Scaling Seagrass Restoration

KEY CHALLENGES AND EMERGING OPPORTUNITIES

The Nature Conservancy

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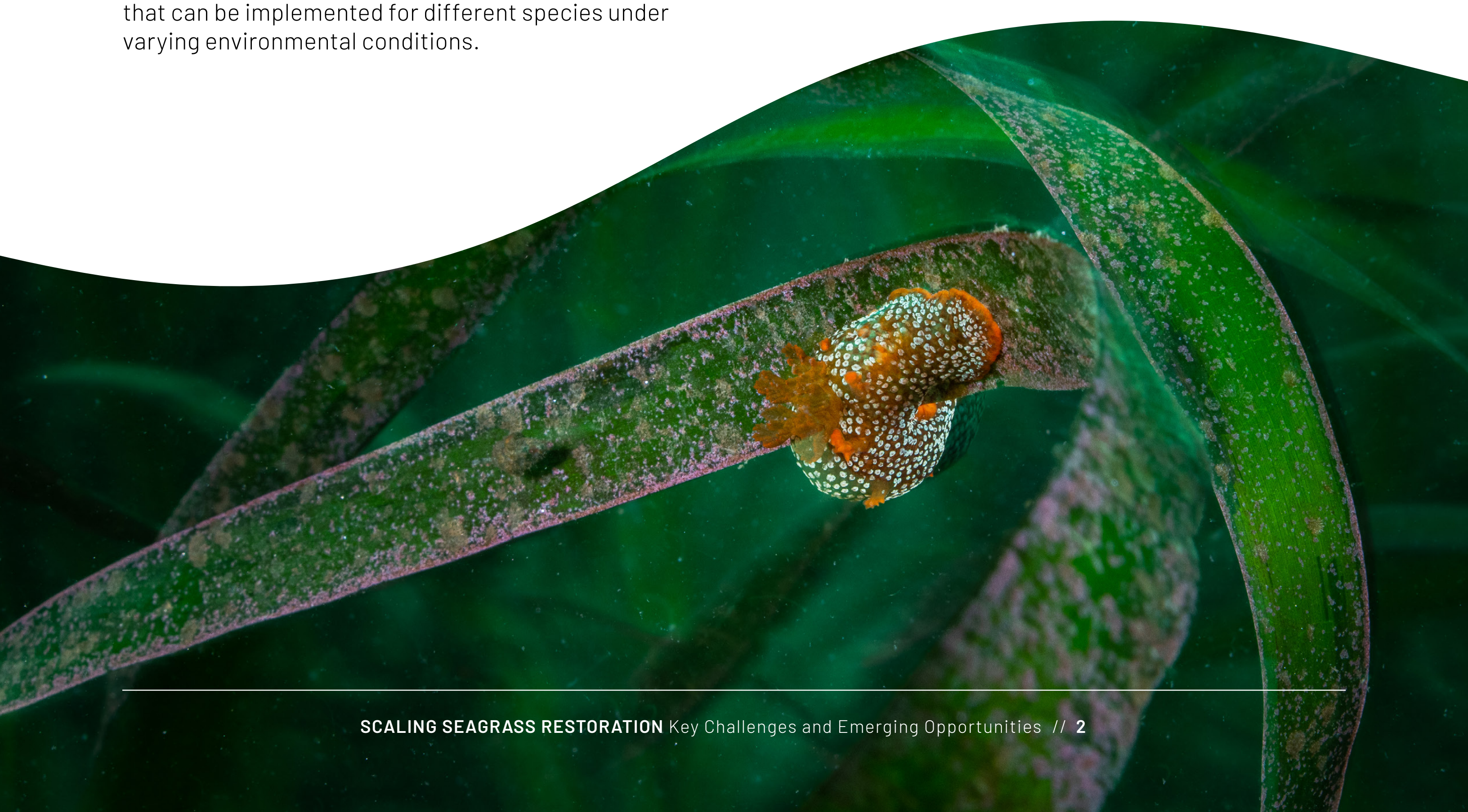
SECTION 1 EXECUTIVE SUMMARY

Seagrasses provide the foundation for one of the most biodiverse, productive, and ecologically important ecosystems on Earth. They support thriving coastal ecosystems through sediment stabilization, and they augment the production of diverse and abundant juvenile and adult species, including those that comprise the backbone of recreational and commercial fisheries. Seagrasses are also considered one of the most globally important blue carbon ecosystems. However, coastal development, pollution, and anthropogenic climate change are rapidly destroying these keystone coastal ecosystems. With many of these threats ongoing, critical ecosystem functions and services continue to be lost, and natural recovery may not be possible without active restoration. However, to date, most existing restoration efforts are relatively small-scale (average planting areas <100 m^2), expensive, and experience low survival.

To address these challenges, The Nature Conservancy embarked on an effort to explore and advance ways to accelerate the pace and scale of seagrass restoration. Our investigation relied on 21 expert interviews and 21 expert surveys from academic, private consulting, NGO, and government affiliated individuals to explore the limitations, constraints, and challenges facing seagrass restoration practitioners. The interviews focused on identifying bottlenecks and major challenges to scaling restoration in order to reveal cross-cutting solutions that can be implemented for different species under varying environmental conditions.

Across both interviews and surveys, funding was identified as the most prevalent challenge for its role in preventing successful scaled seagrass restoration, as it was often limited and only available for short-term projects. Most experts also highlighted bottlenecks associated with the regulatory gauntlet of regionally specific and non-standardized processes required for permitting seagrass restoration projects. Inadequate public perception and community engagement and the general lack of awareness of the value of seagrass ecosystems has also impeded scaling. Finally, a lack of infrastructure to support restoration efforts, as well as insufficient knowledge of basic components of the biology, ecology, and genetics of seagrass were highlighted as common factors hindering scaling efforts.

Actionable solutions from information sharing within and outside of the seagrass restoration community to methods to improve community engagement were further discussed, and seed-based restoration emerged as a consensus opportunity to scale seagrass recovery. However, critical information gaps exist, and immediate next steps will require advancing our understanding of seagrass biology and ecology, including aspects like flowering and germination timing to aid seed collection, production, and storage.



SECTION 2

BACKGROUND

Seagrasses—submerged, flowering marine plants—provide the foundation for one of the most biodiverse, productive, and ecologically important ecosystems on Earth. Found in meadows along the coast of every continent except Antarctica (UNEP, 2020), seagrasses support thriving coastal ecosystems through sediment stabilization (Hemminga and Duarte, 2000), and they augment the production of diverse and abundant juvenile and adult species, providing essential nursery habitat and foraging grounds for nearly 20% of the world's largest fisheries (Unsworth et al., 2019). Seagrasses are also considered one of the most globally important blue carbon ecosystems, accounting for roughly 10% of the total carbon sequestered in the ocean (Duarte et al., 2005).

But seagrass meadows are currently under threat. Coastal development, pollution, and anthropogenic climate change are rapidly damaging these keystone coastal ecosystems, and at least 29% of the world's seagrass habitat has been destroyed (Waycott et al., 2009). With many of these threats ongoing, critical ecosystem functions and services continue to be lost.

To address threats to seagrasses, seagrass restoration has gained traction as a critical conservation intervention. However, its success rate has paled in comparison to other marine restoration efforts (Bayraktarov et al., 2016). An assessment of nearly 2000 seagrass restoration trials globally, found that most projects are small-scale, with planting areas less than 100 m^2 on average, and survival is low at <40% after three years (van Katwijk et al., 2016). Similarly, a sweeping review of seagrass restoration projects conducted between 1989 to 2020 along the US West coast found that 30-60% of restoration efforts failed to achieve stated objectives (Ward and Beheshti, 2023).

Despite myriad rapid advancements in seagrass restoration, a critical gap remains in identifying the key bottlenecks preventing restoration efforts from achieving scale as well as the enabling conditions that have supported successful large-scale seagrass restoration. To fill this gap, The Nature Conservancy embarked on an effort to explore and advance ways to accelerate the pace and scale of seagrass recovery by conducting a global study to identify challenges preventing restoration efforts from scaling. Specifically, this investigation focused on:

- **Boots on the ground restoration:** This study focuses on the challenges and operations that need to be streamlined to conduct active seagrass restoration (post site selection; Figure 1).
- **Scaling:** In scenarios where there is a trade-off between scientific precision versus scaling (consider an analogy of throwing many darts at a dartboard at once versus throwing one dart at a time), we bias towards scaling (i.e., many darts) as long as the return on investment is high.
- **Expert informed research:** We assembled experts based on word of mouth, literature, and news searches and interviewed and surveyed experts to identify what they have encountered first or second hand in scaling seagrass restoration.

SECTION

3 METHODS

3.1 EXPERT INPUT

An initial globally representative list of seagrass restoration experts was identified by leveraging TNC's expansive restoration network, conducting a literature review of major seagrass restoration reports and peer-reviewed publications, using online searches exploring current restoration efforts, and word of mouth (including solicitation from interviewees). This resulted in a list of 80 individuals representing all populated continents and coming from research, practitioner, and government backgrounds.

3.2 SEAGRASS RESTORATION EXPERT INTERVIEWS

From the list of experts, we identified 21 individuals with broad geographic representation, seagrass-species expertise, and restoration method experience to contact for interviews. From there, a snowballing strategy was adopted to identify additional experts based on interviewee recommendations or personal connections. A total of 27 individuals were contacted with requests for interviews.

Each expert interview was 60 minutes and conducted on video conference. An automatic transcription agent (Otter.ai) was used to capture the conversation. The format of each interview was semi-structured with three primary elements: (i) interviewee's background and involvement in seagrass restoration, (ii) identification of critical challenges, and (iii) brainstorming potential solutions. A majority of the interview time (70%) was dedicated to the discussion of key challenges, followed by identifying possible solutions (30%). Time permitting, interviewees were asked "if you had a magic wand, what would you do" to engage in "blue sky" brainstorming. A standardized interview guide is included in *Appendix A*.

Site planning and preparation	Optimal sites selected for seagrass growth and survival (e.g., clear, shallow waters).
Production	Seeds and/or propagules harvested and stored for future dispersal and/or transplantation.
Field restoration	Seeding or transplanting of species to the restoration site.
Monitoring and management	Ongoing monitoring and management activities to ensure restoration success and learn from failures.
Scaling	Approaches that expand to ecosystem wide scales.

Figure 1. Overview of the steps involved in a seagrass restoration project. This report focuses on field restoration, with some attention given to production.

Post interview, responses were anonymized and coded by sector for quoting, summarizing, and quantifying key findings: SNP- small non-governmental organizations with less than 50 employees; LNP- large non governmental organizations with 50 or more employees; GOV- government agencies; ACA- academic; PRV- private consulting. To tabulate responses, all challenges and solutions mentioned by interviewees were tallied; the number of challenges and solutions detailed in subsequent sections therefore exceed the number of respondents.

