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Review

Revegetation through seeding or planting: A worldwide systematic map

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ABSTRACT

Roughly 2 billion ha of land are degraded and in need of ecological restoration worldwide. Active restoration frequently involves revegetation, which leads to the dilemma of whether to conduct direct seeding or to plant nursery-grown seedlings. The choice of revegetation method can regulate plant survival and performance, with economic implications that ultimately feed back to our capacity to conduct restoration. We followed a peer-reviewed protocol to develop a systematic map that collates, describes and catalogues the available studies on how seeding compares to planting in achieving restoration targets. We compiled a database with the characteristics of all retrieved studies, which can be searched to identify studies of particular locations and habitats, objectives of restoration, plant material, technical aspects, and outcomes measured. The search was made in eight languages and retrieved 3355 publications, of which 178 were retained. The systematic map identifies research gaps, such as a lack of studies in the global South, in tropical rainforests, and covering a long time period, which represent opportunities to expand field-based research. Additionally, many studies overlooked reporting on important technical aspects such as seed provenance and nursery cultivation methods, and others such as watering or seedling protection were more frequently applied for planting than for seeding, which limits our capacity to learn from past research. Most studies measured outcomes related to the target plants but avoided measuring general restoration outcomes or economic aspects. This represents a relevant gap in research, as the choice of revegetation method is greatly based on economic aspects and the achievement of restoration goals goes beyond the establishment of plants. Finally, we identified a substantial volume of studies conducted in temperate regions and over short periods (0–5 y). This research cluster calls for a future in-depth synthesis, potentially through meta-analysis, to reveal the overall balance between seeding and planting and assess whether the response to this question is mediated by species traits, environmental characteristics, or technical aspects. Besides identifying research clusters and gaps, the systematic map database allows managers to find the most relevant scientific literature on the appropriateness of seeding *vs.* planting for particular conditions, such as certain species or habitats.

1. Introduction

Humans have altered natural ecosystems for millennia (Nogué et al., 2021), and roughly 2 billion ha of land are in need of ecological restoration worldwide (Cernansky, 2018). Even areas that are currently covered by vegetation require adaptation to future climate and novel disturbance regimes (Hoegh-Guldberg et al., 2008; Leverkus et al., 2021b), for instance by enriching plantation forests –frequently conifer monocultures– with deciduous trees (Astrup et al., 2018; Leverkus et al., 2021b; Pausas and Keeley, 2019). New policies from local to

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international, boosted by the UN Decade on Ecosystem Restoration (FAO and SER, 2021), and the publication of international standards, which establish the principles in ecological restoration (Gann et al., 2019), are providing momentum for restoration worldwide.

Revegetation constitutes a fundamental step in most ecological-restoration projects, with major potential benefits related to increasing native plant cover, retaining soil, sequestering and storing carbon, regulating greenhouse gases, and providing other ecosystem services (Chazdon, 2008; Nave et al., 2018; Nwaishi et al., 2016). However, revegetation success is not guaranteed, and careful choice of methods is needed to meet restoration targets so that allocated resources are effectively spent. Revegetation failure often results from adverse biotic or abiotic conditions and their interactions with inappropriate technical choices (Löf et al., 2019; Shackelford et al., 2021). For instance, in Mediterranean areas, the long, dry summers, coupled with poor, erosion-prone soils, are common threats for seedlings (Leverkus et al., 2015; Rey Benayas et al., 2015; Shackelford et al., 2021). Biotic stress, primarily through herbivory and seed predation, can also cause great losses and modulate revegetation success depending on the type of herbivores present (Gordon et al., 2004; Leverkus et al., 2013; Rey Benayas et al., 2015). It is thus essential to identify the causes of failure and develop techniques to improve the success of revegetation (Bocio et al., 2004; Jiménez et al., 2007, 2016, 2017).

Many scientific and technical developments have addressed the growing demand for knowledge on how to improve revegetation success. This includes, for example, seed treatments such as coating and scarification (Brown et al., 2021; Pedrini et al., 2020), soil preparation techniques (Bocio et al., 2004), greenhouse-cultivation methods (Villar-Salvador et al., 2004), soil amendment (Jiménez et al., 2016, 2017), post-planting treatments (Jiménez et al., 2007), and protection devices to prevent seed predation and herbivory (Castro et al., 2015). However, key questions remain, such as the balance of seeding *versus* planting as revegetation options, as it can modulate the stresses suffered by plants. Current methods for revegetation with many trees and shrubs rely mostly on the planting of nursery-grown seedlings. The alternative approach, direct seeding in the field, is often discarded due to the perceived risk of low germination and establishment rates, partly driven by high seed predation and the vulnerability of young seedlings (Allen et al., 2001; Dey et al., 2008; Leverkus et al., 2013, 2017; Savill et al., 1997). For some species, both methods are possible, yet considerable debate still exists (e.g. Löf et al., 2019). Seedling planting has several advantages over seeding, such as generally faster seedling growth and establishment (Allen et al., 2001; Fields-Johnson et al., 2010; Löf et al., 2004), and the avoidance of seed predation (Stewart et al., 2000). However, planting can also increase the risk of transferring plant diseases from nurseries to the field (Lilja et al., 2010; Zentmyer, 1985). Seeding operations, on the other hand, are easier to conduct and generally less costly; they allow greater flexibility in terms of their timing, and they permit restoration in terrain where planting is too difficult (Allen et al., 2001).

Diverse studies have reviewed the success of revegetation [e.g., on direct seeding (Ceccon et al., 2016; Grossnickle and Ivetić, 2017; Löf et al., 2019) and on seeding compared to planting (Dey et al., 2008; Palma and Laurance, 2015)] but, to our knowledge, none of them has followed a reproducible and systematic approach; specifically searched for studies comparing the two revegetation methods; or clearly identified research clusters and gaps. Here, we identify and describe the available studies that address the research question of which revegetation method –direct seeding or seedling planting– is most successful for achieving restoration targets. For this, we use a systematic mapping approach, which aims to identify, collate, catalogue, and describe the evidence related to a particular topic (James et al., 2016). The process and rigour of a systematic map is the same as for systematic reviews, yet a systematic map does not attempt to answer the study question but rather to identify research clusters and gaps to guide future field-based and synthesis research (James et al., 2016). By extracting and presenting relevant meta-data from the available literature, we thus aim to identify aspects of the research question that are in need of additional empirical research, and others that are ripe for in-depth synthesis. Finally, this study also targets land managers who face the question which of the two revegetation methods to apply, for whom we compiled a systematic map database that allows identifying relevant studies given particular site characteristics or species.

2. Methods

Systematic maps and reviews follow the same systematic searches and selection techniques based on a protocol to minimize bias in the identification and selection of evidence, but differ in their mode of synthesis, analyses and outputs (CEE, 2022). Therefore, we produced this systematic map following the guidelines for systematic reviews in environmental management as proposed by the Collaboration for Environmental Evidence (CEE, 2022) and other sources (James et al., 2016; Koricheva et al., 2013; Pullin and Stewart, 2006; Sutherland et al., 2004). The Methods described below expand on those previously laid out in our systematic review protocol (Supplement S1 in Leverkus et al., 2021a).

2.1. Research question

We established a search strategy to identify the scientific literature that addresses the following main research question: *Which revegetation method, direct seeding or seedling planting, is most successful in achieving restoration targets?*

This question implies the following PICO elements (Higgins and Green, 2011). As the focus of the identified literature should be the comparison of two interventions –namely direct seeding and seedling planting–, we replaced the “intervention” and “control” elements of the PICO statement with the two “interventions” indicated below.

