Functional assisted migration to sustain ecosystem functions under climate change

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Abstract

1. Climate change is rapidly altering habitats, forcing many plant species to shift their distribution. However, slow dispersal rates and habitat fragmentation hinder their ability to track these changes, risking local extinctions and reduced ecosystem functioning. Current management strategies may not suffice to address these challenges.
2. We propose functional assisted migration (FAM) as a novel strategy to sustain ecosystem functionality under climate change by translocating non-native plant species capable of filling functional gaps in vulnerable ecosystems. By aligning plant communities with future climate conditions, FAM further enhances ecosystem resilience to withstand additional stressors.
3. To operationalize FAM, we outline key criteria and a data-driven workflow for species selection. Species selected for FAM should meet four key criteria: adaptation to the future climate, adaptation to edaphic conditions, the ability to fill functional gaps, and a low risk of invasiveness. The structured workflow, integrating climate analogue analyses, species distribution models, and functional trait assessments, provides a data-driven backbone for selecting non-native plant species suitable for FAM.
4. *Synthesis and applications*: By prioritizing ecosystem functionality and resilience, FAM offers a forward-thinking solution to one of conservation science's most pressing challenges. FAM complements traditional conservation efforts by targeting regions where natural dispersal and conventional strategies fall short, but empirical research remains essential to validate its ecological impacts and contributions.

1. The need for functional assisted migration

Climate change significantly alters habitat suitability and the spatial distribution of species, with most species expected to shift their ranges toward higher latitudes and altitudes (Chen et al., 2011). However, rates of species redistributions are substantially lower than the velocity of climate change (Corlett & Westcott, 2013; Lenoir et al., 2020). Factors such as slow dispersal speeds, habitat fragmentation due to land-use changes, and reduced biotic connectivity following megafauna extinctions (Fricke et al., 2022) have contributed to a seed dispersal crisis (Mendes et al., 2024). As a result, many plant species are unable to keep pace with climate change, increasing the risk of (local) extinction (Pörtner et al., 2021).

Current adaptive management strategies, including enhancing species and genetic diversity, mitigating local stressors and improving landscape connectivity (Hylander et al., 2022; Moore & Schindler, 2022), may prove insufficient to address the rapid pace of climate change (Hällfors et al., 2017). Consequently, there is a growing call for new, proactive interventionist strategies (Peterson St-Laurent et al., 2021; Prober et al., 2019). Unlike efforts to minimize migration barriers within landscapes, assisted migration directly facilitates species' range shifts to keep pace with changing climates. Also referred to as assisted colonization or managed relocation, this approach involves actively translocating species beyond their native ranges to mimic natural range expansions that would occur under climate change if not for anthropogenic barriers or time constraints (Hällfors et al., 2014). This strategy represents a paradigm shift in conservation, challenging traditional principles that emphasize preserving local biodiversity and avoiding the introduction of alien species (Corlett & Westcott, 2013). While widely proposed as a response to climate change, assisted migration remains highly debated and controversial due to its potential ecological risks and the ethical implications of reshaping how ecosystems are valued and managed (Prober et al., 2019). Logically, caution is required as newly introduced species may become invasive and harm native biodiversity (Pyšek et al., 2020). Critics argue that the impacts of introductions on recipient communities are difficult to predict, advocating against assisted migration based on the precautionary principle (Bucharova, 2017; Ricciardi & Simberloff, 2009). Nevertheless, while the risk of biological invasions cannot be eliminated, careful selection of species for assisted migration may help mitigate this concern.

Invasive alien species typically originate from regions that are spatially and often biogeographically distinct, encountering novel environmental conditions and biotic interactions in their introduced ranges (Urban, 2020). Contrarily, intracontinental, short-distance translocations of species tracking their bioclimatic envelopes are more likely to involve species with an evolutionary history shared with the recipient community. This significantly reduces the likelihood of enemy release and biological invasion (Brian & Catford, 2023). Additionally, species requiring translocation often possess traits such as poor dispersal ability, low competitiveness, or long life cycles, which stand in stark contrast to traits associated with invasiveness (Palma et al., 2021; Zhao et al., 2023). In this paper, we focus on plant communities as plants are less likely than animals to cause rapid extinctions in recipient communities, as predation - an interaction absent in plant introductions - is the primary driver of such extinctions (Sax & Gaines, 2008).