3.3 SEAGRASS RESTORATION EXPERT SURVEY

The seagrass restoration survey included nine open-ended and closed questions which took respondents approximately 10 minutes to complete. The survey was designed to capture similar information as the interviews and contained three primary elements: (i) respondent's background, (ii) scope of their restoration efforts, and (iii) perceptions of major restoration challenges. A list of challenges was compiled from the interviews and survey respondents were asked to prioritize three key challenges from this list. Respondents were then asked specific follow up questions for each of the selected challenges. The magic wand question was included as an open ended question for respondents to answer. The survey was administered through Typeform which allowed for the desired conditional logic, where the selection of a challenge prompted a specific and unique follow up question. A copy of the survey is included in *Appendix B*.

All experts on the original list who were not interviewed were sent the survey (n=53 people), and some were asked to forward the survey on to their networks. One interviewee also responded to the survey; to avoid duplication, their survey responses were removed prior to tallying responses. All survey responses were anonymized using the same sector codes described above. Long form responses were coded thematically based on keywords; as respondents could identify up to three key challenges and their related solutions, the number of challenges and solutions detailed in subsequent sections exceeds the number of respondents.

3.4 ADJACENT SECTOR INTERVIEWS

Interviews were solicited from experts in agriculture, robotics, forestry, blue carbon, ocean conservation foundations, and kelp restoration. These interviews were conducted opportunistically based on relevant expertise. Interviews lasted 30 minutes and did not have a script but followed the same general format as seagrass expert interviews. Key challenges for seagrass restoration were briefly shared and the remaining time was used to discuss parallel challenges in these diverse sectors and identify possible cross-cutting solutions.

The interviews were conducted both in person and on video conference. Notes from in person interviews were captured post-interview and automatic transcription (Otter.ia) was used for video conference interviews. All interviews were anonymized using a similar coding system to the seagrass interviews and survey. As this was not central to study objectives, results of adjacent sector interviews are presented in *Appendix C*.

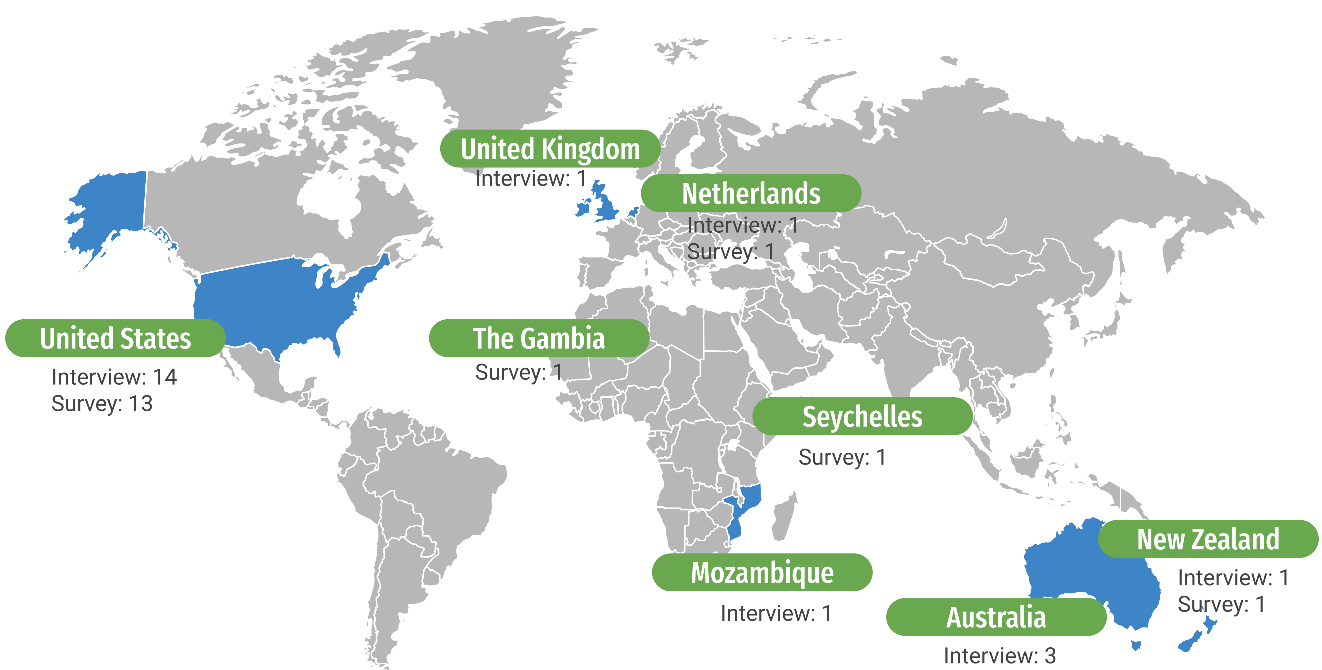
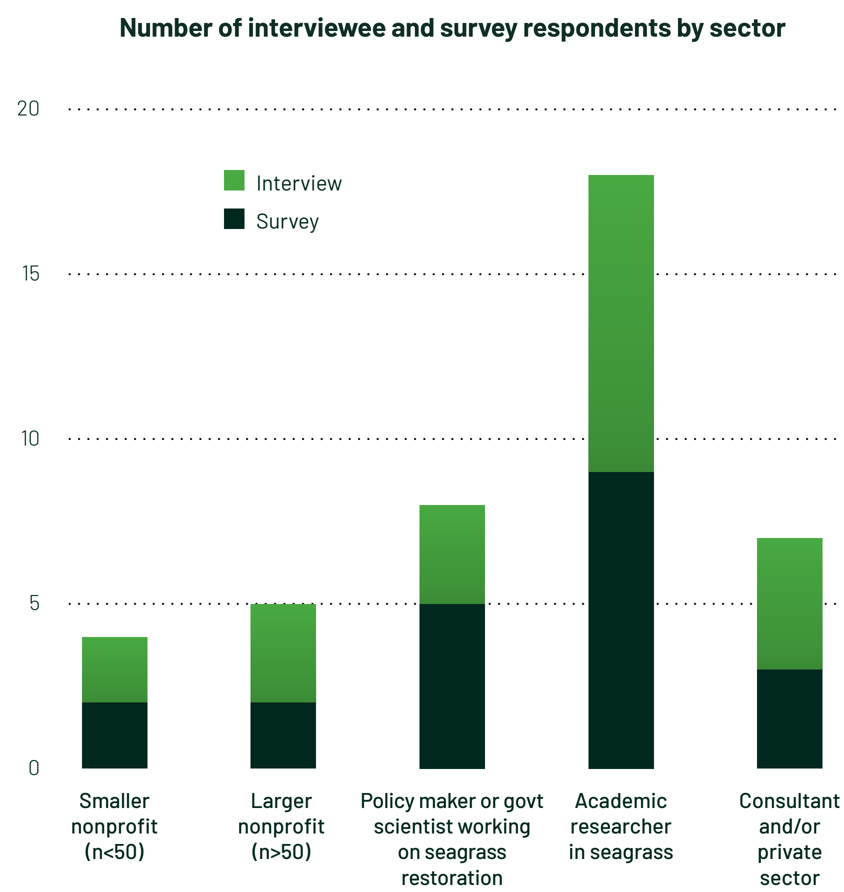
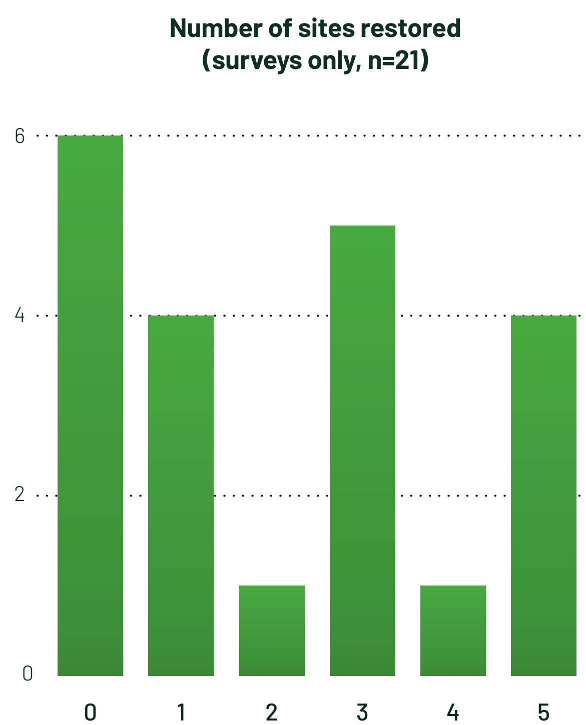


Figure 2. Locations of interview and survey respondents.





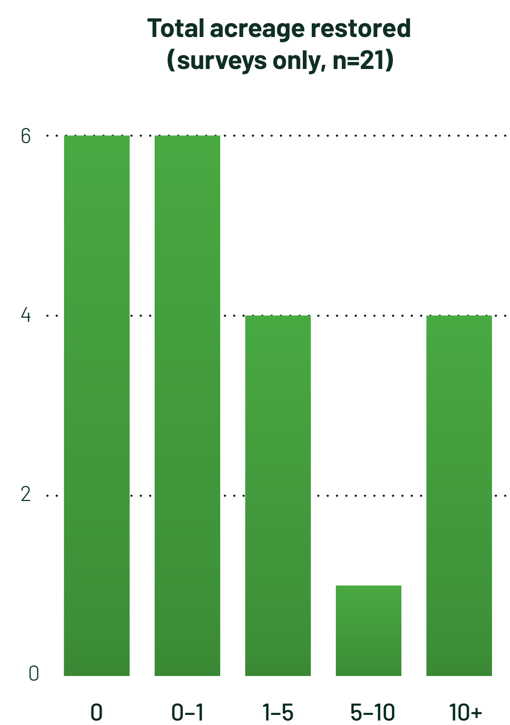


Figure 3. Overview of seagrass expert interviewees and survey respondents.

SECTION

4 OVERVIEW OF INTERVIEWEES AND SURVEY RESPONDENTS

We conducted 21 seagrass expert interviews and received 21 survey responses. The geographic distribution of seagrass expert interview and survey respondents is displayed in Figure 2. While we aimed for geographic breadth, a substantial number of participants, both in interviews and surveys, were from the US (namely California, Virginia, and Florida) followed by Australia (Figure 2).

Academic researchers were the largest group of interview and survey respondents (43% in both cases; Figure 3). The survey had higher participation from government scientists and policy makers than the interviews (24% and 14%, respectively), whereas the interviews had more participation from consultants and private sector individuals than the surveys (19.5% and 14%, respectively). Participation from large nonprofits was slightly higher in interviews compared to surveys (14% and 9.5%, respectively) and small nonprofit representation was the same in both (9.5%). Survey respondents had led or participated in seagrass restoration projects in 0-5 sites (2-3, on average), with most projects being 0-5 acres (Figure 4). Names, titles, and affiliations of interviewees are listed in *Appendix D*; survey respondents remained anonymous.

