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Review

Meta-analysis reveals the effectiveness and best practices for the iconic Mediterranean seagrass restoration

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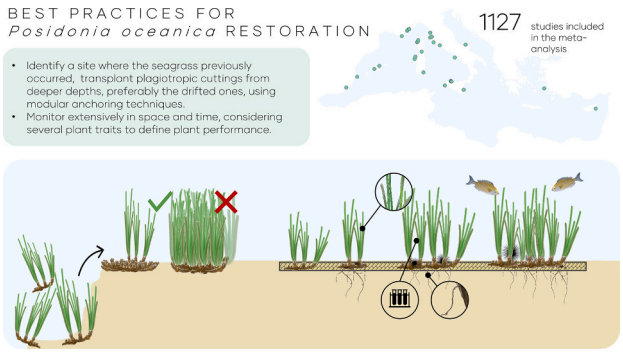
HIGHLIGHTS

- Restoration programs have become a global priority to reverse seagrass decline
- A meta-analysis evidenced the best practices for *Posidonia oceanica* restoration
- The importance of the right selection of donor and receiving site was highlighted
- Restorations should be monitored extensively in space and time
- Higher biological levels should be considered to define the functional recovery

GRAPHICAL ABSTRACT



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ABSTRACT

Seagrass forest restoration programs have become a global priority to reverse their decline and regain their ecosystem services. However, defining the restoration effectiveness has remained controversial, probably due to the wide selection of procedures experienced mainly on short-term periods and local scales. Here, scientific literature from 40 years of experience on experimental works and active restoration interventions of the Mediterranean foundation seagrass *Posidonia oceanica* has been systematically summarized through a meta-analysis. Twenty-five variables concerning the characteristics of the site selection, procedural context, and plant performance evidenced the best practices for the seagrass restoration. Results have evidenced the importance of the correct selection of the donor and receiving site, the use of plagiotropic cuttings bearing at least three shoots, and the need of monitoring the total extent of restored area for long term periods, considering more than one plant trait to define the plant performance. Higher biological levels should be also considered to estimate the recovery of the habitat structure and ecosystem functioning.

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1. Introduction

Over the past century, marine coastal ecosystems have experienced a rapid deterioration, resulting in profound impacts on their ecological integrity, especially for seagrass beds whose loss and fragmentation has recorded up to one third of the original cover (Halpern et al., 2015; Lotze et al., 2006; Waycott et al., 2009). The major stressors driving the seagrass decline are primarily related to the growth of coastal human population, such as increased sedimentary dynamics, mechanical damages, invasion of alien species, and the consequences of climate change (Bockelmann et al., 2012; Giakoumi et al., 2015; Unsworth et al., 2015; Waycott et al., 2009). This has resulted in a loss of essential ecosystem services provided by such foundation species, impairing both ecological and socio-economics features, such as blue carbon sequestration, nutrient cycling, nursery grounds, protecting shorelines from erosion and contributing to sediment dynamics (Fourqurean et al., 2012; Hemminga and Duarte, 2000; Larkum et al., 2006; Macreadie et al., 2014). Moreover, seagrass natural rehabilitation is a process that can take several years for a successful ecosystem re-establishment (Greening et al., 2011; Lotze et al., 2006; Vaudrey et al., 2010). Evidence suggests that protection measures alone are still insufficient to guarantee the preservation of seagrass meadows, probably due to a lack of integration of coastal management approaches to the jurisdictions (Griffiths et al., 2020). Thus, active conservation measures such restoration has become a priority. Therefore, recognizing these threats and setting seagrass restoration initiatives have been proposed as a global priority (Abelson et al., 2016; Possingham et al., 2015; Suding et al., 2015).

Ecological restoration, "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (SER, 2004), is becoming increasingly widespread in several countries, characterised by different species and wide range of areas. With its leading role in global environmental policy (Baker and Eckerberg, 2013; Bullock et al., 2011), ecological restoration has been implemented into international agreements which aims at restoring, by 2030, 350 million of hectares of degraded ecosystems (EC, 2020; United Nations, 2015; UNEP, 2019; 2021). Thus, the systematic understanding of the effectiveness and best practices for seagrass restoration is imperative to improve knowledge and to make better policies on this topic. Their outcomes, in fact, differ widely through time and among actions, ranging from near-total success to complete failure (Orth et al., 2020; Tan et al., 2020; van Katwijk et al., 2016), evidencing that there are still many knowledge gaps that require urgent attention and resolution. The efficacy, cost-effectiveness and scalability of restoration actions may be influenced by the implementation of several planting techniques. This is particularly true for of species-specific contexts, where the generalisation of restoration techniques cannot be applied. Moreover, restoration can also be altered by climate change (Harris et al., 2006; Pramova et al., 2019; Suding et al., 2015), although its effect and magnitude is still uncertain (Choi, 2007; Rohr et al., 2013). This claims for a collaborative effort from scientists and stakeholders to develop a collective knowledge, engage with emerging tools, technology, including anticipatory actions to boost resilience of restored populations to future conditions (Aitken and Whitlock, 2013; Heller and Zavaleta, 2009; Oliver et al., 2012) that lead to efficient seagrass restoration.

In the Mediterranean Sea, seagrass forest restoration programs have been mainly focused on the endemic *Posidonia oceanica* (L.) Delile, 1813, likely due to its unique ecological features. *P. oceanica* is the most abundant seagrass in the infralittoral zone (Boudouresque et al., 2006) with a wide distribution all over the basin (Telesca et al., 2015). *P. oceanica* provides important ecosystem services, spanning from carbon sequestration to benefit for tourism (Pergent et al., 1994; Vassallo et al., 2013). As for other seagrasses, *P. oceanica* beds are likewise exposed to the aforementioned stressors, thereby resulting in local meadow loss across the entire basin (Marbà et al., 2005; Telesca et al., 2015). Considering the very slow growth rate of the seagrass, the natural rehabilitation of this species is difficult, often taking decades for efficient establishment (Greening et al., 2011; Vaudrey et al., 2010). As a consequence, conservation of *P. oceanica* beds through decades has benefited and has been encouraged from the awareness and legal protection measures and regulations, such as the Bern Convention on the conservation of European wildlife and natural habitats (82/72/EEC, The Council of European Communities, 1981), the Mediterranean Action Plan (United Nations Environment Programme, 1976) Habitat Directive (92/43/EEC, The Council of European Communities, 1992), The Water Framework Directive (2000/60/EC, The European Parliament, and The Council of the European Union, 2000) and the Marine Strategy Framework Directive (2008/56/EC, The European Parliament, and The Council of the European Union, 2008).