Emphasizing the risks while overlooking the potential benefits of assisted migration has hindered essential conservation innovation (Brodie et al., 2021; Marvier & Kareiva, 2020). As a result, the existing literature is dominated by theoretical frameworks (McLachlan et al., 2007; Prober et al., 2019), opinion pieces (Bucharova, 2017; Ricciardi & Simberloff, 2009) and studies modelling the need for species translocations (e.g. Bellis et al., 2020; Casazza et al., 2021), with only very few empirical investigations (Twardek et al., 2023). For example, a recent review of species translocations within protected areas identified only 148 (out of 956) studies focusing on plants, of which only four explicitly addressed assisted migration (Langridge et al., 2021). The perceived risks associated with relocating species beyond their current ranges, combined with the lack of standardized procedures and restrictive environmental policies, have severely constrained empirical research on assisted migration, resulting in a critical knowledge gap (Park & Talbot, 2018).

Urgent empirical studies are thus needed to assess the effectiveness and underlying mechanisms of translocations, evaluate how novel interactions affect the persistence of translocated populations and determine how these species influence the functioning of recipient ecosystems (Prober et al., 2019). However, most existing studies and projects on assisted migration adhere to the traditional conservation paradigm, focused on species threatened by climate change (Benomar et al., 2022; Butt et al., 2021). Efforts to translocate species solely to prevent species extinction are likely to face significant resistance and policy conflicts in recipient regions, where the perceived risks are seen to outweigh the potential benefits (Davidson & Simkanin, 2008). Expanding the scope of research to prioritize ecosystem functionality could help address these challenges while unlocking the potential of assisted migration as a conservation tool.

Besides driving species loss, climate change and other disturbances are expected to significantly impact ecosystem functioning. Beyond safeguarding species through translocation, assisted migration offers a promising strategy for restoring or maintaining ecosystem functions in communities threatened by climate-induced extinctions (Lundgren et al., 2024). Here, we introduce the concept of *functional assisted migration* (FAM), which focuses on maintaining ecosystem functionality through the deliberate introduction of species. This approach is similar to the concept of pull-assisted migration proposed by Lunt et al. (Lunt et al., 2013), which also emphasized the introduction of species to support ecosystems. We use the term functional assisted migration because it highlights the overarching goal of sustaining ecosystem functions rather than simply describing the act of translocating species. By prioritizing benefits to the recipient community, functional assisted migration may help shift the risk-benefit balance, as species are introduced to enhance ecosystem functionality rather than merely posing a risk of invasion. This approach aligns with a broader trend in conservation that emphasizes the importance of ecosystem functionality and resilience to sustain ecosystem services under climate change (Moore & Schindler, 2022; Siegel et al., 2024). In this paper, we adopt this functional perspective on assisted migration of plant species and propose a framework for its practical implementation.

2. Filling functional gaps to sustain ecosystem functioning

Biodiversity and ecosystem functioning are linked in complex, non-linear ways. Higher levels of biodiversity enhance a community's ability to capture resources, produce biomass, and cycle nutrients efficiently (Cardinale et al., 2012). Furthermore, biodiversity contributes to greater ecosystem stability in the face of disturbances (Loreau et al., 2021). However, traditional biodiversity metrics, such as species richness, often fail to fully capture the relationship between biodiversity and ecosystem functioning. Functional differences among plant species rather than species identity seem to play a pivotal role in driving ecosystem processes and shaping ecological communities (Cadotte, 2017). Representing biodiversity as a continuum of species' functional traits has therefore significantly advanced our understanding of community assembly, ecosystem functioning and responses to disturbances (e.g. Bektaş et al., 2023). Theoretically, communities with greater functional diversity - characterized by a wide range of trait values - are expected to maintain higher levels of ecosystem functioning. Complementing this, functional redundancy, where multiple species share similar functional traits, enhances ecosystem stability under changing conditions. By providing an insurance effect, functional redundancy ensures that the loss of a species is less likely to result in the complete loss of critical ecosystem functions (de Bello et al., 2021). However, many natural ecosystems have faced a history of degradation and species extinctions (Bardgett et al., 2021; Díaz & Malhi, 2022). As a result, further species loss driven by climate change is likely to create functional gaps within local communities, reducing overall ecosystem functioning. The ongoing loss of biodiversity among native species is already negatively affecting ecosystem functioning, stability and ecosystem service provision worldwide (Gammal et al., 2023; Wang et al., 2021).