SECTION

5 SCALING CHALLENGES

Six major challenges were identified by interview and survey respondents as preventing the successful scaling of seagrass restoration: (i) funding (n=29 respondents), (ii) permitting (n=25), (iii) public perception and awareness (n=22), (iv) curating genetic diversity and increasing biological knowledge (n=21), (v) labor (n=20), and (vi) infrastructure (n=19). These scaling challenges are listed in Table 1 with a sample response representing the common sentiment reported by survey and interview respondents. Each major scaling challenge is discussed in detail in Sections 5.1–5.6.

TABLE 1. Six key challenges consistently identified by interview and survey respondents preventing the successful scaling of seagrass restoration.

Scaling challenge	Section	Number of respondents	Representative response
Funding	5.1	29	"The biggest factor is funding. If we had more money, we'd have more people, which would allow us to do more things than pilot trials. Scaling [without sufficient funding] would be quite challenging." —LNP-2
Permitting	5.2	25	"They are all different, slow, expensive, and seek details that force structure to [restoration methods] that work best by being adaptive. This often results in delays during the planting season such that restoration starts later than desired." —PRV-5
Public perception and awareness	5.3	22	"One of the biggest challenges … is lack of seagrass knowledge and awareness. Many people do not even know the name of seagrass. Many times when I talk to people about seagrasses, they say "what is seagrass? we have never heard of seagrasses …" and ironically even the majority of the educated people in the civil services … does not know about seagrass." —GOV-8
Biological, ecological, and genetic knowledge	5.4	21	"We have really good genetic data of the species. We know the different populations [and] how much connectivity there is between the different populations. What we're interested in doing next is looking at whether there's any sub populations that are better adapted to warmer temperatures or are better at dealing with big storm floods, changes in salinity, or things like that. And can we actively engineer the restored beds so that we enhance the resilience and the capacity of the seagrass to adapt to future change." —ACA-6
Labor	5.5	20	"We found that [restoration] was very labor intensive, tiring, and required a lot of effort by people in the water in the fall when it was cold. And planting was always an issue, especially if it required water where you have to use scuba. We tried to do most of our work in shallow water when it was low tide, but when you plant in the fall here you can get temperatures that are starting to go below 20 C." —ACA-3
Infrastructure	5.6	19	"[We need a] mariculture facility for a donor population…so instead of harvesting from meadows, we could just grab seagrass from a lab that is growing seagrass…it seems like it's getting harder and harder to get permission to harvest." —ACA-1

5.1 FUNDING

Funding was the most prevalent obstacle to scaling seagrass restoration identified by interviewees and surveyed experts (n=29 of 42 seagrass experts). Specifically, four key funding challenges were identified: (i) insufficient quantity and fragmented sourcing (n=20), (ii) funding durations and the limited availability of long-term restoration funding (n=10), (iii) funding constraints preventing the acquisition of key sources of funding or the inclusion of key aspects of the restoration life cycle (n=7), and (iv) the requirement for project success due to the general sentiment that "no one wants to fund a failure" (n=3; Table 2).

Half of seagrass experts who identified funding as a major scaling challenge specifically highlighted insufficient funding as their primary concern. Insufficient funding prevents restoration efforts from getting off the ground. "Without funding we will not be able to carry out key activities like capacity building, monitoring, advocacy and awareness, partnership and importantly planting," GOV-8 noted. New restoration efforts were particularly hard to fund, leading restoration practitioners to choose cost-effective, but potentially not scalable, methods over those with higher up front investment requirements (SNP-1). Most funding was identified as coming from relatively small grants often piecemealed together to adequately fund a single restoration effort (LNP-2). Seagrass may also get passed over by funders for what are perceived to be more charismatic ecosystems (e.g., coral reefs) within limited ocean restoration budgets (ACA-6). Interviewee LNP-2 commented: "We're always having to try [to secure more funding] and there's quite a lot of groups that are interested in funding the project but they only give small amounts. You spend a lot of time talking to them beforehand to tell them about the project and then they give you a bit of money and you spend a lot of time trying to find the money." Another respondent succinctly summarized the specific nature of the funding challenge as "not enough, too fragmented, too time consuming to procure" (ACA-10).

Seagrass restoration requires multiple years of funding to experiment, monitor, and learn, and long term funding (minimum 3-5 years; 20-25 years suggested; PRV-5) was identified as essential but rare. Absent longer term funding, practitioners noted challenges associated with guaranteeing a steady source of trained and well qualified labor (see Section 5.4 for more on the labor challenge), often relying on a workforce primarily composed of volunteers. The vast majority of available funding identified by respondents operates on annual cycles, with recently available COVID-19 related relief funds and US Inflation Reduction Act funding noted as important exceptions for a handful of US projects (PRV-2, SNP-1). "Funding cycles and durations for many agencies and granting entities are designed around short periods of performance," wrote PRV-5. "This drives projects, where successful eelgrass restoration, especially large-scale restoration, requires multiple years with adaptive response to be highly successful. This generally does not fit within a single grant schedule. Since there is no certainty to follow-on funding, long-term infrastructure in planning, test planting, monitoring, and adaptation generally are not undertaken. This impacts both success and overall scale of the restoration."

Respondents noted that funding rarely covered all aspects of seagrass restoration, with site selection, mapping, and continuous monitoring often excluded from their grants (SNP-1) despite incurring large costs and playing an essential role in determining and tracking the outcome of restoration efforts. On the lack of funding or support for site selection, interviewee GOV-2 said, "Sometimes you know there isn't readily available information like a recovery or restoration plan that identifies sites for folks. They have to figure out all that site selection which involves a lot of costs whether it's their own time or hiring someone to help them." Funding for government agencies to update, adapt, and create new policies to support advancements in restoration was also identified as a funding challenge standing in the way of scaling seagrass restoration, particularly as it relates to whole ecosystem restoration efforts (ACA-2).

Several respondents also highlighted a key funding bottleneck related to the success, or lack thereof, of seagrass restoration efforts. Respondents from around the world noted that funders want to see, and may even require, success for continued financial support (LNP-2, GOV-1, ACA-3). This further misaligns incentives toward smaller-scale, higher certainty projects, over larger-scale, potentially more experimental restoration efforts which are critical for ecosystem-level impact. Interviewee ACA-3 observed that diagnosing failed restoration efforts is essential because "people want to see success; you've got to make sure that you understand why plants live and die in that particular area, ... [and] if you don't know why [not a single seed survived], and you try to plant, and nothing comes back, people will be disappointed."

TABLE 2. Key funding challenges identified by seagrass experts. Note that the funding category counts are greater than the number of experts that identified funding as a challenge (n=29), because an individual could identify more than one funding challenge.

Funding challenge	Number of respondents	Select responses
Insufficient quantity and fragmented sourcing	20	"Uncertainty comes into cost because the funding entities (if there's high uncertainty) may be less willing to fund eelgrass restoration projects. I've seen that throughout my career." —GOV-2 "The biggest factor is funding. If we had more money, we'd have more people, which would allow us to do more things than pilot trials. Scaling [without sufficient funding] would be quite challenging." —LNP-2
Funding duration	10	"Under a more program (e.g., 20 acres in 10 years) versus project (3 acres at this location next year) construct, it is possible to intertwine adaptive research and restoration actions that can only function when there is an adequate duration and flexibility to provide benefit." —PRV-5 "People try [restoration] for a year, maybe two or three, it doesn't work, they quit. And so I think that the other really important point is we need to be persistent ... securing that longer term funding and taking that longer term view, I think, is really an important hurdle we need to overcome." —GOV-1
Funding constraints	7	"It'd be great if there's funding for monitoring. Even [having] these bay wide maps [are] helpful to compare with imagery and other GIS type data for site planning, like where you would put out plants." —SNP-1 "Funding can be tricky. We're doing a lot of work right now ... doing restoration in [a location] because of mooring scar damage. From the standpoint of funding ... some of the organizations we've gone to for funding don't want to fund it because they think of it as being mitigation even though there's no one on the hook to do the damage recovery." —ACA-2
Project success	3	"The mechanisms of restoration are probably the most understood for [Z. marina] of any of the seagrasses and obviously what has led us to notable successes. However I will also say that it's also led us to some notable failures. And I think this is another hurdle that we as a group as a research community are currently facing which is sort of a prejudice against seagrass restoration just because the history is not as rosy as I think people would like." —ACA-4 "It's hard to say I know initially we had trouble getting funding because...we had this prior effort in 2012 it didn't work..I think it's on my mind because [name] reached out to me recently he's like 'Oh I heard your grass is doing really well, like did you guys change your protocols or something to have more success so we'd be more open to funding.' I was like...oh we're...basically done now." —SNP-1

5.2 PERMITTING

Challenges associated with the seagrass restoration permitting process were common among experts (n=25 of 42 experts). Overall, experts identified (i) the complex and cumbersome frameworks involved in obtaining permits (n=13), (ii) the length of time to acquire a permit (n=9), and (iii) limitations to harvesting and transplanting methods specified in approved permits (n=4) as key issues, although these varied depending on the region, nature of restoration activity, and involved regulatory bodies (Table 3).

TABLE 3. **Key permitting challenges identified by seagrass experts. Note that the permitting category counts are greater than the number of experts that identified permitting as a challenge (n=25), because an individual could identify more than one permitting challenge.**

Permitting challenge	Number of respondents	Select responses
Current frameworks not equipped for seagrass restoration	13	"In some Australian States, there is no clear regulatory pathway for restoration. Restoration is treated similarly to development applications for bridges and houses, so the timeframes for approval are long and complicated. Also, liability is an issue. The seabed in Australia is crown land, so owned by the Government but often regulators expect [us] to maintain ownership of the restoration site and liability into perpetuity. This issue has been negotiated on a case by case basis, with [our organization] often seeking pro bono legal advice to achieve a satisfactory outcome." —LNP-4 "We have some partners that are working on seagrass restoration projects in Romania. They still don't have a framework to apply for permits [or] even to do restoration with seagrass…[we should] support less developed countries in setting up permitting protocols for seagrass or underwater restoration work." —PRV-4
Length of time to acquire permits	9	"We have to get a letter of permission from [the state regulatory agency] to do the transplantation, and we always wait a really, really long time for that. [In] a particular site that is a consistent … spawning region … they always wait to tell us that we can work in that area until after our window for doing the work [has passed]." —ACA-2 "They are all different, slow, expensive, and seek details that force structure to [restoration methods] that work best by being adaptive. This often results in delays during the planting season such that restoration starts later than desired." —PRV-5
Limitations around harvesting and transplanting	4	"There's this disconnect with how much we're getting permitted to transplant and the scale at which we're hoping to transplant." —ACA-1 "Lack of understanding of the balance of conservative resource management and allocating necessary donor material needed to overcome critical thresholds/feedback mechanisms." —ACA-14 "We have run into issues because you might take seeds from San Diego and put them in San Francisco Bay. You're still technically within the state of California. However, if we take seeds from Virginia and put them in Long Island, we've now crossed four or five states, and we're in completely different waters with different sets of regulations. And while we haven't gotten any hard no's about this idea of moving seeds over this geography, we haven't gotten any resounding yeses either." —ACA-4

Globally, the experts we interviewed and surveyed were frustrated by the regulatory gauntlet of regionally specific and non-standardized permitting processes. A lack of standardized frameworks has created an opaque and poorly documented permitting process that is inefficient, complex, and cumbersome. Each individual seagrass restoration project may require local, state, and federal regulatory approval and specific restoration actions may prompt involvement of additional agencies further complicating and slowing the process. For example, some regions including the U.K. and California require construction permits each time sand is moved or displaced, eliciting additional government agency consultations throughout the permitting process (ACA-2 and SNP-2). In Australia, the selling of seeds triggered a reclassification of a seed production nursery infrastructure project from research to commercial aquaculture, which spurred an entirely separate permitting process (ACA-7). Challenges with agency involvement and tracking compliance are further compounded in geographically small areas where seagrass restoration efforts overlap with multiple federal or state bodies (i.e., northeastern U.S. and the U.K.; ACA-4 and SNP-2). Even existing frameworks, such as the "California Eelgrass Mitigation Act," have been described as complex, not streamlined, and require the involvement of additional government agencies (GOV-2).