- **Population**: Areas subject to revegetation with native species in natural/seminatural terrestrial environments and not for agricultural harvesting
- **Intervention 1**: Direct seeding of propagules (hereafter seeds) in the field
- **Intervention 2**: Planting of seedlings or saplings previously grown in a nursery
- **Outcome**: Any outcome measured

2.2. Search strategy

We conducted our literature searches in three steps.

a) **Primary searches** in Web of Science (WoS) and Scopus. These included simplified combinations of terms aimed for a comprehensive search of the study population and interventions elements in English (but if any publication was retrieved in other languages spoken by the review team, these publications were also evaluated –see section *2.3. Selection criteria,* below). As described in our protocol (Leverkus et al., 2021a), we conducted a scoping exercise of our primary search on 21–23 Dec 2020 to identify the most inclusive and efficient search string. The exercise resulted in the following search terms, which we used to search in titles, abstracts and keywords in WoS and Scopus:

(“seeding” OR sow*) AND (“seedling” OR “planting” OR “plantation” OR transplant*) AND (reforest* OR restor* OR revegetat* OR afforest*)

The search was made on Dec 23, 2020 and updated on Nov 14, 2022. We filtered the results for the categories *Ecology, Plant sciences, Environmental sciences, Forestry, Biodiversity conservation, Agronomy, Environmental engineering, Agriculture multidisciplinary, Multidisciplinary sciences, Environmental studies,* and *Materials science paper wood* (WoS) or

Agricultural and biological sciences, Environmental sciences, Earth and planetary sciences, Engineering, and *Multidisciplinary* (Scopus). After removing duplicate results, this produced 1680 unique references. We contrasted the retrieved titles with a list of articles previously known to be relevant for the review to ensure the comprehensiveness of the search results.

b) **Secondary searches** in additional databases: Directory of Open Access Journals (DOAJ), the United States Department of Agriculture (USDA) and Canadian Forest Service (CFS) databases, SciELO, and Google Scholar. These searches were made from June to August 2021. All results at this stage were compared with references from previous searches, and duplicate references were removed. The search in DOAJ was carried out in "*articles section < in all fields*" which includes title, abstract, keywords, author, DOI, ORCID, and language matches. The search equation was *"(seeding OR sow*) AND (seedling OR planting OR plantation OR transplant*) AND (reforest* OR restor* OR revegetat* OR afforest*)"* and it produced 358 unique references. For the USDA Forest Service database, we introduced the same search equation as for DOAJ in the "*Keywords All fields or Title*" field, which generated 481 unique publications. We carried out the search in CFS in three blocks of equations: a) "*(seeding | sow)*", b) "*(seedling | planting | plantation | transplant)*", c) "*(reforest | restor | revegetat | afforest)"*, with 1107, 3271 and 381 results. As this database did not allow for the "AND" operator, we manually selected the publications that were common to the three blocks. The search equation was introduced in the "*Simple search – keywords"* field, and it retrieved 28 publications for further screening. For the SciELO database, we used the search equation *"("seeding" OR sow*) AND ("seedling" OR "planting" OR "plantation" OR transplant*) AND (reforest* OR restor* OR revegetat* OR afforest*)"* in the "*All indexes*" field, which searches for year, author, sponsor, journal, abstract and title, and it produced 8 unique references.

In addition, we conducted secondary searches in Google Scholar to identify literature in English, Spanish, German, Catalan, Portuguese, French, Japanese, and Italian. For this, the review team included native speakers of all these languages, who searched the terms "*(seeding OR sowing) AND (planting OR transplantation) AND (reforestation OR restoration OR revegetation OR afforestation)*" in their respective languages and assessed the first 100 hits.

c) **Tertiary searches** in the reference lists of previously known review papers (Azam et al., 2012; Ceccon et al., 2016; Dey et al., 2008; Farlee, 2013; Grossnickle and Ivetić, 2017; Löf et al., 2019; Palma and Laurance, 2015; Schmidt, 2008) plus 52 additional original research and review papers identified during the literature searches. All titles in the bibliography of these papers were screened and those in line with our search terms were evaluated. We retrieved 60 new references at this stage.

2.3. Selection criteria

To be included in the review, the retrieved studies had to fulfil each of the following criteria.

- **Study type.** We included only original field and remote-sensing studies. Other types of studies, such as greenhouse and laboratory trials or conceptual articles, were excluded. Modelling studies were revised to search for empirical data validating the models. Reviews were excluded but screened for potential new references as a tertiary source (see above).
- **Population.** Studies had to address the outcomes of revegetation with native plant species in terrestrial habitats. Studies using commercial species for agricultural harvesting were removed.
- **Interventions.** Studies had to include revegetation with each of the two methods independently conducted with the same species: direct seeding of seeds in the field and planting of seedlings previously grown in a nursery. Different methods and timings of the interventions were allowed.
- **Outcome.** Studies had to provide independent measures of how the goals of revegetation were met under each of the two interventions. This could include, yet was not limited to, demographic variables related to the plants themselves (e.g., survival, size, reproduction), general ecological quality indicators (plant density, habitat quality, animal abundance), or technical and economic aspects of revegetation (ease of management actions, cost of revegetation).
- **Language.** Our review encompassed eight key languages for which we expected literature to be available. We excluded studies whose main text was not written in a language that at least one of the review team members could speak.

2.4. Study selection procedure

The publications retrieved in the primary and secondary searches were assessed in a three-step procedure by selecting 1) titles, 2) abstracts, and 3) full papers. Prior to each step, at least two review members revised a subset (5–10%) of the publications, and the agreement among their selection was assessed with kappa tests (Landis and Koch, 1977). Whenever the test indicated heterogeneity in the application of selection criteria described below, the criteria were re-discussed and the preliminary selection procedure and subsequent kappa test were repeated (Côté et al., 2013). After an initial scoping exercise and a revision of 100 titles, 50 abstracts, and 30 full-articles, we defined the selection criteria for each of the three stages as follows.

a) Title stage. At this stage, we selected titles based on their potential relevance in terms of the study type and the study population. We selected studies conservatively, i.e., eliminating only those that evidently failed to address the study population while keeping all those that potentially addressed revegetation through seeding or planting for their assessment at the next stage.
b) Abstract stage. We selected abstracts based on their potential relevance in terms of the study type, population, and the interventions. Studies clearly addressing only direct seeding or seedling planting were removed.
c) Full-article stage. At this stage, we only kept those publications that met all selection criteria.

In the primary and secondary searches, we kept track of the stage at which each publication was eliminated (title, abstract or full-article step) to produce a PRISMA diagram (Moher et al., 2009).

2.5. Study quality assessment

Quality appraisal is not a necessary process in systematic mapping (James et al., 2016). Nevertheless, we considered the reporting quality of the retrieved studies by removing publications that lacked sufficient detail to assess the study selection criteria, such as a clear indication of study species or revegetation method.

2.6. Data extraction and systematic map database

We extracted information from each publication at the scale of individual studies (which sometimes included more than one per publication). We considered studies from the same publication as independent when different experimental designs were implemented (e.g. Youngblood and Zasada, 1991) or when experiments were placed at different locations (separated at least 10 km; e.g., Löf et al., 2004), as they could differ in ecological characteristics such as elevation, type of habitat, or biome. In case one publication described more than one study, one spreadsheet with study characteristics was prepared for each of them. On the contrary, when more than one publication derived from the same study, they were considered the same. In such case, we produced one spreadsheet with information on each unique study. Within each study, detailed information at the scale of species was needed to report methodological aspects such as species name, seedling age, and/or nursery cultivation procedure. Hereafter, we refer to this level of detail as *cases*. For details and coding strategy, see Appendix A.

Data merging, calculations, and graphical output were made with R version 4.2.2 (R Core Team, 2022).

3. Results and discussion

3.1. Literature searches

The primary and secondary searches produced 3355 hits (Fig. 1). Among them, we excluded 49%, at the title stage, an additional 36.2% at abstract stage, and 10.5% at full-article stage (percentages with respect to total; Fig. 1). The reason for the removal of each publication at the abstract and full-article stages (except for the multilingual Google Scholar searches) is detailed in Appendix B. The most common reasons for exclusion were the lack of one of the interventions, i.e. seeding or planting (57.2% and 25% at the abstract and full-article stages, respectively), and not being field-based or remote-sensing studies (28.1% and 30.4%, Appendix B).

After that, 36 new publications were added from tertiary searches. Seven out of 178 retained publications reported more than one independent study (19 studies in total), while another eight publications derived from four independent studies. Thus, we retained 186 studies from 178 publications (Fig. 1) published in 98 journals or proceedings between 1931 and 2022. The use of more than one species in many of these studies yielded a total of 642 cases.