Relying solely on natural migration is unlikely to prevent future declines in ecosystem functioning. Through functional assisted migration, plant species with suitable functional traits can be identified and translocated to fill actual or predicted functional gaps, helping to sustain ecosystem functioning under changing climate conditions (Figure 1a). For example, the functional assisted migration of plants can alleviate constraints on the range expansion of specialist pollinators, supporting their ecological interactions (Stephan et al., 2021), whereas translocating warm-adapted tree species could help maintain a closed forest canopy, preserving critical buffer capacity and microclimate conditions during future drought-spells, essential for the survival of many forest-dwelling species (Xu & Prescott, 2024).

Additionally, climate warming often interacts with other anthropogenic stressors, creating multidirectional global changes that reduce species' tolerance (sensu Van Meerbeek et al., 2021) to individual perturbations (Crall et al., 2018; Williams et al., 2013). By aligning plant communities with future climate conditions, FAM enhances the resilience of ecosystems to withstand additional stressors, such as extreme droughts or nitrogen deposition (Figure 1b).

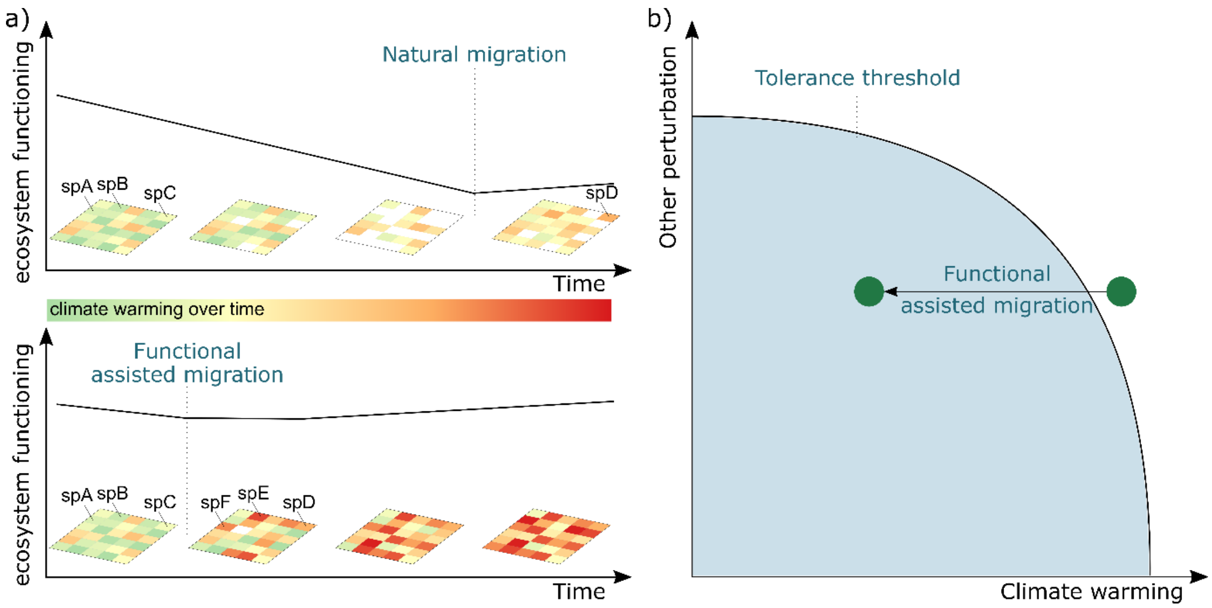

Figure 1. (a) Ecosystem functioning is expected to decline under increasing climate warming as local species A, B, and C are unable to track shifting climate zones and are negatively impacted by climate change (top). Functional assisted migration of species D, E, and F can sustain ecosystem functioning by introducing species better adapted to the new climate conditions (bottom). Tiles represent species with varying optimal temperature ranges, indicated by different colours. (b) Functional assisted migration can also enhance tolerance to additional stressors, such as drought, by relocating species to higher altitudes or latitudes. The blue zone illustrates the survival range of a species under specific environmental conditions.