Multiple experts noted that the existing frameworks designed to protect natural resources during large-scale commercial construction and coastal development projects are the same ones now being used for conservation and restoration purposes (ACA-6 and SNP-2), highlighting a misalignment between permitting requirements and restoration needs. Other practitioners have had to demonstrate that restoration of seagrass is self-mitigating in order to obtain a permit (SNP-4). In Mozambique, one expert noted a complete lack of an existing government agency regulating seagrass restoration, instead relying on voluntary commitment from the community (ACA-9).

According to respondents, seagrass restoration projects were also limited by the length of time required to obtain a permit. The complexity and lack of standardization in permitting make it a time intensive and slow process that is difficult to plan around. This can delay restoration efforts outside of the optimal window of opportunity, thus decreasing chances of success (ACA-2 and PRV-5). As funding is often tied to strict timelines (see Section 5.1), there is pressure to proceed with the proposed restoration, even if environmental conditions are not sufficient. A private consultant (PRV-4) said: "[In multiple global geographies] it just took more time than we hoped for to get permits. I think permitting is a very important aspect to take into account when you're planning a restoration project because it can take longer than you anticipated, and I also hear it from other groups or

people that work on restoration that [it can] really get complicated." A government scientist (GOV-2) mentioned that as seagrass restoration projects become more complex (i.e., large-scale mitigation), there is more likely to be productive interaction between federal and state agencies. However, smaller projects have limited staff capacity and there is less of a chance of federal and state agencies working together to solve a problem. This poses issues for the potential scalability of small restoration projects in the long-term.

Finally, respondents noted that even once permits are obtained, they often come with limitations on harvesting, transplanting, and seeding which can further restrict the scale of restoration projects. For example, California has strict requirements for both the harvesting of the donor material (limited to <10% of the extant meadow often with much less approved) and the radius of transplanting from the donor bed (<50 km) (SNP-1). While these regulations protect the donor meadow from overharvesting, they may hinder large-scale restoration efforts and attempts to increase genetic diversity. In other regions, including the U.S. east coast, Romania, and Australia, efforts to transport seeds of the same species to nearby areas under different regulatory authority have been denied permits. An academic researcher (ACA-6) highlighted this issue stating "the sourcing of the fragments and how far we can move them is a challenge. Western Australia has beautiful meadows. If we could take them from Western Australia 1000 kilometers across to eastern Australia... we'd be fine." However this same researcher acknowledged the ethical, logistical, and biosecurity implications of moving source material to new regions.

5.3 PUBLIC PERCEPTION AND AWARENESS

Improving the public's perception and awareness of the importance of seagrass is required to effectively scale restoration efforts (n=22 out of 42). In particular, experts observed three public perception related barriers: (i) lack of awareness of seagrass and its value (n=10), (ii) potential conflict between seagrass restoration efforts and local industries (n=6), (iii) difficulty maintaining long term interest in restoration efforts (n=3; Table 4) .

TABLE 4. Public perception and awareness challenges were highlighted by 22 (out of 42) interview and survey respondents.

Public perception and awareness challenge	Number of respondents	Select responses
Lack of awareness of seagrass and its value	10	"One [challenge] is, … unlike other systems, such as corals and maybe even things like kelp and oysters, for example, [seagrasses] have a lot [less] public attention. People know what they are. In the case of oysters, they also like to eat them, but seagrasses, the UN just called them in a 2020 report 'the forgotten ecosystem.' [That] is really a terrible place to be when trying to get support for restoration efforts." —ACA-4 "One of the biggest challenges … is lack of seagrass knowledge and awareness. Many people do not even know the name of seagrass. Many times when I talk to people about seagrasses, they say "what is seagrass? we have never heard of seagrasses …" and ironically even the majority of the educated people in the civil services … does not know about seagrass." —GOV-8 "Perceptions of seagrass greatly depend on the community. In Mozambique, a country that relies heavily on seagrass for fisheries, seagrass meadows are valued and individual meadows may even have a unique name. While just across the Indian Ocean in Seychelles, up until recently, there was no local word for seagrass in Seychellois creole. The perception of seagrass varies greatly on the community as fishers and gleaners know the value. However, tourism actors that prize a white sand beach may see seagrass as a nuisance." —LNP-5
Perception that seagrass is adversarial to local industry	6	"One of our biggest industries is hard clam aquaculture. It's a great industry. It happens to overlap a lot with areas that are good for seagrass. The clams are planted in the bottom in a really high density. You roll a net over top of them to keep predators from eating them. Two years later, you dig them up and sell them. That is sort of this tricky thing like the clam aquaculture industry likes the eelgrass in theory, but they're really really worried about the grass spreading too much and them not being able to use [the bottom] or maybe even having regulations change…" —LNP-1 "A huge challenge that we're having is landowners are trying to protect their property because they're having erosion issues. But the regulations protecting seagrasses are not allowing them to go in…we'll be working with the regulatory folks to help address this…it's not even a union, it's like this fighting and competing…we love the coasts for the seagrasses and the benefits we get, but at the same time, we've got the marsh doing the same thing and the marsh providing frankly more protection for the landowners." —LNP-3
Securing long-term interest	4	"Their efforts were pretty much citizen based and it was exclusively adult shoot transplanting and if you're relying on volunteers it certainly reduces the cost. But volunteers also want to see success. And so when things don't work necessarily as advertised, enthusiasm wanes and that program dissipated and now they don't really do seagrass stuff anymore." —GOV-1
Difficult for community groups to engage in restoration	2	"If a community group wanted to do restoration without being aligned with a science organization, I think it's very hard for them to get permission to do it … it's been brought up as a frustration by community groups." —LNP-2

The United Nations Environment Programme deemed seagrass "the forgotten ecosystem" (UNEP, 2020), lacking the publicity and charisma of other marine habitats on the receiving end of restoration efforts including corals, mangroves, and oyster beds. Seagrass experts from nearly every geographic region similarly highlighted the limited visibility of seagrass ecosystems, particularly relative to other marine ecosystems, and identified the public's lack of knowledge of what seagrass is and what value seagrass has as a key communication and community engagement barrier preventing large scale restoration. Survey respondent ACA-15 identified the "lack of stakeholder understanding about seagrass functions and services" as a key challenge preventing restoration efforts from scaling, and interviewee ACA-6 noted that there is "a general lack of understanding of what seagrass is. Often people have a negative view of seagrass because it gets stuck in their propellers or moorings. They don't see it as something that should be protected or something that's positive. There's a lack of education, and even among stakeholders like people who sail or have moorings, there's often a question of why do we need to protect this?" The same respondent also explained that numerous local traditions had historically been linked to seagrass, but the connection had been lost (ACA-6), leading seagrass to be undervalued and underrecognized by the local community.

In addition to the lack of awareness around the importance of seagrass broadly, ineffective communication about specific restoration projects is also a barrier to public buy-in. "I sometimes feel like we're not effective enough at communicating the good news stories," said ACA-6, "...people are not aware of [the successes]. And then you know, there's this constant kind of perception that things only keep getting worse. And that's not true." Another respondent said "people try it for a year, maybe two or three, and if it doesn't work out, they quit," (GOV-1) reiterating this sentiment of poor communication of results as a barrier to securing long term interest by funders and community groups involved in the work. On the other hand, in instances where community groups are interested in being involved and performing the restoration themselves (without support from a science-based organization), there can be too many regulatory hurdles to overcome (LNP-2).

Respondents consistently noted that conservation and restoration efforts can place seagrass in an adversarial position with local industries, with competition for space driving potential conflicts between fisheries and other marine based industries, community members, and restoration practitioners. Shellfish and boating industries in particular may perceive that their activities are undermined by seagrass restoration. LNP-2 mentioned the local Indigenous community was concerned that seagrass restoration was displacing the native shellfish population which supports culturally important subsistence fishing practices. In Virginia, USA, restoration practitioners work closely with shellfish farmers to develop recommendation guidelines and best practices to ensure compatibility between aquaculture operations and seagrass restoration (LNP-1). Respondent LNP-3 further noted that, in a different US location, bottom aquaculture operations do not commonly overlap with seagrass meadows, but where they do, conflict has followed.

5.4 BIOLOGICAL, ECOLOGICAL, AND GENETIC KNOWLEDGE

Several seagrass restoration practitioners and academics highlighted significant gaps in the scientific knowledge of seagrasses standing in the way of successfully scaling restoration efforts (n=21 of 42). Although a wide range of experts were interviewed (each at different stages in scaling their seagrass restoration efforts and with varying levels of success), many mentioned insufficient knowledge of some component of the general (i) ecology (n=13), (ii) biology (n=12), and/or (iii) genetics (n=10) of seagrass in their respective projects (Table 5).

There are significant deficiencies in seagrass mapping capabilities that result in large gaps in our understanding of the spatial extent of seagrass habitats (ACA-4 and SNP-2). Practitioners agreed that having an ecological baseline for a proposed restoration project greatly increases the chance of success. There are numerous examples of regional mapping and monitoring programs, but mapping and monitoring methods are not always transferable to other areas (GOV-1 and ACA-4). For example, using drones and aerial imagery to map seagrass extent is a widely adopted approach in relatively clear water, but is not possible in areas such as San Francisco, California, USA, where turbidity and strong tidal currents make monitoring difficult (ACA-2). Aside from site selection, insufficient mapping and monitoring also poses issues for determining the effectiveness of restoration efforts (ACA-2). Even when there are standardized monitoring systems in place (such as aircraft for mapping purposes), it can still be difficult to ensure conditions between monitoring efforts are similar (i.e., max seagrass seasonal extent, turbidity, etc.). Processing imagery can also take up to a year, possibly delaying siting of future restoration efforts (LNP-1).