Many efforts have been made to re-habilitate and re-create ("the act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been reduced or lost" and "the creation for a second time of a system or habitat in order to increase the carrying capacity and the ecological goods and services of the overall system" respectively, Elliott et al., 2007) *P. oceanica* meadows in recent decades to reverse the plant decline and improve the productivity and capacity its ecosystem (Boudouresque et al., 2021). Nevertheless, despite the extensive array of procedures employed in diverse contexts, the outcomes of these interventions remain the subject of considerable controversy. This is partly due to the scarce availability of comprehensive data collection initiatives, which primarily concentrate on the description of novel techniques, rather than on the provision of general and long-term outcomes (e g., Bacci and La Porta, 2022). The reasons underpinning the failure of restoration trials may be complex. Such factors may include, but are not necessarily limited to, inappropriate selection of the site and site-specific procedures, environmental disturbances, inadequate spatial scale, insufficient monitoring periods, and not considering wider integrated coastal zone management plans (Boudouresque et al., 2021; Fraschetti et al., 2021; Mancini et al., 2021; Tan et al., 2020; van Katwijk et al., 2016). Recent evidence, however, identified failure restorations when using sods and soft bottoms, while higher success was linked to hard substrates and plagiotropic rhizomes and seedlings (Pansini et al., 2022; Pergent-Martini et al., 2024). Moreover, current evidence (Abelson et al., 2020; Fraschetti et al., 2021) suggests the need of multidisciplinary research techniques and approaches and the incorporation of socio-economic elements are needed to create opportunities for partnerships. The success of *P. oceanica* restoration actions should be based on past experimental studies, especially those which examined plant responses to both current and future climate (Pansini et al., 2021, 2023; Pazzaglia et al., 2021; Stipcich et al., 2022), relying upon whether transplants are able to persist under future conditions. For these reasons, investigating *P. oceanica* restoration effectiveness through a systematic literature reviewing approach would provide a comprehensive baseline produced by a standardised approach that avoids biases due the review process (Moher et al., 2009).

In this context, this study aimed at identifying the main outcomes of past *P. oceanica* restoration actions through a meta-analysis of literature at the Mediterranean scale. The type of effect of the main techniques and methodologies used for restorations were estimated and quantified to highlight the conditions that would lead to a success or a failure and to assist stakeholders and management strategies. Results highlighted the effectiveness of past restoration actions and helped driving the best practices to inform managers in future operas.

2. Material and methods

2.1. Literature search and data collection

A search of the literature was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Hutton et al., 2015), a protocol developed a priori to minimise the subjectivity during the review process, composed in multiple stages, from the collection of literature data to the compilation of data

required for effect size analyses. The search question and the selection criteria were defined following the PECO formulation guidance (Morgan et al., 2018). The objectives were stated in the primary search question to include all studies that assessed quantitative data to evaluate the effectiveness of *Posidonia oceanica* restoration. Population of subjects (P) included *Posidonia oceanica* as the target population; the Exposure (E) encompassed human mediated active restorations, transplantations, re-creations or rehabilitations in the Mediterranean Sea; reference meadows or initial restoration time were used as Comparators (C); quantitative data on morphometrical, biochemical and life-history plant traits reflected the Outcomes (O) of the restorations.

A literature searching process was conducted using the databases ISI Web of Science (Clarivate., 2024) and Scopus (Elsevier., 2024) to consider peer-reviewed literature, conference proceedings and patents published with no temporal scale or language restriction and a final search date on the 24th of January 2024. Two search strings were performed using specific keyword and Boolean operators and wildcards and undertaken within Title, Abstract and Keywords as follows: (*"Posidonia oceanica" AND ("restor*" OR "rehabilit*" OR "re-creat*" OR "transplant*" OR "re-implant*"))* and (*"Posidonia oceanica" OR "seagrass*") AND *Mediterran* AND ("restor*" OR "rehabilit*" OR "re-creat*" OR "transplant*" OR "re-implant*"))* for a total of 621 initial identified records (Fig. S1). After the removal of the duplicates, 308 documents were examined for the screening process. The selection criteria encompassed all studies that reported on a site where human-mediated interventions were conducted to re-habilitate, re-create or enhance recovery of a degraded or changed *P. oceanica* habitat type (sensu Elliott et al., 2007), where response variables were quantitatively expressed as a measure of transplanting intervention outcome. Only those studies in which the transplanted *P. oceanica* plants could be compared with a control group, (i.e., an untreated reference meadow and initial restoration time) were selected. Secondary documents such as reviews, studies on restoration technique insight, mesocosm experiments, or documents with insufficient data were excluded. Moreover, studies that did not report the mean values of measured response variables, the number of replicates per treatment, or the measures of variability around the mean, were necessarily excluded from the analysis. The suitable records were included for the data extraction and analysis, and when a document contained multiple information, each individual component was analysed within a separate case study. The final dataset was composed by 33 documents (Table S1; Fig. S1), consisting of a total of 1127 case studies, (available in the Pansini et al., 2025a data repository). Twenty-five categorical and continuous variables were then extracted (Table 1). Data was obtained from graphs and figures using WebPlotDigitizer (Rohatgi, 2021), or retrieved directly from tables, main texts or supporting information of the documents.

2.2. Analysis of restoration effect

For each case study ($k = 1127$ in total), the restoration effect size and variance were calculated using Hedges' *g*, which weighs cases by their sample size and the inverse of their variance. Its value can be interpreted as a small, medium, large and very large effect ($|g| \leq 0.2$, $0.2 \leq |g| \geq 0.5$, $0.5 \leq |g| \geq 0.8$ and $|g| \geq 0.8$, respectively), corresponding to a small, medium, large and very large restoration outcome, either success or failure depending on the direction of the *g* (positive or negative, respectively). The value is determined as follows (Borenstein et al., 2009):

$$\text{Hedges}'g = \frac{(\overline{Y}t - \overline{Y}c)}{\text{standard deviation pooled}} x\, J$$

where *Yc* and *Yt* are the mean of the control and transplanted *P. oceanica* groups, respectively, which are divided by the pooled standard deviation (Hedges and Olkin, 2014; Sarà, 2007). *J* is the correction for bias attributed to different sample sizes, calculated as:

Table 1
List of variables obtained from each document with their description and class units.

