range shifts may alter interactions with native species, potentially leading to varying ecological impacts (Hui and Richardson, 2019). Moreover, the common assumption that a species has uniform impacts across its entire range is likely oversimplified, as local environmental conditions and context-dependent interactions can significantly modulate these effects (e.g., Catford et al., 2022; Hirsch et al., 2017; Pyšek et al., 2020b). Species distribution for alien species are often based on distribution data within their invaded

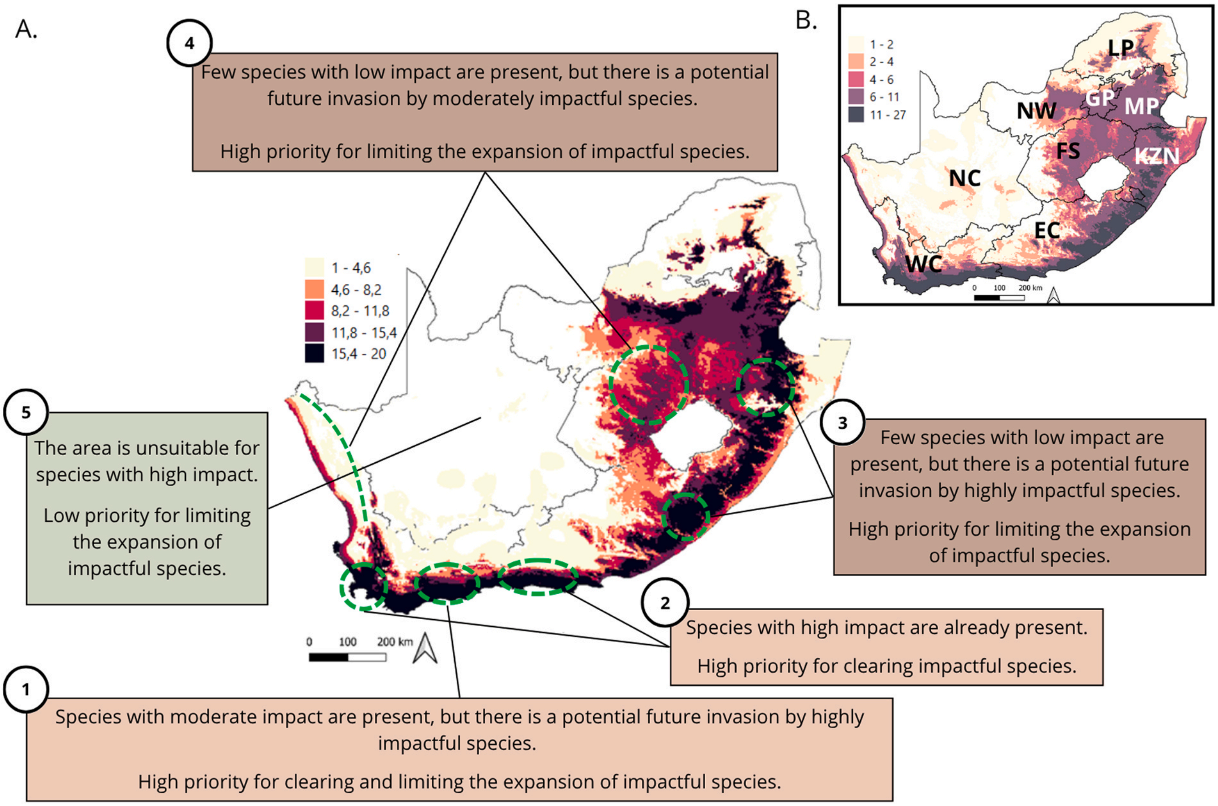


**Fig. 6.** A. Example of management areas (green dotted line) and strategies based on the future mean cumulative risk map of 11 assessed invasive *Acacia* species alien to South Africa (with 22 species excluded due to Data Deficiency) and their potential distribution (Kumschick et al., 2025). The encircled numbers show the prioritisation order of management areas. The colour gradient represents the aggregated impact scores per 4 km x 4 km grid cell. B. potential species richness of the 30 alien *Acacia* species from Kumschick et al. (2025). The colour gradient represents the predicted number of *Acacia* species per 4 × 4 km grid cell. The acronyms represent the provinces: Limpopo (LP), North-West Province (NW), Gauteng (GP), Mpumalanga (MP), Northern Cape (NC), Free State (FS), Kwazulu-Natal (KZN), Western Cape (WC), and Eastern Cape (EC).

range. However, these species often have not yet fully occupied their potential ecological niche, which can result in an underestimation of their potential distribution (Eckert et al., 2020). Furthermore, projections of future impacts based on distribution models introduce additional sources of uncertainty, due to variable environmental predictors, dispersal assumptions, and model choice (Northrop and Chandler, 2014). As result, the future risk maps should be seen as indicative rather than predictive. Future efforts should aim to incorporate dynamic, context-dependent impact assessments, such as site-specific conditions, to improve risk maps.

## CRediT authorship contribution statement

**Christophe Botella:** Writing – review & editing, Methodology. **Sabrina Kumschick:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Boulesnane Guengant Océane:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Mathieu Rouget:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Antoine Becker-Scarpitta:** Writing – review & editing, Methodology, Formal analysis.

## Ethical statement

This study exclusively uses previously published data on plant species. No new fieldwork or experimental manipulation of living organisms was performed. As such, ethical approval was not required.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the principal author used ChatGPT in order to correct and improve certain sentences. After using this tool/service, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2025.e03660.

## Data availability

Codes are available on https://github.com/Oceane-Boulesnane-Guengant/Risk_maps_Acacia_SA
Data and code for Risk maps (GitHub)

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