3. Functional assisted migration in practice

To guide the selection of non-native plant species for functional assisted migration, we developed a structured six-step workflow (Figure 2). This process integrates four key criteria that candidate species must meet to effectively sustain ecosystem functionality under changing climate conditions: (1) The species should be adapted to future climate conditions of the target region; (2) The species should be adapted to edaphic conditions, including soil moisture, pH and nutrient levels; (3) The species should be capable of filling functional gaps induced by climate change. Non-native species should therefore have functional traits or phylogenies similar to those of the native species they are intended to replace; (4) The species should pose a low risk of invasiveness. The process begins with gathering plant community data from climate analogues, i.e. areas where the current climate closely resembles the projected future climate of the target region (Dobrowski et al., 2021). In subsequent steps, species that fail to meet the criteria are progressively excluded. Finally, we recommend experimental research to test species combinations and empirically evaluate the outcomes of FAM with the selected species.

Step 1: Climate analogues - The first step involves conducting a climate similarity assessment to identify non-native species growing in climate analogues for the target region. Climate similarity can be quantified as the Euclidean distance between the locations within a multidimensional climate space, which is defined by various climate variables. This analysis must account for climate extremes, not just mean conditions, as extremes are expected to become more frequent in the future and could play a critical role in shaping species distributions (Fonteyn et al., 2024). For regions with high climate similarity, plot data are retrieved from plot databases such as sPlotOpen (Sabatini et al., 2021) and the European Vegetation Archive (Chytrý et al., 2016). Since climate similarity is a continuous metric, no universal threshold exists for identifying climate analogues. Therefore, we recommend performing the climate similarity analyses and subsequent steps using varying distance thresholds. Additionally, the climate similarity assessment can be repeated for different climate scenarios and time horizons according to the research questions and goals, each yielding distinct plots and, consequently, varying species sets.

Step 2: Co-occurrence analysis - Non-native species that often co-occur with the native species from the target community are likely to be adapted to similar biotic and abiotic conditions, and due to co-evolution with native species in similar environments, they are less likely to exhibit invasive behaviour within the target area. To begin, the composition of the target plant community must be characterized by identifying its characteristic species. This selection can be guided by expert knowledge or existing species lists. To identify non-native species that co-occur with these characteristic species, several co-occurrence analysis methods are available (Arita, 2016). Among these, we recommend ordination analysis, which positions species in a low-dimensional space based on their co-occurrence patterns. Species that frequently co-occur in vegetation plots are placed closer together in the ordination diagram. Traditionally, ordination of vegetation data (plots × species) has been performed using non-metric multidimensional scaling (NMDS). Recently, however, model-based ordination methods have emerged (van der Veen et al., 2021). These methods, grounded in the generalized linear regression framework, provide advanced tools for diagnosing model fit and conducting model selection. From the ordination results, non-native species positioned close to the characteristic species of the target community are selected for further analysis. The definition of "close" in ordination space is, however, not absolute. Both the distance and the number of close characteristic native species are variables without clear thresholds. However, the information provided by the native species can be used to establish reasonable cut-offs. Specifically, the number of other native species within a circle of increasing radius could be calculated for each species in the ordination diagram. By analysing how native species cluster in ordination space (and are thus close to other native species), one or more cut-off values can be determined to select non-native species for subsequent steps.

Step 3: Climate suitability - Even though non-native species are selected from plots in climate analogue regions, these plots might still be at the edge of the species' distribution range. As a result, the future climate conditions in the target region might only marginally support certain non-native species. To refine the selection, species distribution modelling (SDM) can be used to evaluate the suitability of future climate conditions for each non-native species and the trend in suitability from the present to the future. Only non-native species with a positive trend and high future climate suitability should proceed to further analyses. Simultaneously, SDMs should be conducted for the characteristic native species of the target plant community. This will help identify native species likely to struggle under future climate conditions, which is essential for recognizing potential future functional gaps in the ecosystem (see Step 4). SDMs can be executed using the plot databases from Step 1 and presence-absence algorithms such as logistic regression or Boosted Regression Trees (Elith et al., 2008). Alternatively, presence-only data from large databases, such as GBIF.org, can be utilized with algorithms like MaxEnt, which is specifically designed for presence-only data (Valavi et al., 2022).