Variables	Description	Class unit
Physical characteristics of the sites		
Receiving site	Site of the restoration intervention	
Previous *P. oceanica* occurrence	*P. oceanica* occurrence before the decline (categorical)	Yes
		No
Depth	Depth of the receiving site (continuous)	-m
Substrate (CMECS)	Type of substrate in which the intervention has occurred, following Coastal and Marine Ecological Classification Standard (CMECS) (categorical)	Anthropogenic Biogenic Geologic
Substrate	Type of substrate in which the intervention has occurred (categorical)	Anthropogenic rock reef Anthropogenic rock rubble Dead matte Meadow Pebble Sand
Cause of decline	Cause of meadow decline in the receiving site (categorical)	Aquaculture Chemical pollution Mechanical damage None
Cause of decline removal	Removal of the cause of meadow decline in the receiving site (categorical)	Yes No
Donor site	Site of collection	
Depth	Depth of the donor site (continuous)	-m
Cause of decline	Cause of meadow decline of the donor site (categorical)	Mechanical damage None
Donor - receiving spatial distance	Distance from donor to receiving site (continuous)	km
Donor - receiving depth range	Depth difference between the donor site and the intervention receiving site: + if receiving site is shallower; − if the receiving site is deeper (continuous)	m
Procedural context of the transplanting intervention		
Aim	Purpose of the intervention. Experiment is a manipulative approach to test the performance of *P. oceanica* to a specific factor; Compensation is a restoration action to compensate for the loss of a *P. oceanica* meadow (categorical)	Experiment Pilot transplantation Compensation
Classification	Classification of the intervention following Elliott et al. (2007, categorical)	*Re*-creation Re-establishment Re-habilitation
Total restoration area	Total restoration area (continuous)	m^2
n° of shoots/plant portion	continuous	n
Shoot density	continuous	n/m^2
Plant portion type	Portion of the plant used for the transplanting intervention (categorical)	Plagiotropic rhizome Orthotropic rhizome Sod Seedling
Treatment before the intervention	Manipulation applied to the plant portions before the transplanting intervention (categorical)	Cutting preparation Field acclimation Aquaria acclimation Aquaria nutrient input None
Treatment during the intervention	Manipulation of the plant portions during the transplanting intervention (categorical)	Nutrient input Low irradiance

(*continued on next page*)

Table 1 (*continued*)

Variables	Description	Class unit
		High irradiance and warm temperature
		Warm temperature
		None
Plant portion collection	Type of collection of the plant portion used in the intervention (categorical)	Already detached
		Beach-cast detached
		Harvested from meadow
Anchoring technique	Technique applied to anchor the transplanted plant portion to the substrate (categorical)	Mat
		Mesh
		Modular block
		Organic mesh
		Organic peg
		Pot
		None
Season of intervention	categorical	Spring
		Summer
		Autumn
		Winter
Year of intervention	continuous	yyyy
Monitoring time	Time elapsed from the start of the transplanting intervention for each survey	months
Plant performance		
Ctrl type	Type of control used to evaluate the transplanted plants performance (categorical)	Transplanted plants at Time 0
		Untouched reference site
Plant trait	Explanatory variables measured for each survey, for above and below ground tissues. Biochemistry includes elemental and pigment analyses; Development includes growth data; Morphology includes size and biomass metrics, density and cover (categorical)	Biochemistry
		Development
		Morphology
		Survival

$$J = 1 - \frac{3}{4(N_t + N_c - 2) - 1}$$

The pooled standard deviation was calculated as follow:

$$standard\ deviation\ pooled = \sqrt{\frac{(N_t - 1)xs.d._t{}^2 + (N_c - 1)xs.d._c{}^2}{N_t + N_c - 2}}$$

where N represents the sample size and s.d. is the standard deviation of the transplanted or the control group. The Variance for each effect size (V_g) was calculated as follows (Koricheva et al., 2013):

$$V_g = \frac{N_t + N_c}{n_t n_c} + \frac{g^2}{2(n_t n_c)}$$

Then, to investigate any difference in pooled effect size of each considered variable, two types of subgroup analysis were performed, depending on its characteristics (categorical or continuous, Table 1), except for the "removal of the cause of decline", where in all case studies the cause of decline was removed. Mixed-effects models were run testing the effects of the categorical variables, treated as fixed factor and moderator, while mixed-effects meta regression models were conducted with the continuous variables. Each model included the case study number (ID.CS column, Pansini et al., 2025a repository) and the response variable (the measure of transplanting intervention outcome) as a random factor to account for heterogeneity and non-independence of results from the same study (Berlino et al., 2021; Konstantopoulos, 2011).

The restoration effect size for the models were significant at $p \leq 0.05$ and, for categorical variables, if their 95 % CI did not overlap with zero. Tests for moderators (Qm) identified differences between significant effects sizes of each mixed-model.

The meta-analyses were performed with the R metafor package (Berlino et al., 2023; Salerno et al., 2021; Viechtbauer, 2010) using the 'rma.mv' function.

2.3. Publication bias

Since results in meta-analysis might be distorted by publication bias (Koricheva et al., 2013), the overestimate of the restoration effect was evaluated using Egger's regression test (Egger et al., 1997) that included the standard error of the effect size as a moderator (Habeck and Schultz, 2015). Publication bias was detected when the intercept of the model was different from zero at $p \leq 0.05$. In case of potential bias, the data were examined for outliers by looking at the effect sizes with standardised residual with absolute value >3 (Viechtbauer, 2010) using the rstandard function in R. Sensitivity analysis compared fitted random-effects models with and without the influence of the potential outliers and in case of a change of the outcome, outliers detected in the sensitivity analysis were excluded. Then, mixed-effects models were re-run. Otherwise, the sensitivity analyses indicated that results of the models were robust against publication bias (Table S2).

3. Results

Restoration and experimental sites were mostly spanned through the northern Mediterranean Sea, with a higher distribution in Italy (26 sites), while the number of case studies were equally distributed in France and Italy, and with a lesser extent in Spain, Greece, and Cyprus (Fig. 1).