The searches in non-English languages allowed us to increase the amount of studies by 17.1%, providing 103 out of 642 cases. Although there is a general bias in the publication of scientific studies towards the English language (Song et al., 2010), there is also a growing amount of literature in the field of ecology in other languages (Chowdhury et al., 2022). To avoid cascading language biases to ecological syntheses, it is

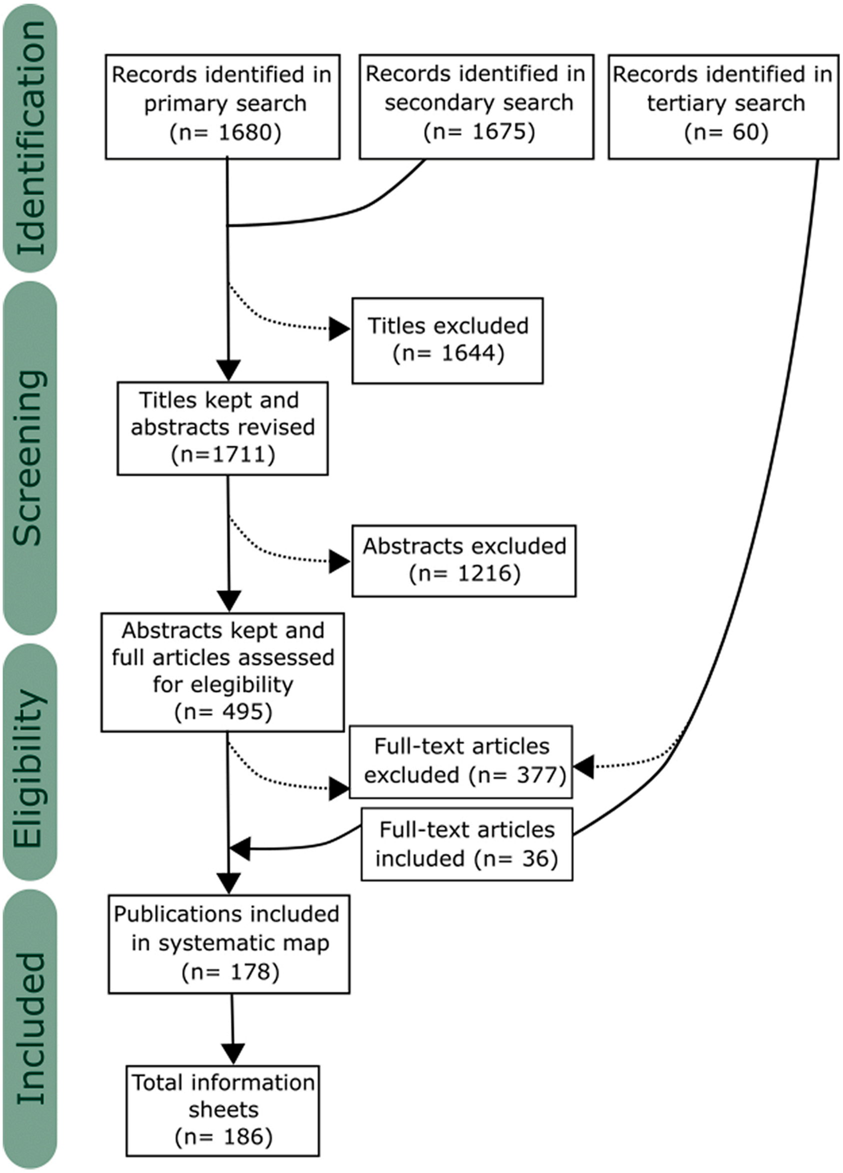

Fig. 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram. Each field shows the number of publications retrieved, kept and excluded after each step of the literature search and selection procedures. The primary search was conducted in Web of Science and Scopus; secondary searches included specialized databases and Google Scholar in eight languages; tertiary searches were made in the reference lists of identified reviews of similar topics.

important that reviews cover more languages, particularly as language bias can be reflected in the effect sizes (Konno et al., 2020).

3.2. Location of studies

The 186 studies were located in 33 countries from five continents, but concentrated in North America ($n = 84$) and Europe ($n = 42$). Oceania, South America and Asia accounted for 31.2% of the studies in practically equal parts, while only four studies came from Africa (Table 1, Fig. 2A). Within the main clusters, the publications were also concentrated in some countries. The USA was the country with the most contributions in North America ($n = 71$), Australia in Oceania ($n = 18$), Spain in Europe ($n = 15$), and Brazil in South America ($n = 15$). According to a recent global analysis of human pressures (Cernansky, 2018), the most suitable areas for ecological restoration are located in North America, Europe and South America (mostly Brazil), which roughly corresponds to the high productivity in terms of research studies in these areas. On the contrary, much of Africa and East Asia also have large areas in need of restoration, but we found a gap of studies in these regions (Fig. 2A). This coincides with many other syntheses in ecology that highlight geographic biases involving large understudied areas in the global South (e.g. Casimiro et al., 2019; Chausson et al., 2020; Leverkus et al., 2018; Sturtevant and Fortin, 2021; Thorn et al., 2018; Watson and Medeiros, 2021).

The studies were located in seven out of the world's nine biomes (classified according to Whittaker, 1975), with about one-third of the studies located in temperate seasonal forests and another third in woodlands and shrublands (Fig. 2A). There was no representation of the tundra and the tropical rainforest biomes. Large-seeded species tend to be the most adequate for both seeding and planting by having a higher probability of germination and success (Ceccon et al., 2016; Loydi et al., 2013) and, in the case of tundra, the lack of studies on seeding *vs.* planting could be related to a low abundance of large-seeded species (Bruun et al., 2008; Jaganathan et al., 2015). Besides, the absence of studies in tundra and tropical rainforests could also be related to these being the two biomes with the highest proportion of the world's undisturbed ecosystems (based on the Intact Forest Landscapes project, Potapov et al., 2008), and therefore with lesser restoration needs. However, the tropical rainforest biome presents large disturbed areas with restoration opportunities (Brancalion et al., 2019; Lewis et al., 2015; Malhi et al., 2014), which reinforces the idea of geographic bias in knowledge towards more developed regions. Across all biomes, the studies were located from sea level to 2400 m elevation, but there was a bimodal and non-symmetric distribution of elevation within each of the biomes (Fig. 2B). Many studies were located in lowlands across all biomes (Fig. 2B), possibly due to their accessibility, but also to their traditional exploitation by humans generating a need for restoration (Aide and Grau, 2004). The second peak in the density of studies across all biomes (Fig. 2B) represents studies in mountains, while intermediate elevations are relatively understudied. A possible reason for restoration efforts at mountains could be related to land abandonment and rural depopulation, which is widespread at high elevations (Lasanta et al., 2016; Rey Benayas et al., 2007).

Table 1
Distribution of the number of publications and studies across geographic areas. Countries that reported one publication and study are grouped for each continent.

Continent	Country	No. Of publications	No. Of studies
North America	USA	70	71
	Canada	9	9
	Mexico	4	4
Oceania	Australia	14	18
	New Zealand	1	1
Europe	Spain	14	15
	Finland	6	6
	Germany	5	5
	Sweden	4	5
	Czech Republic	3	3
	France	2	2
	Turkey	2	2
	Denmark, Hungary, Italy, Luxembourg, Poland, United Kingdom	6	6
South America	Brazil	15	15
	Argentina	4	4
	Bolivia	1	1
Asia	Japan	5	5
	China	3	3
	Lebanon	1	2
	Azerbaijan, India, Malaysia, Taiwan, Thailand	5	5
Africa	Burkina Faso, Cameroon, Democratic Republic of the Congo, Morocco	4	4
TOTAL		**178**	**186**

The main causes of land degradation worldwide include agriculture, mining, deforestation, invasive species, wildfires and overgrazing (Bardgett et al., 2021; Guerra et al., 2020; Medeiros et al., 2022; Oldeman, 1991; Thompson et al., 2013). In accordance with this, the range of causes of land degradation reported by the studies found in our systematic review (Fig. 3A) included agriculture as the most frequently cited (21.8% of studies). The abandonment of agricultural lands is a global phenomenon caused by ecological, socio-economic and mismanagement-related drivers, and it is increasing in recent decades (Rey Benayas et al., 2007). This process can reduce the provision of ecosystem services by triggering ecological processes such as soil erosion and desertification, biodiversity loss or increasing wildfire risk (Mantero et al., 2020; Rey Benayas et al., 2007). Therefore, abandoned agricultural lands represent a focus of restoration actions via revegetation, especially in North America and Europe (Young, 2000). Other causes of degradation included dispersal or regeneration limitations of native species (20.1% of studies), quarry or mining activities (12.3%), and disturbances such as deforestation, wildfires, and the presence of invasive species (each one representing <10%). Among the objectives of restoration, a high number of studies aimed at the establishment of target species (29.6%), habitat conservation (19%) and diversity increase (14.5%) (Fig. 3B). It is noteworthy that about 10.1% of studies did not mention why the land needed restoration and 10.6% lacked information on the targets of restoration.