TABLE 5. Biological, ecological, and genetic knowledge gap challenges identified by 21 (of 42) interview and survey respondents. Note that the category counts sum to >21, because an individual could identify more than one knowledge gap challenge.

Knowledge gap challenges	Number of respondents	Select responses
General ecological knowledge	13	"We [have] very poor data on the presence of seagrass…The maps of seagrass in the UK are shocking….So that is a big challenge because if you're looking to identify a donor meadow [or] you're looking to explore opportunities for restoration you need to understand where those sites may be."—SNP-2 "Aerial imagery was supposed to be [available] this last summer, but the Canadian wildfires actually drifted so far south that it screwed up the visibility and they couldn't take any imagery from the air. So we've been thinking about using satellite images, Planet in particular but also Sentinel and Landsat depending on how far you want to go back to be able to fill in gaps for which we don't have any sense of seagrass extent."—ACA-4
General biological knowledge	12	"In the areas we are working in across Europe, there are four different seagrass species, and each of these reproduces differently. Scaling restoration of each individual species would need to be done differently."—SNP-2 "If we knew as much about *Z. marina* as we did about oats or any land-based crop, we would be way ahead of where we are. If you had a 10% success rate in agriculture, that would be considered absolutely terrible, but that is actually really good for where we are with seagrass."—SNP-2
Genetic diversity	10	"Understanding how to optimize and build genetically diverse sustainable meadows is where we think everybody wants to go and make that argument in the face of some practitioners who come from different backgrounds and have different perspectives." —GOV-3 "We have really good genetic data of the species. We know the different populations [and] how much connectivity there is between the different populations. What we're interested in doing next is looking at whether there's any sub populations that are better adapted to warmer temperatures or are better at dealing with big storm floods, changes in salinity, or things like that. And can we actively engineer the restored beds so that we enhance the resilience and the capacity of the seagrass to adapt to future change." —ACA-6

Knowledge of the general biology of the target species is foundational to developing a successful restoration project (ACA-3), yet general biological knowledge of species in need of restoration remains incomplete. Knowing when and where to harvest was identified as one the biggest issues limiting success across seagrass restoration projects (ACA-3). In the world's largest seagrass restoration project (Virginia Bays, USA), decades of research contributed to understanding the timing of seagrass flowering, seed germination, seed storage, and dispersal. In other regions, such as the northwest U.S. and the U.K., this biological knowledge of seagrass life history is lacking, and it is not well understood why seagrass of the same species and geographic region can be either annuals or perennials (ACA-8 and SNP-2). In those particular locations, there is insufficient knowledge on when shoots develop, the timing of seed development, and how to extract the seeds from the plant efficiently. One scientist noted that intensive research is required to harvest seeds including weekly tracking of seed development and targeting low tides to avoid the need for scuba (though scuba may still be required; ACA-1). Further, flowering production can be highly variable among beds in the same area requiring additional monitoring efforts. Most researchers agreed an improved life history understanding of the local populations they work with would greatly bolster successful scaled restoration.

In over 20% of our conversations, there were concerns that complications and unknowns related to seagrass genetics could impact the scalability of restoration efforts. Many experts agreed that restoring genetically diverse seagrass meadows increases success, while also building local resilience to climate change via opportunities for adaptation (GOV-2, SNP-2, and ACA-5). An important distinction noted by one researcher is that the role of genetics is not to figure out the best material to plant, but rather to ensure there is a high variety of genetic types and source populations being used when restoring (ACA-5). Although there is a tradeoff in the immediate short-term success of planting diversity, the resulting genetically diverse meadow could be more adaptive and resilient to climate change over time (ACA-5). Despite seagrass restoration efforts proliferating globally for the last several decades, there remains a lack of genetic information to inform both restoration methodology and permitting (see Section 5 .2; SNP-1, ACA-5).

Generally, seagrass restoration decisions are made based on policy rather than genetics (SNP-2). While sourcing seagrass material for restoration purposes is often geographically restricted by regulatory agencies, in some regions, researchers have determined this is not the best practice. For example, in Scotland, Brexit complicated the selection of a genetically appropriate donor population for seagrass. Despite the genetic suitability of Dutch seeds, political barriers necessitated the use of seeds from other regions in the U.K., which are geographically closer but more genetically distant (SNP-2). Across the Atlantic, the southeastern U.S. is experiencing warmer and wetter summers. In those areas, seagrass extent will likely decline, raising concerns for more northerly areas (i.e., Virginia and New England) 10-20 years into the future (ACA-4). To address this, a team of researchers is pursuing an effort to move seagrass material from the south, where adaptation to higher temperatures has already occurred, to the north, thereby possibly buffering northerly populations against future change (ACA-4). Notably, there is currently no regulatory framework to allow this. These examples illustrate the complexities in restoration efforts where political and regulatory factors interfere with scientific considerations due to the unknowns and a dearth of available general biological, ecological, and genetic information.

5.5 LABOR

Nearly half of respondents specified labor as a major barrier to scaling restoration (n=20 out of 42). Labor issues include both (i) the lack of funding available to support persistent skilled labor (n=16), and (ii) the resulting reliance on volunteer labor to scale efforts (n=13; Table 6).

TABLE 6. Labor challenges identified by 20 (of 42) interview and survey respondents. Note that the labor category counts sum to >20, because an individual could identify more than one labor challenge.

Labor challenges	Number of respondents	Select responses
Skilled and expensive labor	16	"We found that [restoration] was very labor intensive, tiring, and required a lot of effort by people in the water in the fall when it was cold. And planting was always an issue, especially if it required water where you have to use scuba. We tried to do most of our work in shallow water when it was low tide, but when you plant in the fall here you can get temperatures that are starting to go below 20 C." —ACA-3 "[There is a need to be] able to consistently fund key personnel so that these jobs are well paying, desirable, and have career opportunities within them." —ACA-13
Reliance on volunteer labor	13	"Finding volunteers or funding workers to collect or cultivate shoots or seeds for planting [is a key challenge]."—GOV-4 "Knowing when to start and if you use volunteer labor, you've got a bunch of people who are there on waiting lists to start on days that you may not have any work to do. Or you might cancel the days that they're signed up for because the water got hot too quick and the seeds all released from the plants already. So there's just sort of this uncertainty. You have to reserve a big window of your time and get some of your volunteers to reserve that window of time as well and just be flexible to start or stop whatever the plants dictate." —LNP-1

Throughout the interview and survey process, a recurrent theme was the intensive and expensive labor required to perform on-the-ground restoration. In all types of restoration methods reviewed, skilled labor was defined as paid students, academics, consultants, and researchers. Numerous respondents and interviewees noted that paid labor is often required due to the intensive hours, skill requirements, ambiguity of field work, poor conditions (i.e., muddy, cold, low visibility), and boat capacity when projects are not shore based (ACA-2, ACA-3, LNP-1). Although projects have seen increased success and efficiencies using paid labor, several experts also mentioned the clear dependence on funding availability, and that it is difficult to retain talent if funding is uncertain and not multi-year (LNP-1, ACA-13). There is also a stark difference in labor between often volunteer driven local restoration projects compared to primarily skilled, paid labor supporting large-scale mitigation efforts (PRV-1). Aside from mitigation restoration, which is typically well funded, a notable large-scale seagrass project that has seen success in the Virginia Bays, USA resulted from the collaboration of multiple organizations and universities working together to provide financial support and consistent funding. In this specific project, volunteers were useful for community engagement, education, and seed gathering, but paid labor was also required to fill critical project roles (LNP-1).

Due to the intertidal and subtidal nature of seagrass restoration, the workforce is often required to have technical scuba training (i.e., scientific diver certification). Scuba gear, training, certifications, and labor are all expensive, resulting in a shortage of labor even when funding is available. A government scientist (GOV-3) reported that, even for experienced divers in good conditions, planting shoots into the ground while diving (and figuring out the arrangement and distribution) is very difficult. A consultant (PRV-4) also discussed how certain restoration techniques were more labor intensive: "Relocation of sods or shoots in permanently submerged conditions needs to be done with divers. Manual diving work goes slow, and some countries have restrictions on who can perform diving work." Ultimately, tough working conditions, limited funding, and a lack of trained divers limits restoration scaling efforts.

Using volunteers, while free, poses other unique challenges. Coordinating volunteers is a heavy lift, whether it is mobilizing a large group on short notice during peak harvesting times or training volunteers to effectively help efforts (LNP-1, ACA-2). One interviewee described training volunteers as being "immensely difficult," noting that even helping people feel comfortable with putting their face in the muddy, cold, and high turbidity water is a challenge (ACA-2). A government scientist noted that it is difficult to keep people's interest long-term if they aren't being compensated (GOV-1).

Volunteer labor is most likely to be successful for shore-based restoration efforts where access is not a barrier and broad community participation across age groups is possible (GOV-3). One researcher (ACA-9) mentioned that in their region of work there is a complete lack of available funding for restoration and restoration activities rely on volunteer labor. Volunteers in this region are recruited primarily via the downstream recovery of fisheries following restoration, highlighting the important interplay between restoration project success and volunteer willingness to engage. In fact, restoration project success was deemed critically important for retaining volunteer interest and engagement by several interviewees and survey respondents.

Nearly all individuals who listed labor as a key scaling challenge thought that with the right amount of money, they would be able to procure skilled labor. One academic researcher shared: "Actually this is also about resourcing. Salaries are a large part of the restoration cost. I think the right workers are available once funds are available (ACA-10)". Another identified that "being able to consistently fund key personnel so that these jobs are well paying, desirable, and have career opportunities within them" would go a long way toward addressing labor challenges (ACA-13).

5.6 INFRASTRUCTURE

Scaling seagrass restoration will require infrastructure that does not currently exist (n=19 of 42 respondents), and which may be "years away" from being developed (GOV-2). Seagrass experts noted that infrastructure supporting existing seagrass restoration is currently fairly limited and reliant on academic institutions or willing fishery and aquaculture industry partners (e.g., in Virginia and Florida, USA and New South Wales, Australia). In particular, experts discussed the need for (i) new nursery (n=13) and (ii) seed storage (n=7) infrastructure (Table 7).

TABLE 7. Infrastructure challenges identified by 19 (of 42) experts. Infrastructure category counts sum to >19, because an individual could identify more than one infrastructure challenge.