Overall, the effect of restoration in *P. oceanica* was not significant (g = 0.11 ± 0.74; Fig. S2). Nevertheless, restoration interventions performed in more recent years (after 2011; Fig. S3) led to success.

3.1. Subgroup analysis

3.1.1. Physical characteristics of the sites

Significant differences between groups were found in eight out of nine considered variables, all of them with very large restoration effects. The previous absence of a *P. oceanica* meadow in receiving site led to very high restoration failure (g = −1.32 ± 0.55) similarly to transplanting inside a healthy continuous meadow (g = −1.17 ± 0.71) or using plant material coming from a site which was unaffected by stressors (g = −0.81 ± 0.58). On the contrary, successful outcome was associated to shallower transplanting sites, using plant material coming from similar depths or deeper than 15.5 m, and from meadows distancing >173.8 km from the receiving site. Sites in which the meadow declined due to a mechanical damage resulted suitable for restoration (g = 0.82 ± 0.73) while no significant information was gained for other causes of decline, as chemical inputs or aquacultures. Anthropogenic, biogenic or geologic substrates did provide positive nor negative outcomes (Fig. 2, Tables S2 and S3).

3.1.2. Procedural context of the transplanting intervention

P. oceanica restoration was negatively influenced when the extension area was higher than 6.32 km^2 and when transplanted shoot density exceeded 38.9 shoots m^2. Very high failure outcomes were also associated to pilot restoration trials (g = −1.17 ± 1.14) using sods (g = −3.64 ± 2.67), anchoring with mats (consisting of a gridded module covered by organic tissue and filled with sand; g = −5.84 ± 4.53), and the transplanting during autumn (g = 0.61 ± 0.53). Conversely, the use of plagiotropic rhizomes, with a minimum of two shoots per ramet, led to restoration success (g = 1.12 ± 0.55), while no information on restoration effect was detected for the use of orthotropic shoots, seedlings or mixed material. Restoration classified as re-habilitation were more

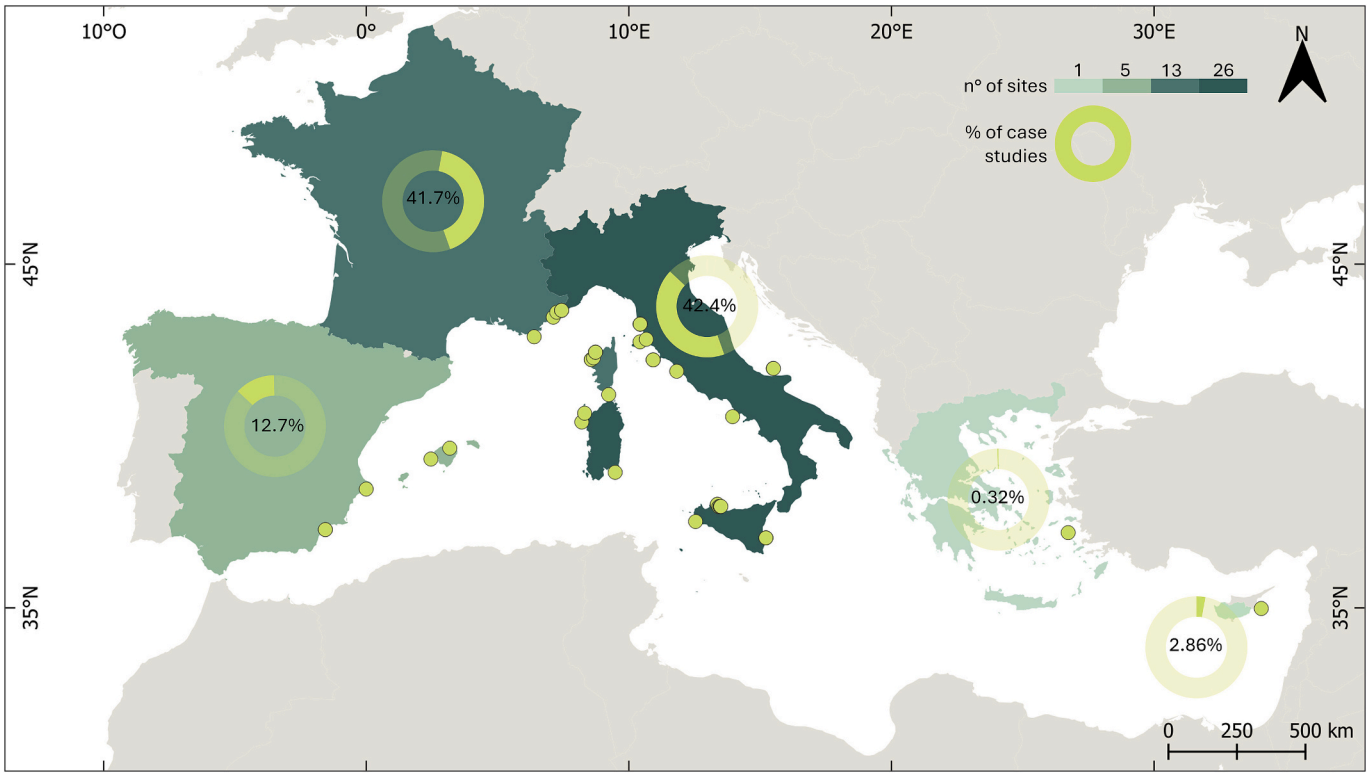


Fig. 1. Geographical distribution of the study sites.

successful (g = 0.79 ± 0.78) with respect to re-creations and re-establishments. A positive effect was detected adding nutrient input (g = 0.77 ± 0.57) and anchoring the plant using a modular system (i.e., modules containing several samples, such as grids; g = 1.85 ± 1.32) with respect to individual or none anchoring techniques. Moreover, first signs of success resulted visible after 20 months of monitoring. Restoring plants, whether already detached or harvested from meadows, did not differ significantly, as the plant treatment before transplantation (as cutting preparation or material acclimation) did not lead neither to positive nor negative outcomes (Fig. 3, Tables S2 and S3).