3.3. Characteristics of habitat and plant material

More than half of the retrieved studies were carried out in forests and woodlands (64%), followed by grasslands (12.9%), wetlands (7.5%), and shrublands (7%, Fig. 4A). The publications report 437 different species from 77 families used in field experiments (Appendix C: Table S2). Most species were trees (56.2%), most of them Fagaceae, Fabaceae and Pinaceae; and shrubs (20.9%), with Asteraceae and Rosaceae as the most frequent families (Fig. 4B). Herbs, grasses and sedges were less studied, with 14.8%, 5.9% and 1.9% of species, respectively (Fig. 4B). The predominance of woody species likely results from their use for restoring previously forested ecosystems (e.g. (Guerra et al., 2020; Medeiros et al., 2022). Besides, they usually have larger seed size, allowing an easy manipulation for revegetation experiments, and a higher germination and success probability than small-seeded species, particularly for seeding (Ceccon et al., 2016; Grossnickle and Ivetić, 2017). However, plant species with small seeds, such as grasses, herbs and sedges, inhabit a wide range of open habitats and could be an essential part of many restoration projects, and several studies exemplify that they can be both seeded and planted (e.g. Valkó et al., 2018; Wallin et al., 2009; Wirth and Pyke, 2003).

Certain characteristics related to plant material can define the success of revegetation and modulate whether seeding or planting will result in more effective restoration outcomes. Among them, seedling age

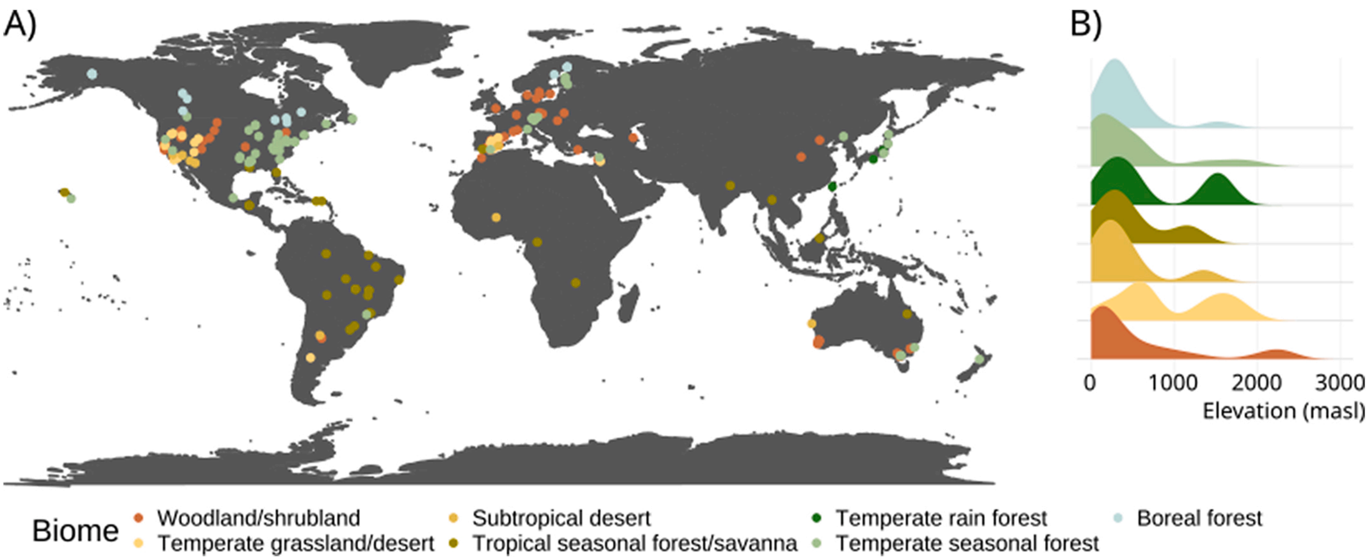

Fig. 2. A) Global distribution of the individual studies identified in the systematic map ($n = 186$). B) Density distribution of the elevation at which studies were located, ranging from sea level to 2400 m a.s.l. Each point indicates a study location and colors illustrate biomes as categorized by Whittaker (1975).

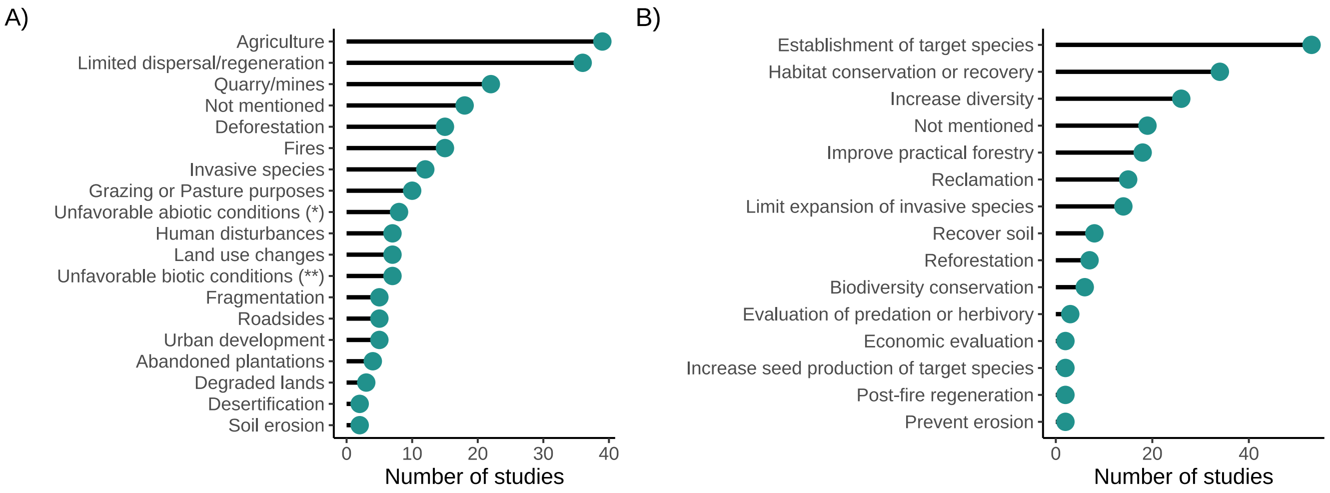

Fig. 3. Rank-abundance of A) causes of land degradation and B) objectives of restoration described in each study. (*) indicates causes of degradation such as poor or compacted soils and droughts, while (**) indicates pests or diseases.