Infrastructure challenges	Number of respondents	Select responses
Nurseries	13	"[We need a] mariculture facility for a donor population...so instead of harvesting from meadows, we could just grab seagrass from a lab that is growing seagrass...it seems like it's getting harder and harder to get permission to harvest." —ACA-1 "Some further experimenting and testing of the potential of 'seagrass nurseries' (ex-situ facilities where large quantities of seagrass 'stock'—plants, sods, or seeds—are reared in mesocosm-style tanks or aquaculture facilities, or perhaps floating or suspended facilities in the field) may also have some merit, as long as the focus is to look for approaches that can ultimately produce large quantities of seagrass stock at minimal costs for large-scale field application in restoration programs." —PRV-6 "I would pour in 100s of millions of dollars into the field to 1) produce professional-scale nurseries for the 10 most commonly restored seagrass species that can produce large amounts of viable seeds." —ACA-17
Seed storage/ curing	7	"[We need to] set up seed storage and germination facilities." —ACA-15 "[We need to be] able to generate a series of systems of infrastructure that would support these large scale seeding efforts, and so we're trying to do that now. But you need flow through seawater, you need people who you know can develop systems to efficiently separate the seeds which are negatively buoyant from the plant material which is positively buoyant... if you don't have some kind of system to separate the plant material from the seeds, you're left with trying to use tweezers to pull out a million seeds one at a time... so having the proper infrastructure to allow us to do this at scale would be my second wish. —GOV-1

Several respondents identified the potential for nursery infrastructure to overcome current harvesting challenges. A limited number of propagules can be harvested using current methods and manual harvesting is very expensive. For seed-based restoration efforts, low seeding survival rates, around 5-10% (ACA-7), suggest that restoring hundreds of acres will require harvesting two to four million seeds. Strategically located nurseries could be used to augment seed availability and will be essential to support large-scale restoration projects. Nurseries could also be used to cultivate seedlings and provide a sustainable alternative for shoot harvesting to reduce dependence on donor beds, which can be ecologically disruptive (GOV-4). This donor to nursery paradigm shift is already occurring in locations lacking sufficient donor beds for collection (GOV-3). In Queensland, Australia, an aquarium system was converted to first create a seed curing facility and then a self-contained nursery. Initially, "it was just for holding the flowers that we collected and to get the seeds out, but then we started to actually grow seagrass in the tanks and that's been building ever since. So, we have populations of seagrass here that flower each year. And we collect the seeds from those as well to sort of supplement what we're getting from the field" (ACA-7).

Existing seagrass nurseries are small-scale and reliant on partnerships with research institutions and industries. Moving towards a large-scale nursery production model will not be without challenges (ACA-7, LNP-1). In Queensland, Australia, seed translocation is highly regulated via a "100 kilometer rule," forcing restoration practitioners to set up nursery networks to prevent population mixing—a particularly daunting challenge when considering restoration across 6,973 km of mainland coastline in the state. As nurseries scale up, "we have to suddenly be classed as agriculture, which comes with other ... permitting and regulations and things" (ACA-7).

Additional research and development is needed to bridge the gap between existing and large-scale functioning nurseries able to achieve seed/shoot production at the scale required (ACA-17). Absent advancements that allow for automation, operating a nursery also requires full time labor (LNP-1). One interviewee was quick to note the importance of ensuring that a nursery "is a worthy investment. You [have] to choose your nursery location really wisely, in terms of proximity to where you can have a large enough nursery and where seagrass restoration is needed, and where it is likely to be successful with a nursery based approach" (PRV-1). Interview respondents also warned that self contained nurseries could run the risk of creating genetic bottlenecks. "There was maybe not a need to think through the genetic questions from a donor bed perspective, but once you're in a nursery, things have changed... And so we as an industry and as a science sub discipline haven't worked through that yet... there's sort of a blank page when it comes to what should be our guiding principles for nursery restoration," said interviewee GOV-3. To overcome this challenge, some experts advised periodic collection of flowers from natural, wild populations to maintain and enhance genetic diversity and ensure a broad genetic base for restoration efforts (ACA-7).

Infrastructure to support seed-based restoration at scale was also of interest, including seed curing facilities—holding tanks with a sea water flow through or recirculating system used to store seeds and ensure seed viability between collection and planting (GOV-1, ACA-4, ACA-6, LNP-3). Centrifuge systems may also be required to effectively separate vegetative shoots (i.e., plant material) from seeds (GOV-1). Large scale restoration efforts require the curing of millions of seeds (e.g., 1-2 million held in Virginia), which may need to be held in geographic proximity to the restoration site (depending on permitting requirements). However, as noted by multiple respondents, seed curing methods and infrastructure requirements are not one size fits all. Some locations must store seeds in refrigerators while others lose viability using refrigeration methods (ACA-7). There is often an element of trial and error associated with curing seeds and developing appropriate infrastructure, with LNP-1 commenting that "a couple of years of big high seed mortality for unknown reasons are a challenge. [We have] a seed curing facility but once you're down to just seeds you're really trying to just hold the seeds at a temperature that doesn't get too hot or too cold and [with the] right amount of oxygen in the water because they're not going to germinate until the water temperature drops."

SECTION 6
SCOPING SOLUTIONS

Though the primary objective of both interviews and surveys was to identify shared and unique challenges preventing seagrass restoration from scaling, potential solutions were also discussed at a high level. In this section, we present a comprehensive list of solutions proposed to address the six shared challenges identified (Section 6.1; Table 8), highlighting key solutions and enabling conditions shared by interview and survey respondents. In each of our interviews and surveys, we asked experts to propose their "magic wand wishlist" to scale seagrass restoration—i.e., if they were unconstrained by time, practicality, and resources, what would they do? Key insights from these discussions are shared in Section 6.2. Finally, we elaborate on a key consensus opportunity identified by multiple experts—expanding seed-based restoration—and summarize what has been done and what could be done in the future to advance this potential solution towards scaling seagrass restoration (Section 6.3).

6.1 PROPOSED SOLUTIONS

Through the interviews and surveys, a number of possible solutions were identified to address key challenges preventing effective scaling of seagrass restoration efforts. A comprehensive list of these solutions are presented in Table 8, with additional details discussed in Sections 6.1.1-6.1.6.

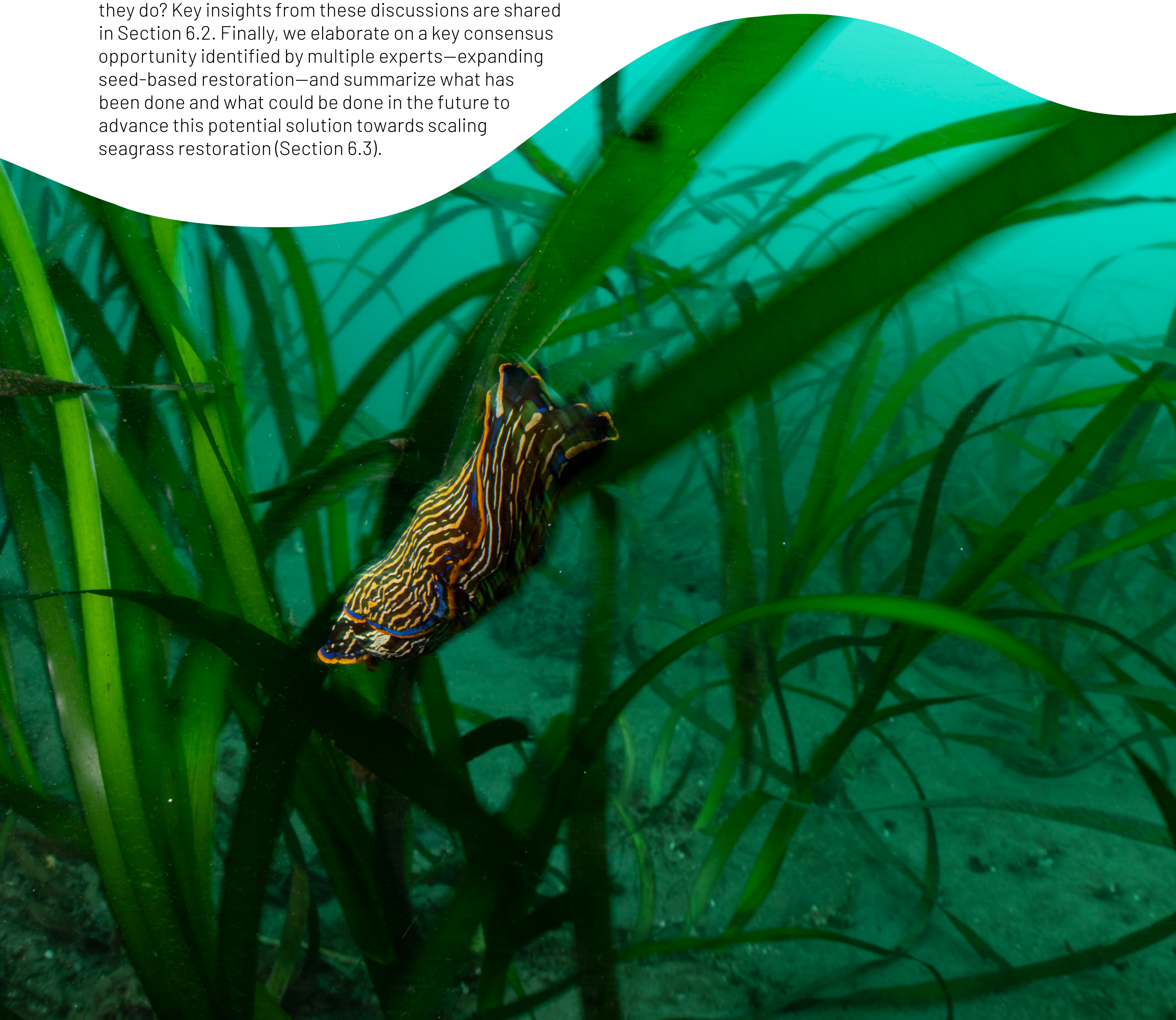


TABLE 8. Potential solutions identified by interview and survey respondents to the primary identified challenges to scaling seagrass restoration.