3.1.3. Plant performance

Restoration evaluation was overall dependent on the plant trait considered: where plant survival was used, a strong negative effect was evidenced (g = −3.50 ± 0.58), while the opposite trend was detected using plant size metrics, biomass and growth measures (i.e., morphology and development g = 0.92 ± 0.56 and 1.06 ± 0.82, respectively), regardless the type of control group (whether a reference meadow or the restoration starting time). None of the selected studies included analyses on biodiversity associated to *P. oceanica* ecosystem (i.e., feeders, herbivores, predators; Fig. 4, Tables S2 and S3).

4. Discussion

4.1. The effect of restoration in Posidonia oceanica is hampered by uneven results

This meta-analysis provided information on the restoration effectiveness of the foundation seagrass *Posidonia oceanica,* investigating a total of 25 variables regarding the transplanting context, tools, techniques, and plant performances. Although the issue has been evaluated by a small portion of studies and the high heterogeneity of the available data, the approach of the meta-synthesis allowed estimating potential patterns of success or failure in restorations to foster profitable actions and minimise the meadow regression (resumed in Table 2). Generally, the obtained evidence gave both expected results and novelties compared to previous *P. oceanica* restoration reviews that used different approaches (Boudouresque et al., 2021; Pansini et al., 2022; Pergent-Martini et al., 2024). Our synthesis of the evidence highlighted that the overall effect of restoration on *P. oceanica* did not lead to a significant outcome, likely for the wide portfolio of practices used for the restoration of the seagrass, taken as a whole, which may have hampered conclusive findings (Boudouresque et al., 2021; Pansini et al., 2022). This result is in contrast with Pansini et al. (2022) review that reported a higher restoration success in the selected studies, although the restorations were defined as successful only when specified by the authors of each case study. However, this evidence has showed the novelty that *P. oceanica* restoration actions are increasing in success, as a slight trend is detectable in those performed after 2011, indicating that the development of tools and procedures has advanced since previous lessons have been learned, including failures.

4.2. Physical characteristics of the sites

Important significant effects need to be related to site selection. The very large failure effect of restorations in sites where *P. oceanica* never occurred indicated that the habitat suitability for the persistence of this slow-growing species (Boudouresque et al., 2006) should be absolutely evaluated prior to the action. Conversely, restoration efforts in sites affected by mechanical damage, such as anchoring, dredging, bombing or shipwrecks, have shown positive outcomes, likely because these stressors did not significantly disrupt the environmental conditions required for the successful establishment and stabilization of new plants. These results evidenced the need of an accurate identification of the restoration site, also considering field and transplant tests (Fraschetti et al., 2021; Pirrotta et al., 2015; van Katwijk et al., 2009).

Results gained did not evidence a favourable substrate type, although in the past evidence dead matte and soft bottoms were considered favouring and compromising transplanting actions, respectively (Pansini et al., 2022; Pergent-Martini et al., 2024). This is possibly

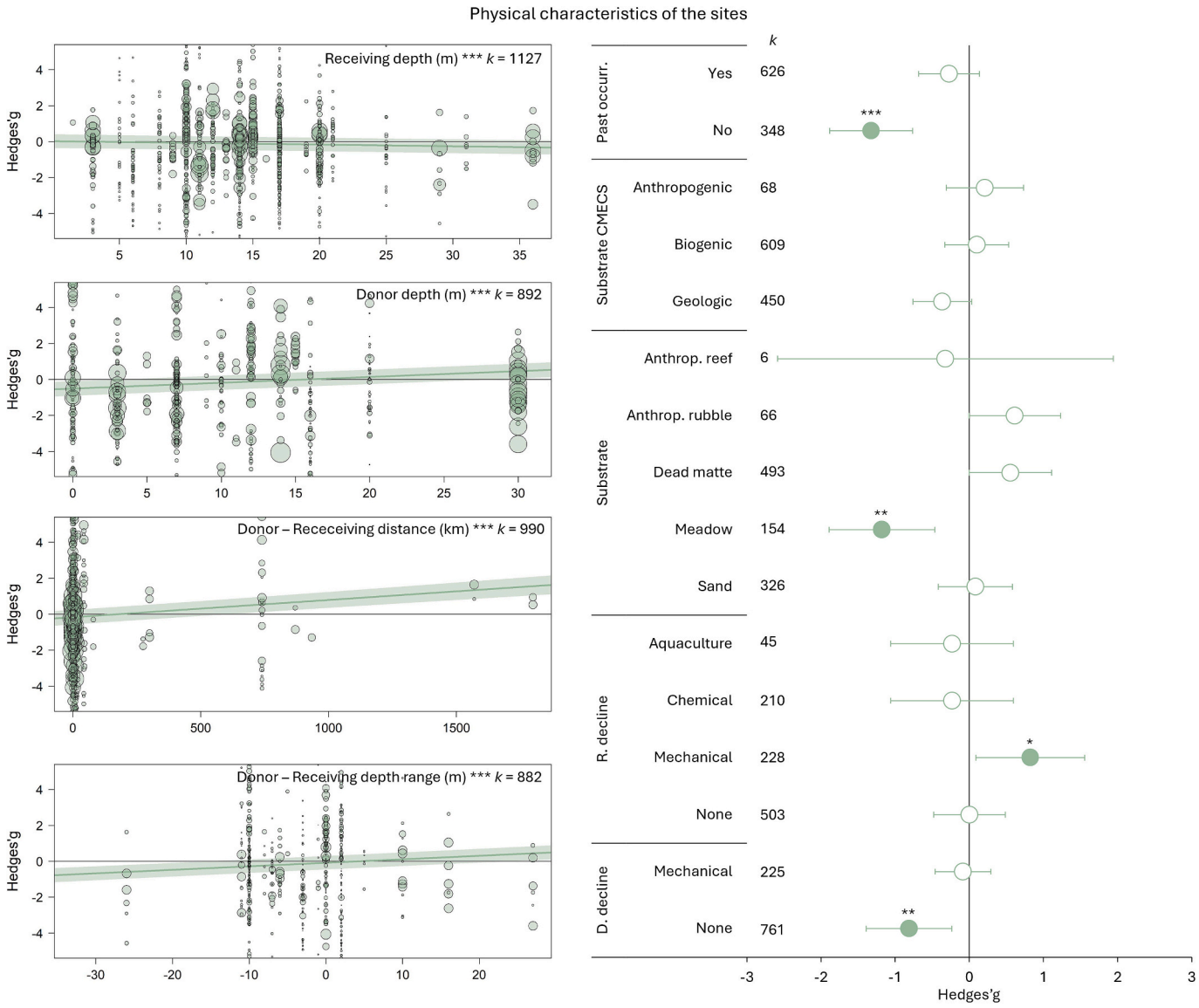


Fig. 2. Meta-regressions and Forest plot of the variables concerning the physical characteristics of the sites. Point size in meta regressions is related to the SE of each case study; lines indicate 95 % CI. Asterisks indicate significance level (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$). Occurr. = occurrence; Anthrop. = anthropogenic; R. receiving site; D. = donor site.