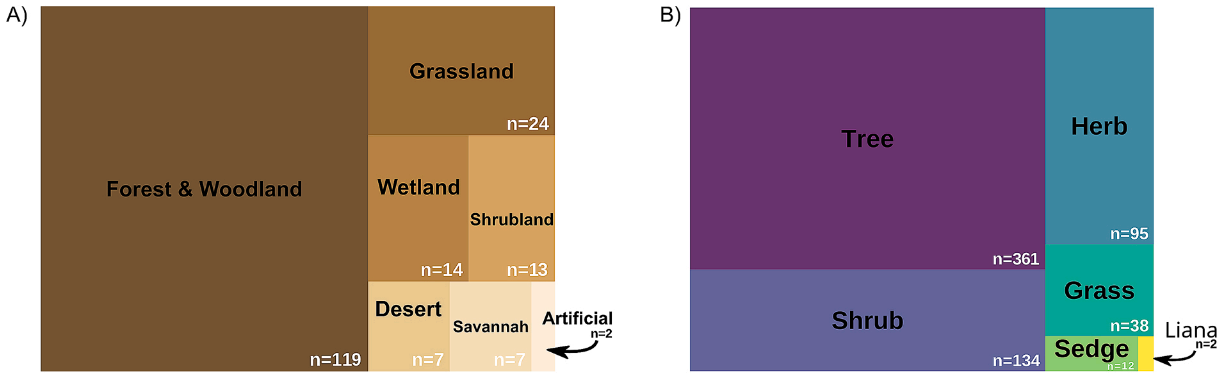

Fig. 4. A) Number of studies by type of habitat ($n = 186$), and B) number of cases by growth form ($n = 642$).

and size at planting can define establishment probability, as taller seedlings tend to perform better (Andivia et al., 2021). However, this relationship is non-linear, as older seedlings growing in small containers for a long time could develop an abnormal root morphology or generate few new roots after planting, resulting in revegetation failure (González-Rodríguez et al., 2011). We found systematic differences in seedling ages-at-planting between growth forms, with trees and shrubs having been cultivated for longer (mean ± SE =11.8 ± 0.6 and 8.5 ± 0.7 months, respectively) than other non-woody species (5.8 ± 1.0 and 4.9 ± 0.6 months for grasses and herbs, respectively).

The origin and provenance of plant material could also be relevant for revegetation success, because local seeds are often better adapted to environmental conditions (Gustafson et al., 2005). Likely for this reason, most of the studies used seeds harvested in the neighbourhood or local areas around study sites for both seeding and planting (Fig. 5A and B). Contrarily, the purposeful use of non-local seeds that can be suitable for ecosystem restoration in a scenario of climate change and shifting disturbance regimes may represent new study opportunities (e.g. Breed et al., 2013; Hancock et al., 2012; Hancock and Hughes, 2014; Leverkus et al., 2021b). Our review also revealed that more than one-third of the studies omitted any information on the seed source (Fig. 5A and B), which represents a critical gap in reporting to better understand the results of revegetation studies.

3.4. *Characteristics of seeding and planting procedure*

Several technical aspects of revegetation can modify revegetation outcomes (e.g. Ceccon et al., 2016; Su et al., 2021; Wang et al., 2021). In our systematic map, some studies applied seed/seedling protection (40.8% of cases, Fig. 6), a key issue in many revegetation trials to prevent predation and/or herbivory (Löf et al., 2019). However, only 27.4% of cases applied the same protection to both revegetation methods, with fences and tree-shelters as the most common ones. In other cases, the type of protection was different across methods (1.9%) or was only applied to planting (11.3%) or seeding (6.5%), which likely generated confounding effects with the implications of revegetation method. Other studies applied watering (32.7%, Fig. 6), yet while half of them applied it to both revegetation methods (16.7%), the other half only applied it after planting (15.9%), which might favour this method and produce bias. Other technical aspects such as pre- and post-revegetation treatments were applied in 68.5% and 49.1% of cases, respectively. In most cases, pre-revegetation treatments were applied to both methods, but in 14.3% of them they were applied only for seeding. As such treatments could regulate seedling performance and revegetation success, they should be taken into account as moderators in potential future meta-analysis (Koricheva et al., 2013). For instance, direct seeding may fail due to seed predation or competition with surrounding vegetation. In such cases, seed protection (such as the use of repellents or physical barriers for predators) and post-revegetation treatments (such as weeding) can increase the establishment rates and field performance (Grossnickle and Ivetić, 2017 and references therein). In addition, irrigation usually improves seedling survival and growth rates (Young and Evans, 2005), which in turn can change the effect of revegetation method (Haroutunian et al., 2017).

A detailed description of the methodology, including technical details and experimental design, is key for reproducibility in any scientific study. However, in this systematic map we observed a widespread lack of information on technical aspects about revegetation. For example, most studies did not report any detail about seed selection (93.9% of cases), seed pre-treatments (74.8%), nursery cultivation method (49.4%), seedling age (36.8%), type of seeding (49.2%), or whether planting was performed mechanically or manually (74%, Fig. 6). This precludes replicating previous research and also learning about how these variables could influence the measured responses. As increasingly recognised, the value of ecological case studies is leveraged when they are collated and research findings are summarised in a broader context (Gurevitch et al., 2018). To achieve this, detailed reporting of meta-data is essential –yet frequently not done (Andivia et al., 2019).

3.5. *Outcomes measured*

Experiments were monitored for a period ranging from one month to 32 years after the seeding or planting. The number of measurements made ranged from one to 40 (Fig. 7). However, most studies included

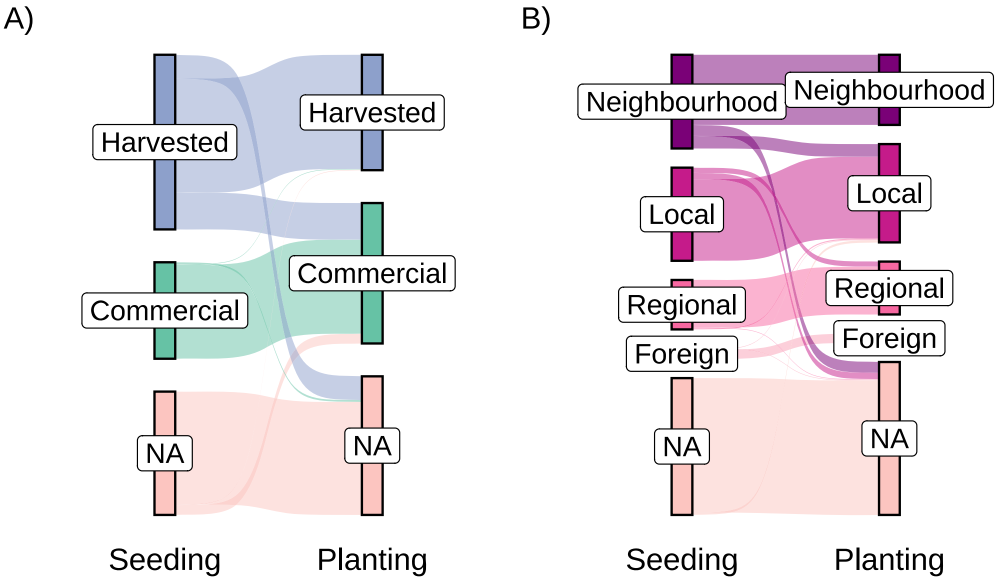

Fig. 5. Flow plot representing the A) origin ($n = 646$) and B) provenance ($n = 667$) of seeds for seeding and seeds/seedlings for planting across cases. Links represent plant material information for seeding and planting coming from the same case. When one species of the same case had more than one value for origin or provenance of plant material, all categories are shown independently; thus, n is greater than the number of cases ($n = 642$, Appendix C: Table S2).

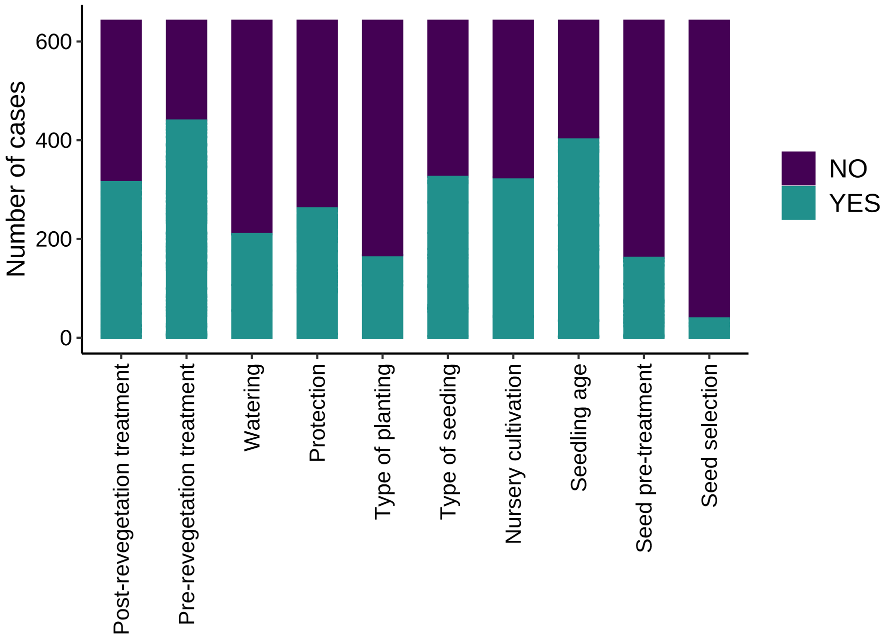

Fig. 6. Number of cases ($n = 642$) in which technical aspects of experimental design and methodology were detailed in the publication or not.