Challenges identified	Proposed solutions
Funding	• Explore opportunities for mitigation, in lieu fee, or other longer-term enhancement programs, but note these may be geographically limited in scope (PRV-5, ACA-16, ACA-7) • Seek blended funding/financing approaches (government, philanthropy, industry and foundations) (PRV-5) • Seek government agency funding opportunities (GOV-5) • Match the funding source to the scale of the restoration project (GOV-5) • Experiment with different business models (e.g., blue carbon, blue bonds, private funding, partner with corporations as a mitigation arm) (Blue carbon: PRV-1, ACA-7, PRV-4, PRV-3, ACA-6, LNP-1, GOV-1; Blue bonds: PRV-1; Private funding: PRV-3 for coral on private revenue stream, SNP-2 on Sky Ocean rescue, ACA-12, ACA-14, ACA-15) • Boost education and awareness around seagrass (SNP-2, PRV-4)
Permitting	• Creating a single position to process seagrass and related restoration permits (SNP-4) • Create more flexible and adaptive permitting processes which allows streamlining and fast tracking restoration permits (GOV-3, ACA-16) separating this permitting from other infrastructure (ACA-15, SNP-4) • Build a standardized network across coasts and broad geographies not defined by local regulatory entities (region-wide rather than state-by-state) (ACA-4) • Standardizing guidelines and definitions in the context of seagrass restoration, relying on an ecologically sound definitions rather than technology/mapping limitations (GOV-1) • For geographies lacking restoration protocols, share and adopt existing regulatory and permitting frameworks (PRV-4)
Public perception and awareness	• Support First Nation and Community Based organizations as leaders in restoration efforts (ACA-6 on reestablishing cultural connections with seagrass, ACA-7 on drone seeding education) • Translate community needs into environmental goals (PRV-2) • Host educational workshops and community events, using citizen science initiatives to engage the local community and make them active members of the restoration process (GOV-3, GOV-1, ACA-7, SNP-2) • Establish shore-based restoration programs where possible (GOV-3) • Engage with shellfish farmers and recreational and commercial fisherman to raise awareness and build goodwill (ACA-15, GOV-3, ACA-8, LNP-1, PRV-3, ACA-3)
Biological, ecological, and genetic knowledge	• Invest more in research in genetic lineage (ACA-4) • Look to common gardens to cultivate different genetic strains in the same environment (ACA-5) • Apply learnings from other sectors on flowering and precision agriculture (ACA-8, LNP-2, ACA-7, ACA-3, PRV-2)
Labor	• Develop a skilled workforce (e.g., scuba certification) (ACA-1) • Explore opportunities for mechanization and automation for collecting and planting (ACA-7 re. direct injection, LNP-2, SNP-2 re. a sled system for cutting and planting seagrass, ACA-6 re. robotics and using bags on barges, GOV-3 re. lifting sods, ACA-10, PRV-6, PRV-7 re. other solutions) • Engage community members as volunteers (ACA-4, ACA-7, PRV-1, ACA-1, GOV-4, ACA-16, GOV-7, PRV-6)
Infrastructure	• Work with private industry partners such as resorts and mariculture facilities and academic and state institutions which have flow through seawater tanks (ACA-7, GOV-1, ACA-3, LNP-1), share facilities with shellfish hatcheries (GOV-9) • Explore remote setting for aquaculture nursery (similar to studies in shellfish) (LNP-4)

6.1.1 Funding

Although inadequate funding was overwhelmingly considered a primary barrier to scaling seagrass restoration, promising solutions were scarce. There was general consensus that unlocking funding opportunities will require "raising the need and importance for seagrass restoration" (PRV-4), possibly through education and awareness campaigns (PRV-4, SNP-2).

Multiple experts from research, practitioner, and government backgrounds emphasized the role of long-term enhancement programs—including compensatory mitigation and in lieu fee programs—in supporting existing seagrass restoration efforts (PRV-5, ACA-16, ACA-7, LNP-2), with forestry and port companies specifically highlighted as key funders in some locations (LNP-2, ACA-7). Mitigation and long-term enhancement programs have made it "possible to intertwine adaptive research and restoration actions that can only function when there is an adequate duration and flexibility to provide benefit," noted one respondent (PRV-5). However, they went on to point out that, in some contexts, reliance on mitigation programs may limit the geographic extent of restoration projects to development in adjacent locations. Another respondent cautioned that while resource damage assessment related funding was sometimes accessible, mitigation programs require navigating extensive legal processes and establishing damages as "unavoidable adverse impacts" due to development and economic growth, which is often problematic and may stand in the way of accessing funds (ACA-2).

Funding from government agencies was highlighted by respondents from the US and Australia (GOV-5, ACA-15, ACA-4), with respect to the importance of "agencies put[ting] these projects on their workplans" (GOV-5) to ensure budget needs are identified and accommodated. Pairing seagrass restoration projects with existing government water quality monitoring programs was mentioned as a means to unlock additional funding (ACA-14). With relatively equal frequency, respondents highlighted the critical role of private donors (ACA-14, ACA-12, LNP-5), the general need to "get funding faster" (ACA-12), and the importance of having multiple, less restrictive funding sources simultaneously (LNP-5).

Respondents suggested that project co-development and partnerships could help overcome funding barriers at local (GOV-5), regional (ACA-16), and international (ACA-10) scales. "Pooling resources," noted survey respondent ACA-10, "means we learn more with [the] same funding." Identifying opportunities for inter-agency partnership may be another means to further leverage available resources (SNP-4).

Shifting from species-level to ecosystem-level restoration was identified as potential means to scale up available funding, for example by "including shellfish reef and seagrass restoration projects in a broader seascape proposals. Seascape [restoration] is the emerging approach in Australia," noted one respondent (LNP-4).

Finally, respondents discussed the potential for blended financing solutions, including market based mechanisms, to address funding gaps. One expert commented that a "high focus on coastal resilience and carbon sequestration has opened up new funding in recent years" (SNP-3), though some respondents countered that only very large scale efforts are likely to appreciably benefit from carbon markets (PRV-1). Aligning incentives with other industries, including tourism, has also been successful in obtaining and retaining funding for some restoration efforts, including the Tampa Bay, Florida, USA program (PRV-2). Commercialization opportunities were thought to be rare, though one respondent noted historical uses of seagrass for insulation, roofing, and bedding in Europe, suggesting that commercial pathways could potentially be viable in the future (SNP-2).

6.1.2 Permitting

Respondents frequently voiced concerns around the permitting process, and enabling large-scale restoration will certainly require engagement in this sphere. While participants were daunted by the task of addressing permitting challenges, numerous plausible solutions were presented ranging from creating localized "how to" documents to a complete overhaul of the regulatory process.

Restoration permitting guidance is often lacking for large and small scale projects alike. Numerous respondents noted a dearth of information surrounding the basic steps to even follow to start the permitting process. To address this, a government scientist suggested developing localized permitting "fact sheets" that identify important points of contacts and step-by-step directions for obtaining a permit (GOV-2). Ultimately these fact sheets could streamline and facilitate the process, making restoration more accessible (GOV-2).

In much of the world, restoration permitting follows an existing framework that is designed to protect natural resources (ACA-6, SNP-2, GOV-2). Therefore, the process often includes oversight and required reviews from local, state, and federal regulatory agencies. As this legislation historically focused on protection deals with development projects, restoration projects have not always been the top priority (GOV-2). Therefore, many respondents presented a solution where an entirely new agency would be developed specifically to review restoration projects (GOV-3, ACA-16, ACA-10, ACA-15, GOV-5). In this solution, either a single agency would be consulted for restoration projects, or there would be an overarching body in charge of helping practitioners acquire the permits necessary for restoration (GOV-5).

Alternatively, some called for improved collaboration between local, state, and federal regulatory agencies involved in permitting restoration projects. One government scientist commented on the lack of communication between state and federal agencies recognizing that "internal work needs to be done on working with each other to navigate restoration projects - not by sidestepping the regulations, but by finding a more efficient path through the process" (GOV-2). Alongside the need for enhanced collaboration, an academic researcher suggested linking developmental permitting with experimental/scientific permitting to quicken the process (ACA-12). Other respondents suggested dedicating staff to true habitat restoration-specific projects (rather than development or infrastructure) to improve efficiency throughout the review process (SNP-4, ACA-15). Furthermore, in areas where seagrass habitat crosses state or international boundaries, some respondents called for the creation of a standardized permitting framework across coasts and broad geographies to curtail the need to navigate multiple, individual processes through local regulatory entities (SNP-2, ACA-4).

It is important to note that while some respondents requested a streamlined permitting process, they also acknowledged the need for stringent regulations and agency review due to a history of poorly conceived restoration projects that failed to deliver anticipated benefits (PRV-5, GOV-2). A consultant reiterated the importance of the "expectation of success based on well-developed plans and past restoration successes" for facilitating improvements and efficiencies within the permitting process (PRV-5).

Respondents were also asked specifically how TNC could help with permitting restoration projects. Answers ranged from acting as a liaison with government agencies, using its influence for reform, creating best practice guides for navigating permitting processes, to working to establish fast track permitting pathways for marine habitat restoration efforts, amongst other suggestions (*Appendix E*).

6.1.3 Public perception and awareness

Effective communication of the important ecosystem services seagrass provides at both local (e.g., coastal protection, nutrient remediation, fishery enhancement) and global (e.g., carbon sequestration) scales was identified as an important enabling condition for successful seagrass restoration efforts. Both economic

valuation approaches (e.g., the Seagrass Ecosystem Services Project in the Indo-Pacific) and non-monetary based valuations can effectively accomplish this goal. For example, in Tampa Bay, Florida, USA, rather than focussing on the inherent value of seagrass, a restoration project was initially able to propose seagrass as the solution to specific issues identified by community members including the desire for better fishing opportunities, clearer water, and less seaweed invading their bay (PRV-2). Through a collective decision making process and an education campaign connecting seagrass to the community's priorities, restoration practitioners worked alongside fishers, the utilities industry, and local community groups towards the shared goal of cleaning up the bay and restoring local seagrass beds. Only then was an economic valuation completed to quantify the local benefits of seagrass in terms of enhancing water clarity via reducing water pollutants and preventing eutrophication, resulting in further increases in community engagement and a general awareness of the importance of seagrass restoration efforts (PRV-2).

A crucial aspect of seagrass restoration identified by respondents is understanding its societal impact and identifying the beneficiaries of these efforts. Transitioning towards community-driven restoration initiatives is vital in this context, and community engagement through volunteer participation in seagrass restoration was consistently highlighted as a key enabler of successful restoration efforts. As one respondent noted: "Community groups aren't going anywhere… That's because they're by definition in those communities. And so… having them engaged in this process leaves them in a good position to be able to continue to assess without the need for … scientists or managers… but something I've thought about [is] how do we ensure the longevity of these efforts beyond when funding runs out, and I see community engagement as being a pivotal pillar in that" (ACA-4).

Community based restoration—particularly shore-based—efforts were identified as an important avenue for engaging a volunteer workforce and overcoming cost challenges (GOV-3). For example, a collaboration between the Virginia Institute of Marine Science (VIMS) and TNC in the Virginia Bays mobilized over 1,000 volunteers to establish the largest seagrass restoration effort on the planet (LNP-1, ACA-3). Similar success stories shared by respondents include a community science initiative in Queensland, in which 30-40 individuals participated in flower collection (ACA-7), an effort in New Zealand using volunteer assistance to harvest 3,000 flowers (LNP-2), and Save the Bay in New England, USA, which is donor funded and engages volunteers in community-based seagrass restoration (GOV-1). Project Seagrass' Scotland arm was also identified as a volunteer-driven operation (SNP-2). Across restoration project sizes, most restoration projects reliant on volunteer engagement consistently reported a larger volunteer workforce than full time staff (SNP-1, SNP-2, LNP-2, LNP-1, ACA-3, ACA-7, PRV-1, ACA-1).

Initiatives in Australia, New Zealand, and Mozambique further exemplify how training and empowering local communities, including First Nations, can enhance seagrass restoration efforts. One respondent remarked: "We … have a new project that is starting next year, which is focusing on restoring not just the ecology of the system, but the cultural connections as well. So in the case of Indigenous Australians a lot of their song lines would refer to seagrass ecosystems" (ACA-6).