due to the high ability of the plant to colonise both soft and hard bottoms (Hemminga and Duarte, 2000). Restoring patches inside or very near living meadows resulted unsuccessful, confirming previous restoration guidelines (Boudouresque et al., 2021). This may be interpreted as due to the competition for resources (e.g., light and nutrients) among unmanipulated plants inside a meadow (which can benefit from clonal integration) with the transplanted ones, with the former advantaged on the latter. Such evidence should thus discourage interventions aimed at bridging the gap between very small, fragmented meadows which, conversely, seemed to have risen very recently (author's personal observation).

Information was also gained on the selection of appropriate donor plants: transplanting cuttings that did not experience any (direct) cause of decline resulted less suitable for restoration purposes than stressed cuttings, showing to be poor resistant to transplants. Unfortunately, so many past restorations have been the result of compensatory measures to coastal development (Boudouresque et al., 2021) and were made by destroying unstressed meadows: based on the evidence here gained, future proposals should be designed with weak expectations and their rejection should also be considered.

Moreover, suitable characteristics seemed to be achieved by restoring with genetically diverse donor material, as the further the donor site, the better the success. This could contribute to seagrass productivity and recovery potential (Procaccini and Piazzi, 2001; Reusch et al., 2005; Reusch and Hughes, 2006; Williams, 2001). A significant restoration success is also showed when transplanting plants of similar origin, or deeper than 4.34 m respect of the receiving sites, confirming previous guidelines (Pergent-Martini et al., 2024), suggesting that the suitability of a depth range may vary depending on environmental characteristics (Dattolo et al., 2013; van Katwijk et al., 2009) such as higher light availability which can promote plant performance (Mancini et al., 2021; Ruiz and Romero, 2001). Thus, the focus of successful restoration should be on using plants that may acclimatize to the local environmental and climate conditions and that thus may also increase the probability that the meadow would be adapted to climate change effects (Coleman et al., 2020), although a realistic restoration action should also prioritise a reasonable cost-effectiveness of transplantation.

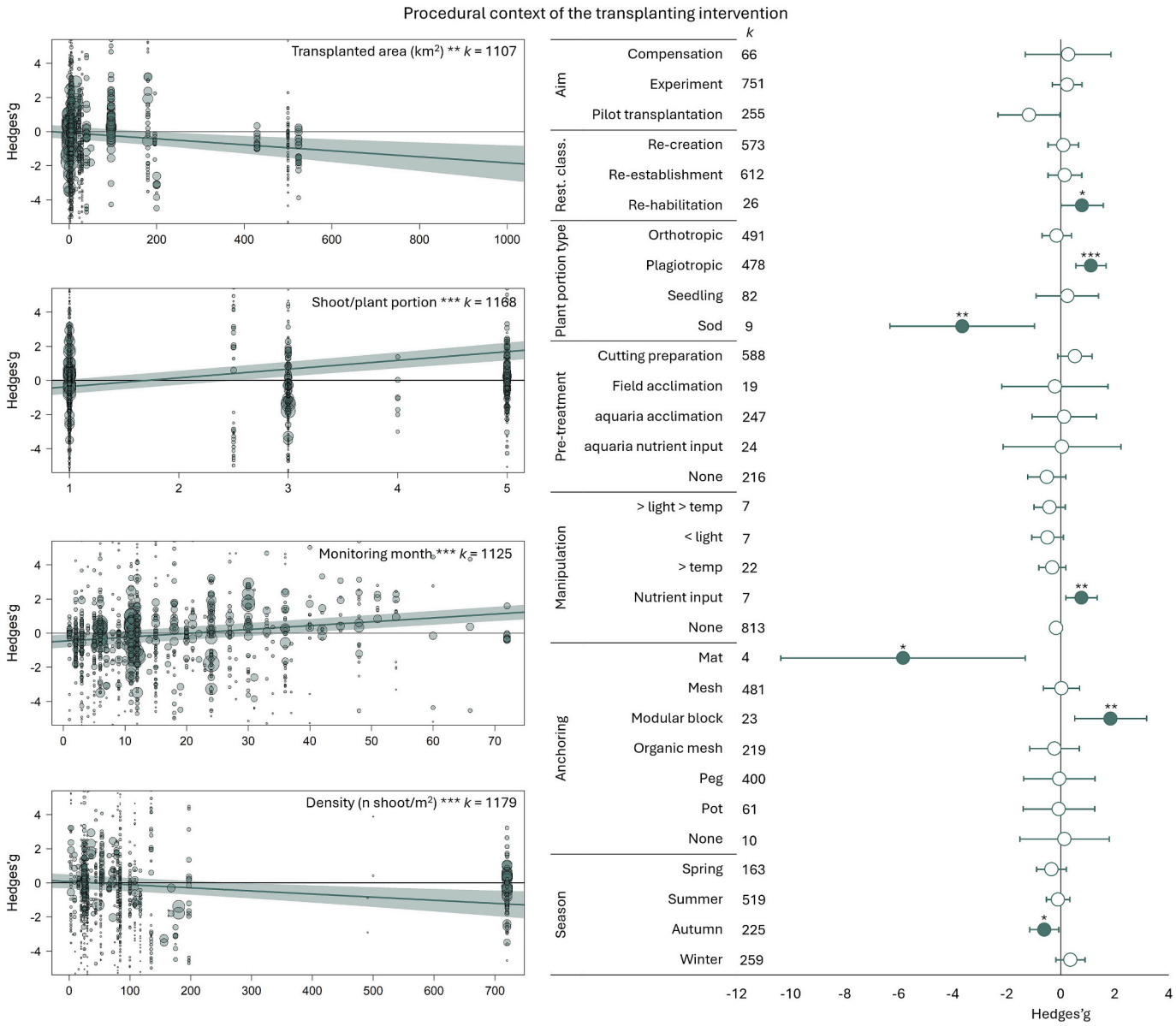


Fig. 3. Meta-regressions and Forest plot of the variables concerning the procedural context of the transplanting interventions. Point size in meta regressions is related to the SE of each case study; lines indicate 95 % CI. Asterisks indicate significance level (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$).