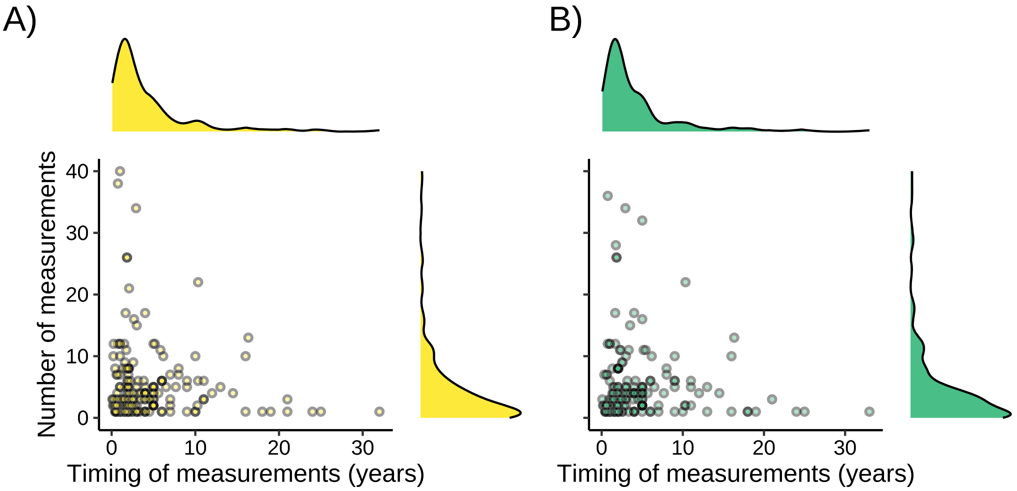

Fig. 7. Time elapsed between seeding (A) or planting (B) and the last measurement of response variables *vs.* total number of measurements in each study ($n = 186$). Density plots for timing (top) and number of measurements (right) were added to the X and Y axes, respectively.

very few measurement times (1–5 in >70% of the cases), and close to 80% of the records were concentrated in the first 5 years, with two years after revegetation being the most common timing (Fig. 7). This has been reported in many other ecological syntheses, in which our understanding is limited to the average duration of research projects (Leverkus et al., 2018; Lozano-Baez et al., 2019; Sasmito et al., 2019). Long-term studies could provide high-value information about the drivers of revegetation success and ecological dynamics in general (Herrick et al., 2006; Leverkus and Crawley, 2020). On the other hand, we found no correlation between the study duration and the number of measurements made (Pearson correlation: $r_{seeding} = -0.01$, $p = 0.98$; $r_{planting} = 0.09$, $p = 0.21$), since the few available long-term studies were only monitored sporadically and the few intensely monitored studies were only followed for a short period (Fig. 7). There is thus a clear gap in detailed long-term monitoring.

The retrieved studies examined a wide range of outcomes, with 40 different response variables (Appendix A). These included 22 demographic response variables, 15 environmental quality variables and 3 economic ones. Demographic variables were the most common (98.4% of the studies, Fig. 8A), especially those related to seedling survival (78.9%) and growth (51.9%, Fig. 8B). This result was expected, as species establishment is usually used as a sign of success in restoration. However, this concentration of response variables limits the scope of a potential future meta-analysis testing effects of seeding *versus* planting to the response of seedling survival and growth.

The second most frequent general outcome was related to environmental response variables, which were considered in 27.4% of the studies. This included the cover, abundance and growth of surrounding

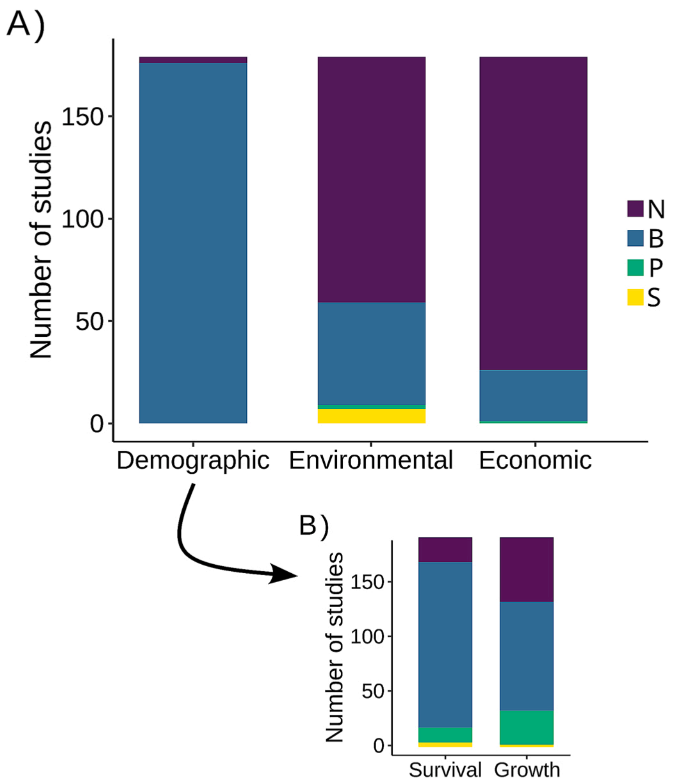

Fig. 8. Number of studies ($n = 186$) where A) demographic, environmental and economic general outcomes were either not measured (N), were measured only for seeding (S) or planting (P), or were measured for both revegetation methods (B). The number of studies reporting the two most common response variables is represented in panel B).

vegetation, which could affect the performance of target species either positively (facilitation) or negatively (competition) (Gómez-Aparicio, 2009). Besides, soil characteristics (8.1%) would indicate the availability of water and nutrients for target seedlings. Given that our searches targeted studies comparing seeding and planting methods, it is understandable that few environmental quality and non-target species outcomes were measured. However, there is room for more research on these aspects, as the targets of ecological restoration go beyond the mere establishment of particular species (Prach et al., 2019), and some key aspects of the seeding *vs.* planting debate –such as the spread of fungal diseases from the nursery (Lilja et al., 2010)– would need to be addressed beyond the target plants themselves. Seeding and planting could also themselves create different environmental conditions –for instance if one method generates a more heterogeneous habitat structure (e.g. Davies et al., 2020, 2013)– and ultimately favour different biotic communities and ecological processes.

Our systematic map revealed an important gap in reporting the costs associated to revegetation, since only 28 out of 186 studies provided data on costs related to restoration management and seedling production (Fig. 8A). Thus, this essential factor for decision-making in restoration projects (Leverkus, 2016; Leverkus et al., 2012), and particularly regarding the seeding *vs.* planting dilemma (Leverkus et al., 2021a), clearly remains a neglected aspect of published studies.

Despite the potential limitations of this systematic map derived from its research question and selection criteria –which excluded studies on only one revegetation method, with non-native species, or for purposes other than ecological restoration– the lack of restrictions on site location, target species, or outcomes measured produce a high generality of our findings. The systematic map followed a rigorous and transparent protocol to minimize common sources of bias, such as reviewer bias or the exclusion of grey literature or non-English language studies (Song et al., 2010). The research clusters and gaps identified in this paper may thus be regarded as a sound guide to inform new field-based and synthesis work.