Step 4: Functional gaps - Predicted species loss driven by climate change and other disturbances can be analysed in terms of changes in functional trait space, i.e. the multidimensional space defined by functional traits as axes. To explore this, data for traits relevant to the target ecosystem functions (Streit & Bellwood, 2023) of all species should first be extracted from trait databases such as TRY (Kattge et al., 2020). For example, if the objective is to preserve the microclimate buffering capacity of a forest, traits like maximum tree height, leaf area index, and deciduousness are particularly important (De Frenne et al., 2021). By applying ordination analysis, native species assemblages can be visualized within a low-dimensional trait space (Mammola & Cardoso, 2020). Overlaying these graphs with information from the SDMs (Step 3) enables the identification of potential functional gaps. Adding climate-resilient non-native species to these graphs helps pinpoint candidates that could fill these functional gaps. As an alternative to functional traits, phylogenetic relatedness can be used as a proxy for functional similarity, leveraging the concept of phylogenetic niche conservatism - the tendency of closely related species to share similar traits (Swenson, 2019). Using tools like the Analysis of Phylogenetics and Evolution (APE) package in R (Paradis et al., 2004), researchers can construct a phylogenetic tree that includes both native and non-native species. By marking native species likely to face local extinction, it becomes possible to identify non-native species that could serve as suitable candidates for functional assisted migration.

Step 5: Edaphic suitability - In addition to climate suitability, it is essential to consider edaphic suitability when selecting non-native species. The chosen species should be well-adapted to the soil conditions of the target area. While edaphic variables can be integrated into species distribution models (SDMs), the coarse spatial resolution of available geodata often fails to capture fine-scale environmental variation. To address this limitation, edaphic suitability should be verified through an additional step. A practical approach involves using ecological indicator values, which are ordinal scales that describe the optimal conditions of a species' realized ecological niche along specific environmental gradients (Dengler et al., 2023). Ecological indicator values for soil moisture, soil pH, and soil nitrogen content in non-native species can be compared to those of characteristic species within the native community, ensuring alignment with the local edaphic conditions.

Step 6: Experimental validation - To minimize the risk of introducing harmful invasive species, a thorough final assessment of invasiveness is essential. This involves cross-referencing candidate species with existing invasive species lists from other regions (e.g. Pagad et al., 2022) and consulting experts to exclude any species with invasive potential. Additionally, experimental research plays a critical role in evaluating the effects of functional assisted migration on recipient communities, species interactions and overall ecosystem functioning. To achieve this, combinations of native and selected non-native species should be tested under controlled environmental conditions. Ideally, these experiments should be conducted in the target region but under conditions that simulate the anticipated future climate. This can include climate warming experiments using open-top chambers or active heating methods (Yang et al., 2018). Alternatively, experiments based on space-for-time substitutions in climate-analogue regions offer a simpler approach (De Frenne et al., 2013). If the workflow identifies multiple alternative non-native species to fill the same functional gap, additional selection criteria can be applied. For example, prioritizing rare species may be beneficial, as they are highly vulnerable and often contribute disproportionately to ecosystem functioning (Dee et al., 2019).