4.3. Procedural context

Subgroup analyses on the procedural context of the past restoration actions revealed the importance of considering the functional traits of *P. oceanica* and the correct planning, monitoring, and management strategies. Specifically, successful outcomes were evidenced by transplanting plagiotropic cuttings (especially when bearing more than two shoots) and by adding nutrients, while strong negative effects were shown when using sods as plant material and when transplanting at shoot density higher than 40/m^2). Ecological functions of the shoot orientation in seagrasses are well recognised: plagiotropic axis assumes the role to anchor the plant to the substrate, allowing the horizontal spread and rapid growth (Hemminga and Duarte, 2000), while orthotropic orientation, typically occurring in the inner part of the meadow, is to escape from high sedimentation. Sods, since are collected within the meadow, are mainly made of orthotropic shoots, and can be more susceptible to hydrodynamic forces, than the single transplanted cuttings. In addition, when plagiotropic ramets are longer than the apical-penultimate shoots, the older ones can ensure the ramet propagation and maintenance, providing resources to the younger one (Marbà et al., 2002; Ruocco et al., 2021). Transplanting seedlings were the only other plant material that did not provide significant results, although previous reviews considered them successful (Pansini et al., 2022). While the availability of seeds and seedlings could be supported by an intensified plant sexual reproduction in response to climate change and its use can increase genetic diversity (Kendrick et al., 2017; Pansini et al., 2025b; Stipcich et al., 2024), thereby reducing the impact of collecting cuttings directly from meadows, further investigations and pilot trials are still required to find conclusive evidence on restoration success.

Restoration success is unaffected by any pre-treatment of cuttings before the transplantation (e.g., acclimation period), but plant performance may be increased by the addition of nutrients in the restored area (i.e., photosynthetic activity, P and N storage; Agawin et al., 1996; Ceccherelli and Cinelli, 1997; Leoni et al., 2007), so that the use of enriched zones, at least in the first time of restoration and with a rigorous monitoring program, should be encouraged.

Furthermore, important indications have emerged regarding the transplanting season which have advised against restoration only in the

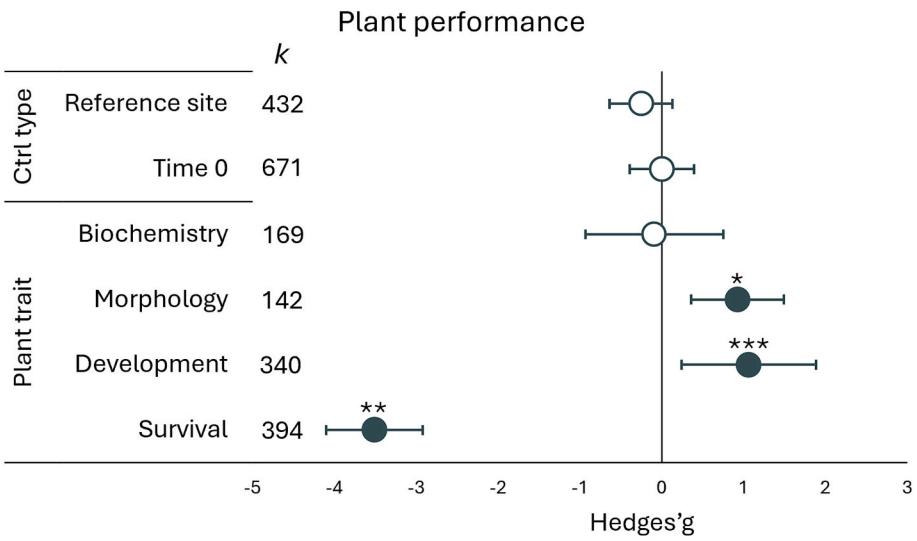
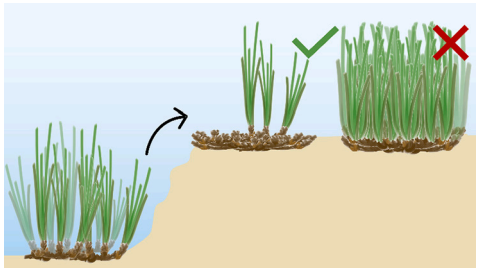
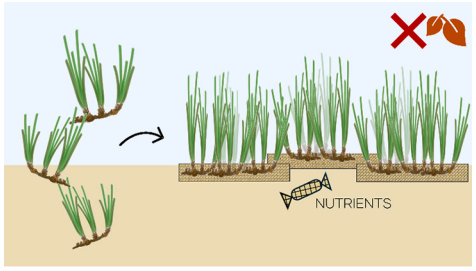
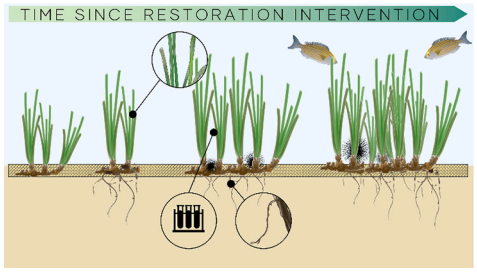


Fig. 4. Forest plot of the variables concerning the plant performance. Asterisks indicate significance level (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$). Ctrl = control, Time 0 = transplanted plant at initial time of transplantation.

Table 2
Summary panel on the best practices for *Posidonia oceanica* restoration.

Best practices for *Posidonia oceanica* Restoration	
	Physical characteristics of the sites • the past occurrence of *P. oceanica* in the restoration site is essential • assessing the conditions of environmental suitability after the cause of its decline • avoiding transplants inside meadows • transplanting diverse cuttings guarantying genetic variability • moving cuttings from deeper donor sites to shallower depths to boost plant performance
	Procedural context of the transplanting intervention • using plagiotropic cuttings bearing at least two shoots • the use of drifted or harvested cuttings do not affect restoration outcome • avoiding the transplantation during autumn • considering the addition of nutrients during the first period of restoration • preferring modular anchoring methods
	Plant performance • preferring a small restoration area and surveying its whole extent of for at least 20 months to assess the early success • investigating more than one plant trait to define plant performance, not limiting only on survival • estimating higher biological levels as ecosystem structure and functioning

autumn period, contrary to previous evidence that indicated only spring as the favourable season (Pergent-Martini et al., 2024). This is not surprising, considering that in autumn the seagrass has a sort of physiological senescent stage with low photosynthetic activity which could increase the plant vulnerability to both manipulations and external influences (e.g. storms) with respect to other seasons (Alcoverro et al., 1997; Pirc, 1989). Therefore, in large restoration actions that require several months of set-up, transplanting actions should probably be interrupted from summer to winter.