4. Conclusions

This systematic map shows that much empirical research has already addressed the question of planting *vs.* seeding for revegetation. Whereas the location of available studies is globally distributed, they are strongly concentrated in some countries and important gaps continue existing in the global South. Other research gaps include an absence of studies in tropical rainforests, few at intermediate elevations, a generalised lack of long-term monitoring, and a limited amount of studies addressing the cost effectiveness or broader ecological implications of seeding and planting. Furthermore, the conditions under which studies were conducted are often insufficiently reported, precluding syntheses of technical aspects such as seed selection and pre-treatment, nursery cultivation methods or the provenance of plant material. The application of intensive watering and seedling protection options mainly under the seedling planting treatment represents a potential risk of systematic bias, which must be accounted for in prospective future reviews. Besides, this systematic map reinforces the notion that economic outcomes should be more thoroughly addressed in future research. Finally, our systematic map reveals some areas ripe for in-depth synthesis, notably studies in temperate regions conducted in a timeframe of up to ~5 years in which the establishment of target species is the main objective. This research cluster is broad enough to allow conducting a detailed synthesis to evaluate revegetation success via seeding *vs.* planting measured as the survival or growth of target species, and the degree to which environmental variables, species traits, and study-specific characteristics modulate the effect of revegetation method.

Author statement

Alba Lázaro-González: Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. Enrique Andivia: Investigation, Writing – review & editing, Arndt Hampe: Investigation, Writing – review & editing, Shun Hasegawa: Investigation, Writing – review & editing, Raffaella Marzano: Investigation, Writing – review & editing, Ana M. C. Santos: Investigation, Writing – review & editing. Jorge Castro: Conceptualization, Writing – review & editing. Alexandro B. Leverkus: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Supervision, Project administration, Funding acquisition.

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.

Data availability

The data tables and references of publications included in this systematic map are available as supplementary material in Appendix C.

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Appendix A. Systematic map database and data coding strategy

We present the systematic map database at the level of individual study sites, which is usually encouraged (James et al., 2016). Additionally, we present a second database at the level of species, called cases, within studies.

For each study in the systematic map database (Appendix C: Table S1), we extracted the available information as follows.

1. *Bibliographic information*. Study ID relates to the publications referenced in Appendix C: References.
2. *Search type and source*: We noted whether each publication was retrieved in the Primary search in *WOS* or *Scopus*; Secondary search in *Scielo*, *DOAJ*, *Canadian* or *USDA Forest Service,* or *Google Scholar;* or Tertiary search in *References* of reviews. In case the same record was found twice, the first search and source is indicated. The languages of the main text is also indicated. Columns in the systematic map database: Search, Source, and Language.
3. *Study location:* Country and coordinates were extracted either using the data provided in each publication (specified as "*publication*" in the *Coordinates observation* column) or based on site descriptions from Google Maps ("*map*" in *Coordinates observation*). In case of two or more nearby locations for one study, the coordinates of a mid-point between locations were taken. Elevation was extracted from the publication if available ("*publication*" in the *Elevation observation* column), as a mean of a range provided ("*mean publication*" in *Elevation observation*), or from the WorldClim elevation database (Fick and Hijmans, 2017) with a 30 s resolution ("*WC(0.5)" in Elevation observation*) or 2.5 min resolution ("*WC (2.5)" in Elevation observation*). Columns: Country, Coordinate X, Coordinate Y, Coordinates observations, Elevation, Elevation observations.
4. *Bioclimatic variables:* For each location, two bioclimatic variables were obtained from WorldClim climate data for 1970–2000 (Fick and Hijmans, 2017): mean annual temperature (MAT) and precipitation (MAP). Columns: MAT, MAP.
5. *Biome*: The biome of each location was classified based on MAT and MAP (Whittaker, 1975) and obtained with R package *plotbiomes* (Stefan and Levin, 2020).
6. *Habitat*: The habitats, based on site description and biome, were classified according to the level 1 of the current version (v3.1) of the IUCN Habitats Classifications Scheme (IUCN, 2012). We obtained 7 different habitats classified as follows:

- *Forest & Woodlands*: including all forest types, woodlands, riparian ecosystems, tree plantations, and timber plantations.
- *Savannah*: including savannahs, dehesas, and rangelands.
- *Shrubland*: including shrublands, coastal scrub, chaparral, and riparian ecosystem shrubs plantations.
- *Grassland*: including grasslands, prairies, steppes, and meadows.
- *Wetland*: including wetlands, floodplains, peatlands, and mires.
- *Desert*: including all deserts.
- *Artificial*: including urban areas and agricultural experimental stations.

7. *Standardized taxon:* The scientific name of each species described in each publication was standardized using the *Taxonstand* package (Cayuela et al., 2021), based on The Plant List (TPL, http://www.theplantlist.org/) in R 4.1.3. Version (R Core Team, 2022). This package provides the matched taxon in TPL as *Accepted, Unresolved* or *Synonym.* In the "Standardized taxon" column, the accepted and unresolved species names were kept, correcting the spelling differences, when necessary, while the synonyms were added entirely. All species are shown in the same cell, comma separated.
8. *Causes of degradation and objectives of restoration:* This information was extracted from the introductions and study site descriptions of each publication, where available. We grouped this information in 18 categories of causes of degradation and 14 types of restoration objectives. Some studies presented more than one cause or objective. Columns: Causes of degradation, Objectives of restoration.
9. *Origin and provenance of plant material*: The origin of plant material for seeding (S) and planting (P) was classified in *Harvested*, when seeds were collected from natural areas, or *Commercial*, when seeds or seedlings were purchased at nurseries. The provenance of plant material for seeding (S) and planting (P) was additionally classified as *Neighbourhood*, when the provenance was the immediate vicinity of the study site; *Local*, near the study site; *Regional*, same state or country of study site; and *Foreign*, when plant material came from other states or countries. Some studies presented more than one value. Columns: Origin of plant material (S), Origin of plant material (P), Provenance of plant material (S), Provenance of plant material (P).
10. *Nursery cultivation*: The seedlings used for planting in each study were classified in two categories of cultivation: *Bare-root*, including seeds germinated in Petri dishes or trays, and *Containerized*, including seedlings grown in any size of containers, tubes, peat pellets, plastic bags, and rootrainers. Some studies presented both types of nursery cultivation.
11. *Seed selection:* The seed lot used in each study was selected by one or more several methods. Here, we classified the seed selection method as *Flotation test*, by removing all floated seeds, *Visual inspection*, by discarding all damaged or undeveloped seeds, or *Size*, by keeping larger seeds.
12. *Seed pre-treatment:* Different seed treatments were used before seeding, categorized as *Boiled, Soaked in water, Scarified, Stratified, Stored at low/room temperature, Cleaned, Pre-germinated,* and *Treated with repellent/fungicide.* Some studies presented more than one seed pre-treatment.
13. *Type of seeding and planting*: Different methods of seeding were classified in: *Broadcasting*, when seeding was carried out by broadcast method; *Balls*, when seeds were mixed with substrate to aid in seeding; *Seeding points*, when one seed (*individually*) or ≥ 2 (*group*) were seeded in a seeding point. In addition, we noted if seeding or planting were carried out mechanically or manually (by hand). Some studies presented more than one value. Columns: Type of seeding, Type of planting.
14. *Protection and Watering*: The studies where any type of seed or seedling protection was used are indicated in the *Protection* column as *S*, *P*, or *B,* when protection was implemented at seeds for seeding, planting, or both methods, respectively. In addition, the protection type was also specified in parentheses. Similarly, the *Watering* column indicates if any watering was applied for seeding (S), planting (P) or both methods (B).
15. *Control treatment*: All studies where natural regeneration, without seeding or planting, was measured are indicated with YES in the *Control treatment* column.
16. *Pre- and post-revegetation treatments*: All applied pre- and post-revegetation treatments (e.g. vegetation clearing, weeding, fertilization, herbicide application, etc) carried out in study areas are indicated in both columns, including whether they were applied in seeding (S), planting (P) or both revegetation methods (B).