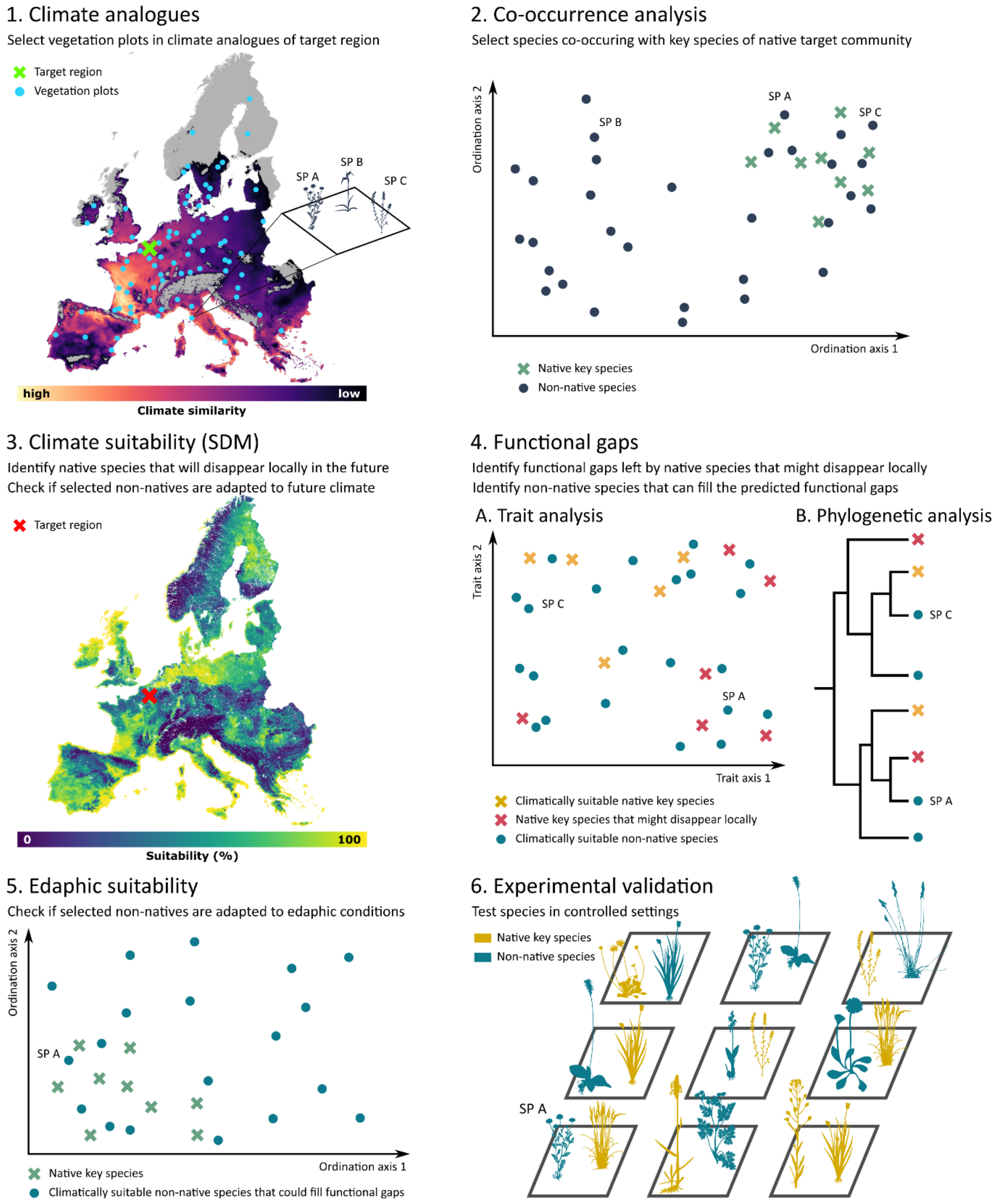

Figure 2. A six-step process for selecting non-native plant species as candidates for functional assisted migration. The process starts by collecting plant community data from climate analogue regions, potentially identifying a broad pool of non-native species. At each subsequent step, species are progressively filtered out based on predefined selection criteria. Finally, the remaining candidate species should be evaluated through controlled experiments. CHELSA bioclimatic variables were used to construct the SDM and climate similarity maps (Brun et al., 2022)*. Occurrence data (Allium neopolitanum) were extracted from GBIF.org.*

4. Concluding remarks

Current management strategies are unlikely to suffice in addressing the unprecedented rates of climate change, which are expected to result in local species extinctions and diminished ecosystem functioning. Functional assisted migration (FAM) offers an innovative approach to maintaining ecosystem functionality by introducing species capable of filling functional gaps created by climate change. In this paper, we propose criteria and a step-by-step framework to guide species selection for FAM, aiming to establish novel plant communities that are resilient to climate change impacts. To maximize success, FAM should prioritize short-range intracontinental translocations of plant species that already co-exist with native communities, are well-adapted to local soil conditions, and can thrive under future climate scenarios in the target area. The novel communities are expected to better withstand future challenges, such as increased drought and elevated temperatures, while maintaining ecosystem functionality. However, empirical data are crucial to validate this hypothesis, optimise the implementation and address potential risks. Note that FAM does not aim to replace traditional conservation methods but to complement them. Natural dispersal mechanisms should still be supported by enhancing biotic connectivity and reducing landscape fragmentation to facilitate species' ability to track shifting climate zones. Nonetheless, FAM should be considered as a targeted strategy in regions where conventional conservation methods fall short. Further research is needed to identify ecosystems and plant communities most at risk of losing functionality under future climate conditions. By prioritizing ecosystem functionality and resilience, FAM offers a forward-thinking solution to one of the most pressing challenges in conservation science.

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Writing – Review & Editing: All authors

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Conflict of interest

The authors have declared no conflict of interest

Data availability

Only freely available data were used in this study

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