Furthermore, information for *Posidonia oceanica* restoration was also gained from the lack of significant effects of other variables. For example, since the performance of cuttings collected among those drifting on the sea bottom did not differ from those manually detached from a meadow, restoring with the formers should be preferred because

is based on wreck material and does not impact a healthy meadow and because it increases the genetic variability (for the multiple origin of cuttings) of the restored patches (Balestri et al., 2011; Ferretto et al., 2021; Mancini et al., 2022; Pansini et al., 2024). From the high variety of tools and techniques involved in plant anchoring, the use of modular blocks, as frames, and biomats, seems to guarantee not only the right adhesion to the substrate, but also the stability of sediments, enhancing the colonisation of other organisms that contributes to re-creating the natural structure of the ecosystem (Piazzi et al., 2021). Further, a very strong failure technique was the use of "mats", gridded structures covered by organic tissue and filled with sand, where cuttings are placed above the grid. Fortunately, this technique was only used in few pilot studies and then abandoned because deemed unreliable (Bacci et al., 2014).

Results related to restoration planning and management highlighted a poor probability of success when transplanting for pilot restoration purposes, although it is well known the importance of conducting pilot restoration before the full-scale restoration to identifying sites with high chance of restoration success (Alagna et al., 2015; Calvo et al., 2021). However, if pilot restorations are not reliable, transplanting additional pilot plots or testing alternative methods should be conducted prior to moving on to a full-scale restoration. Yet, none of the extensive compensation measures included in this review relied on unsuccessful pilot transplantation attempts. The performance of transplanted plants was negatively influenced by the increase of the spatial scale. This finding is probably related to the slow growth rate of *P. oceanica* with respect to the other seagrasses, likely may explaining the contrasting results obtained by van Katwijk et al. (2016). Particularly, also a lack of an extensive monitoring in the whole restored area may have prevented both a reliable plant evaluation and a restoration maintenance during the visits. This life plant trait may also help interpreting why long-term monitoring (although the availability of data remains limited) was positively associated to restoration outcomes, as if only through several years since restoration set-up one can reasonably expect a restoration success. Additionally, monitoring surveys during the first two years (Boudouresque et al., 2021; Pansini et al., 2022; Pergent-Martini et al., 2024) may be misleading, because patches may suffer of eventual losses as the plant may not yet fully established in the new environment. This overall corroborates the requirement for this foundation species of at least 4 years to evaluate the restoration effectiveness (Bacci and La Porta, 2022; Pansini et al., 2024; Pirrotta et al., 2015).

Predictably, rehabilitation actions were positively evaluated. In fact, the prerequisite of habitat suitability can only be guaranteed by the presence of *P. oceanica* meadows before the cause of decline at the restoration area, that often is not ensured by the re-creation of a whole ecosystem (Elliott et al., 2007).

4.4. Plant performance

Finally, the effect of *P. oceanica* restoration success was also evaluated depending on the plant response. Consistent results were obtained regardless the type of control used, whether the restoration initial time or a reference meadow, suggesting that all the plant traits considered in this review are reliable proxy of the success of intervention, independently of the elapsed time since transplantation. Although some evidence suggests that restoration success can be achieved when >50 % of transplanted individuals survived for the entire restored area (Fraschetti et al., 2021), this binomial variable (alive or dead) could be more appropriate in describing the transplantation (but not restoration) outcome (Pergent-Martini et al., 2024). In this study, negative outcomes were associated when evaluating restoration success in terms of survival rate (rate of existing individuals from the initial plantings), highlighting the importance of always adding to survival rates at least one more plant trait that allows estimating any changes in plant performance. In fact, contrary to survival, morphological and development functional traits led to positive outcomes, confirming that when site conditions are suitable, the plant invests more in morphology and development to colonise the new environment (Calvo et al., 2021). Moreover, using these traits would better predict the recovery of habitat structure and ecological functioning, leading to a more comprehensive restoration outcome. Results also highlighted that *P. oceanica* restoration is not yet evaluated on the recovery of its ecosystem traits which remains a big gap to be investigated. At this purpose, many recent techniques should be implemented to assess the ecosystem status of restored meadows, as the ecosystem-based quality index (e.g., EBQI, Personnic et al., 2014), photogrammetry-based mapping (Mancini et al., 2022), and soundscape analysis (La Manna et al., 2024).

5. Conclusions

Restoration success can only be achieved if actions are based on evidence shared with the stakeholder community through published documents that may serve first to identify at least "*what not to do*" and then to learn lessons to improving the future actions. This meta-analysis, collating the experiences of 40 years of research and transplantations of *P. oceanica*, quantified through a standardised approach the effect size of 25 transplanting conditions (Table 2). However, we are aware that this work can only provide generalities that often cannot be applied to all possible conditions, so that local knowledge is still also crucial for the success of seagrass restoration. Moreover, much information can still be gained by investigating further environmental conditions and contexts not considered here through primary field research. This analysis was fostered by the fact that in the whole Mediterranean Sea seagrass restoration actions have been notably increased in number through the last years and will certainly become more common, as both the result of protected area management and to compensate coastal impacts. This suggests that within a decade, significantly more data may become available from newly restored meadows and long-term monitoring of older restoration sites. Such data will be crucial for validating and strengthening the conclusions drawn so far.

CRediT authorship contribution statement

Arianna Pansini: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Manuel Berlino:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Maria Cristina Mangano:** Writing – review & editing, Project administration, Funding acquisition. **Gianluca Sarà:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition. **Giulia Ceccherelli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179325.

Data availability

A complete dataset used for the meta-analysis was deposited in Dryad repository (DOI: 10.5061/dryad.fxpnvx13p).

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