17. Timing and number of measurements: The columns *"Timing of measurements"* correspond to the time elapsed between seeding (S) or planting (P) and the last measurement in seedlings, independently of response variables. The *"Number of measurements"* indicates the total number of times that the most response variable sampled was measured for seeding (S) and planting (P) method.
18. General outcomes: We recorded all response variables measured in each study and grouped them in three main outcome types: *Demographic*, including all variables related to the plants themselves; *Environmental,* measurements related to ecological quality indicators; and *Economic* aspects such as cost of revegetation. All outcome columns indicate if each response variable was measured in seeding (S), planting (P), both revegetation methods (B) or none (0). Columns: Demographic outcomes, Environmental outcomes, Economic outcomes.
19. Specific outcomes: Demographic outcomes include the following response variables: *survival* (e.g. establishment, plant density, number of live seedlings), *growth* (measured as height or diameter), *number of flowers or inflorescences, number of leaves, basal area, biomass, seedling chemical analysis, cover, crown or canopy size, emergence, germination of second-generation, herbivory, mortality causes, phenology, photochemical efficiency, photosynthetic rate, root characteristics, seed production, seedling status, species richness, stomatal conductance,* and *water-use efficiency.* Environmental outcome is composed by *abundance or biomass, cover, diameter at breast height (DBH), density, diversity, emergence, flowering, height,* and *species richness of non-target species in the study,* as well as*, animal activity, bare ground, light intensity, litter depth or litterfall, radiation,* and *soil characteristics.* Finally, economic outcomes refer to *cost by area or plant* and *costs associated with restoration management.* All outcome columns indicate if each response variable was measured in seeding (S), planting (P), both revegetation methods (B) or not-measured (0). In Appendix C: Tables S1 and S2 only variables measured in more than one study are shown.

We present a second database, Appendix C: Table S2, which is organised at a more detailed level. Besides the information from each study shown in Appendix C: Table S1, this database adds species-level data including the taxonomic description and seedling age at the time of planting. This table includes one row for each species, seedling age, and/or nursery cultivation method within each case.

1. Taxonomic description: The family and authority information of each taxon was obtained with the *Taxonstand* package (Cayuela et al., 2021). Species names as written in each publication were also retained ("Taxon from publication" column), as well as the "Taxon status" as *Accepted*, *Unresolved* or *Synonym* (see point 7 above). In addition, a "Group" variable was added classifying all species in *Tree*, *Shrub*, *Herb*, *Grass*, *Sedge*, and *Liana* according to species descriptions from the publication. Columns: Group, Family, Taxon from publication, Taxon status, Standardized taxon, Authority.
2. Seedling age: For seedlings intended for plantation, we registered the time span (in months) from sowing in the nursery to planting in the field. Seedling age was either extracted directly from the publication ("*publication*" in the *Seedling age observation* column), or as a mean of a range provided ("*mean of a range*" in *Seedling age observation*). In case of more than one seedling age for the same species and study (e.g. González-Rodríguez et al., 2011; Mangueira et al., 2019) or the same age but with different nursery cultivation were used (e.g. Zaczek et al., 1997), all of them were added as different rows. Columns: Seedling age, Seedling age observations.

Asterisks (*) in some cells indicate that the treatments described in the columns on protection, watering, and pre- and post-revegetation treatments were additional factors that were tested in the study. Therefore, when cells are marked with asterisks the factors were not applied to all seeds and/or seedlings of the study. Finally, all missing values or insufficient information about any variable is noted as *NA* in Appendix C: Tables S1 and S2.

Appendix B Selection criteria in abstract and full-article stages

From the publications retrieved in the primary and secondary searches, we removed 1216 and 353 publications at the abstract and full-article stages, respectively (Fig. 1 of main text). Of those, we recorded the reasons for exclusion in 943 and 260 of the publications, which correspond to all publications retrieved in primary and secondary searches, except for Google Scholar. Most publications were removed because they did not meet the inclusion criteria related to the intervention, both at the abstract (60.7%) and the full-article stage (41.9%, Figure A1: green circles). This was because some studies addressed only seeding (I in legend figure) or planting (H), translocation was used as planting method (J) or different species were seeded than planted (G). The second reason for exclusion was study type, due to studies not being based on field or remote sensing, with 28.1% and 30.4% of publications removed at the abstract and full-article stages (Figure A1: yellow circles). Lack of fulfilment of study population criteria led to the removal of 11.2% and 3.9% of publications at the abstract and full-article stages, including studies lacking revegetation (B) or restoration objectives (C), with agricultural purposes (D), or using non-native species (E) or freshwater/marine plants (F) (Figure A1: blue circles). Finally, 8.1% of publications did not measure outcomes for each revegetation method or species independently (L), or did not measure outcomes at all (K, Figure A1: red circles), whereas the remaining 7% were publications that we could not access (P, Figure A1: grey circle).

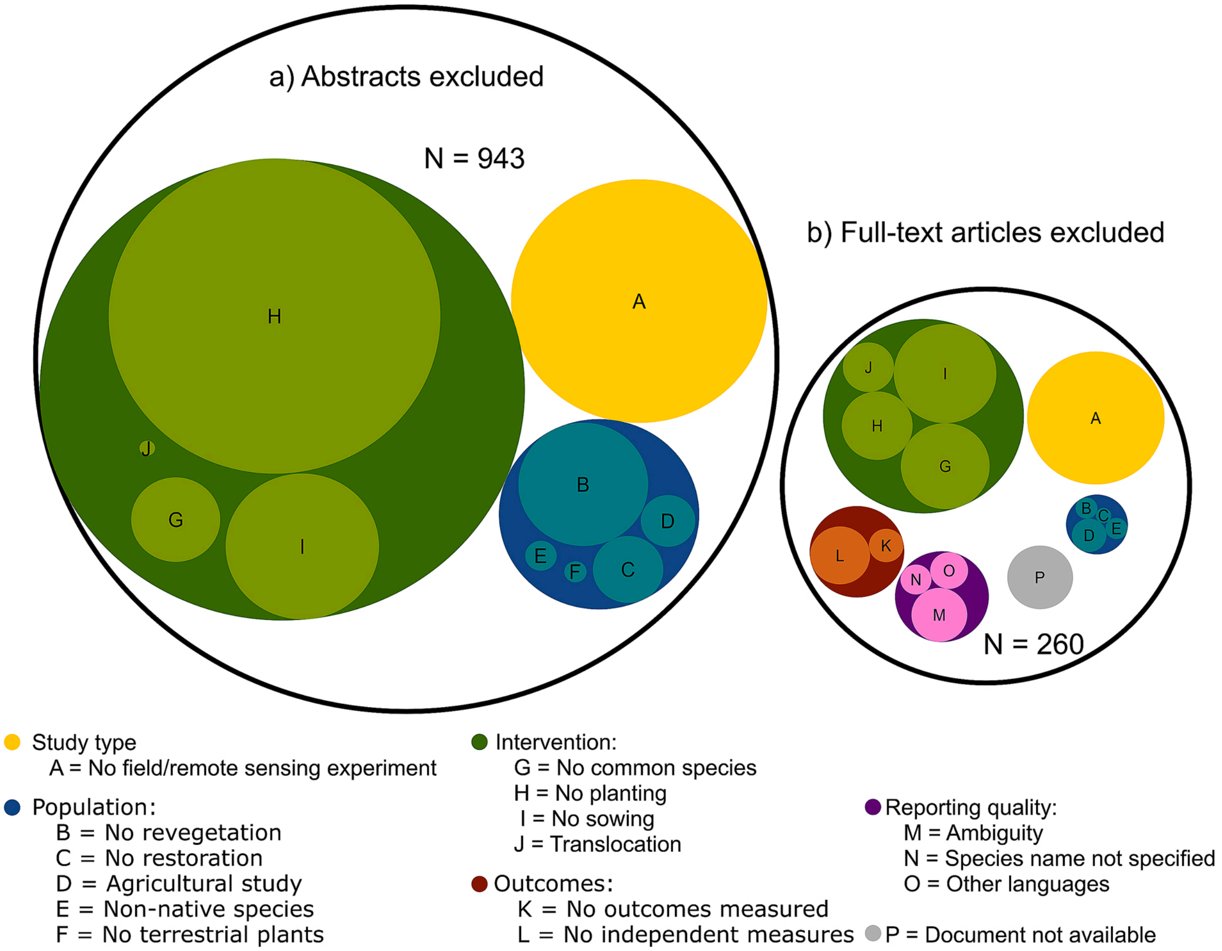

Fig. A1. Number of publications excluded at a) the abstract and b) full-article stages from primary and secondary database searches (except for Google Scholar). Circle size is proportional to the number of publications, the colour of each block indicates the selection criteria, and letters the reason for exclusion.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117713.

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