Public engagement was observed to increase following community events and newspaper articles highlighting restoration efforts, which highlights the opportunity for effective communication of these positive outcomes to garner community support (ACA-6). Numerous seagrass experts expressed a desire to transition towards community-driven restoration initiatives in the future once key permitting and funding obstacles were overcome. In particular, respondents from various geographies noted that restoration permits cannot be issued to community groups, because they require participation from or leadership by scientific entities (for more on permitting challenges, see Section 5.2). Cost requirements associated with seagrass restoration also may disqualify some bottom up, community led restoration projects, particularly where habitat development and engineering are required (GOV-2).

The relatively low success rate of existing seagrass restoration efforts was also seen as a barrier to long term community engagement. People "want to see success," said GOV-1, "And so when things don't work necessarily as advertised, enthusiasm wanes, and [the restoration] program kind of dissipate[s]… We all want immediate gratification. And so it's hard to keep people interested and motivated." Fostering and securing public support while effectively setting the expectation that a restoration project may fail presents a fundamental communication challenge, particularly given the amount of money, including public funding, spent on seagrass restoration (GOV-3).

Though respondents identified community engagement through volunteer networks as a key enabling condition to large scale restoration, one respondent noted that COVID-19 related disruptions to the community engagement/volunteer model did not undermine their restoration efforts, suggesting that it may not be required for large scale restoration (SNP-1). The potential for public engagement through volunteer opportunities and community science efforts to overcome seagrass restoration scaling challenges may also be site- and restoration method- specific, as ACA-2 described an offshore project not suited to volunteer engagement due to limited boat capacity and challenging working conditions.

6.1.4 Biological, ecological, and genetic knowledge

Gaps in the ecological, biological, and genetic knowledge of seagrasses have long hindered the success of scaled restoration efforts. Experts agreed that more foundational research of these components would yield methodological advances and unlock scaling opportunities.

Due to the high variability of reproduction within the same species of seagrass (SNP-2, ACA-8), understanding the timing of the flowering and seed germination is imperative (SNP-2, ACA-8, and ACA-3). Therefore, studying these key indicators of life history should always be done before attempting restoration (ACA-3, SNP-2, LNP-2, ACA-3, and ACA-8).

Large gaps persist in research related to the sediments and seagrass-microbe interactions, which could be critical to understanding seagrass evolution and metabolic flux (ACA-6 and ACA-5). For example, an academic researcher noted limited information available on the rhizome-root structures of seagrass, their microbial communities, and their function (ACA-5). While it is likely the bacteria in this rhizome-root system is essential, another researcher noted a need for preparing sediment before transplanting or seeding efforts (PRV-3). These researchers anticipated that a comprehensive understanding of the sediment and the rhizome-root system is essential to scaling efforts and that more attention should be focused here (ACA-6, PRV-3, and ACA-5). Additionally, many thought applying learnings from other sectors on precision agriculture, where most of these biological constraints are identified and solved for, could be a viable solution (ACA-8, LNP-2, ACA-7, ACA-3, and PRV-2).

While most participants mentioned the lack of ecological monitoring data available (mapping and monitoring), very few offered plausible solutions. There are examples of efficient methodologies for local mapping and monitoring, yet these methods have not been transferable to other regions (GOV-1, ACA-4, and ACA-2). However, one academic researcher pointed out the potential for the rapid advancements in remote sensing for large-scale mapping and monitoring to transform thinking in this space. Existing image processing methods could be applied to readily available historical Landsat imagery data to gain insights into the historical extent of seagrass habitat in suitable locations (i.e., those with sufficiently clear water), informing where scaled restoration efforts may be most successful (ACA-4).

Even though increased understanding of seagrass genetics could improve survival rates, there is a lack of available research, even for the most commonly restored species. Sequencing various seagrass species genomes was identified as one means to increase the knowledge base of seagrass genetics. This information could provide insights for high diversity transplanting

to facilitate future climate change adaptation (ACA-5). It could also allow for the selection of seagrass populations with desired traits. The same researcher highlighted the key role of "common garden experiments," where different stocks of populations could be grown in different locations, to track adaptation across populations *in situ* (ACA-5). Improving our understanding of seagrass genetics may also be essential to effectively transition from donor transplant to nursery-based seeding restoration methods, which may require comprehensive genetic tracking (GOV-3).

6.1.5 Labor

It was suggested that scaled restoration efforts are impeded by labor capacities as there are often shortcomings in sustained funding, workforce development, and engaging volunteer interest. As one consultant put it, "any form of active restoration effort would require more resources (money, laborers/volunteers, and/or mechanized equipment) to enable restoration at a larger scale" (PRV-6).

Requirements for scaling labor were most often tied to the need for sustained funding (see Section 6.1.1) or community engagement (see Section 6.1.3). In numerous interviews, it was suggested that using volunteer labor was essential to scaling restoration given the low costs and large workforce that can be obtained (LNP-1, GOV-1, GOV-3). Initially, this volunteer labor was instrumentally important across large-scale seagrass restoration projects in overcoming cost challenges (GOV-3, SNP-2). However, many respondents suggested volunteer labor alone is insufficient and to scale up operations it is imperative to hire more paid, full-time staff with highly technical training and skills (LNP-1 and ACA-2). Hiring restoration practitioners working in other ecosystems that are currently at more advanced stages of scale or development was also highlighted as a potential way to accelerate restoration efforts (ACA-5). The researcher noted that it would be important to not only learn from other fields, but to actually hire and embed their workforce into seagrass restoration efforts (ACA-5).

Additionally, automation of the restoration process was identified as a potential solution to labor challenges associated with collecting and planting during restoration (SNP-2, GOV-3). For example, in some areas, seeds have been harvested using an underwater sled system for cutting and planting seagrass, reducing the need for large numbers of people in the water (SNP-2), while others have developed methods for direct injection of seeds into the substrate (ACA-7). Some respondents discussed the need for technological advances in the aquaculture process of seed-based restoration, which currently requires significant staff time for rearing and harvesting seeds in tanks (LNP-1, ACA-3, ACA-7). Multiple researchers also mentioned the use of pilot robotics that could facilitate seed dispersal or transplanting (ACA-6 and SNP-2). However, technological advances are not viewed as a panacea for scaling restoration. To date, manual efforts have been more successful than mechanized ones and automation techniques require intensive oversight due to precise and complicated methods (GOV-3).

6.1.6 Infrastructure

Irrespective of restoration method, increasing the pace and scale of seagrass restoration will require a substantial investment in infrastructure (i.e., nurseries). To date, most infrastructure needs are met by universities to advance research and development rather than full scale production. Respondents proposed partnerships with private industry as a potential solution to meet infrastructure demands. In particular, partnerships and lease agreements with mariculture facilities, including shellfish hatcheries with flow through seawater tanks have enabled the expansion of seed-based seagrass restoration operations (ACA-7, GOV-1, ACA-3, LNP-1, GOV-9). Some respondents suggested state facilities—such as fish hatcheries—may be well-suited to host seagrass nurseries (GOV-1). One respondent also highlighted that remote setting options for seagrass nurseries (akin to shellfish restoration operations) should be explored to overcome infrastructure needs (LNP-4).

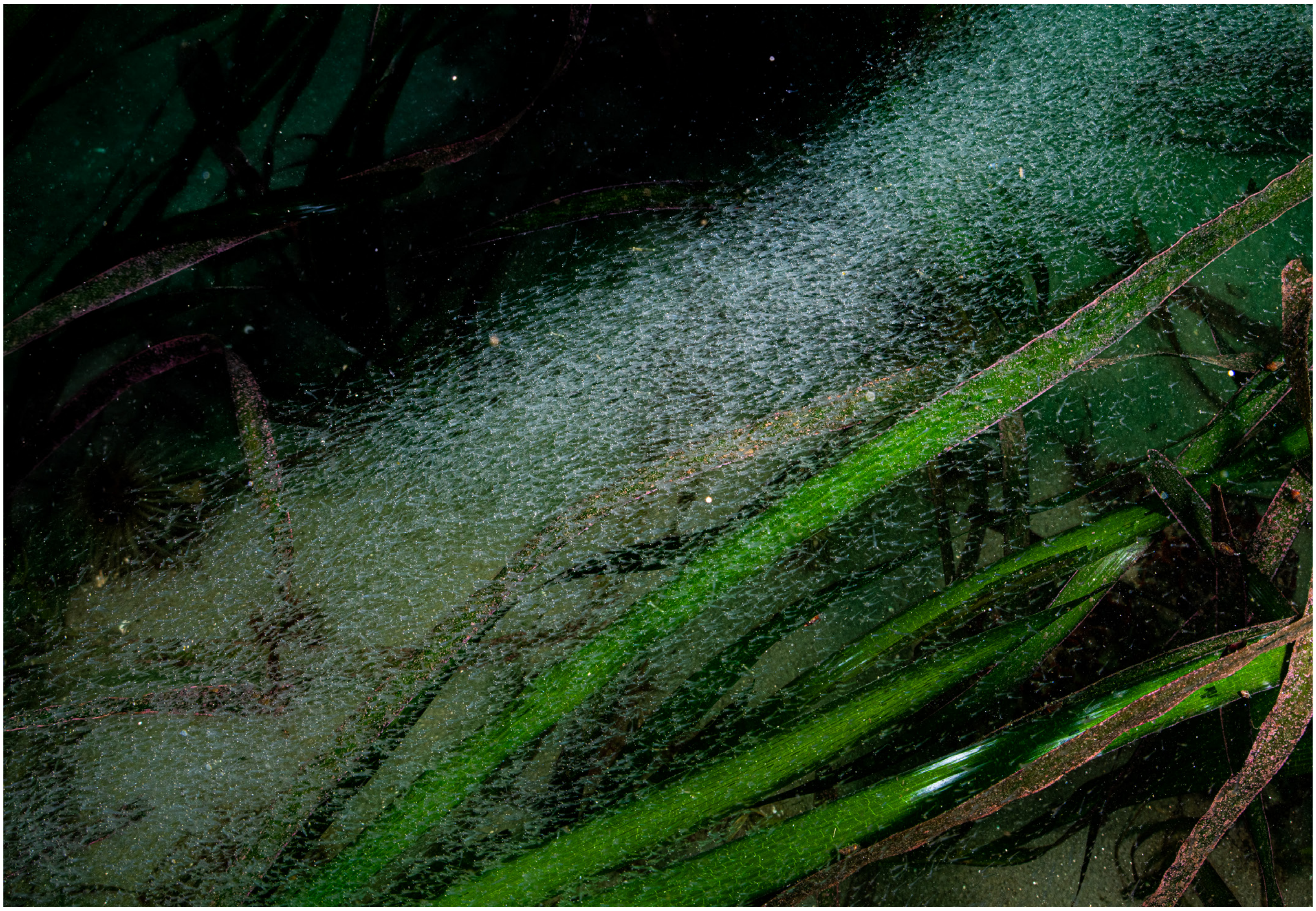
6.2 MAGIC WAND RESPONSES

The 'blue-sky' approach is an important brainstorming method that encourages the identification of a wide range of solutions even if they are not currently feasible. To engage in this type of brainstorming, respondents were asked to suspend reality, and imagine that they have a magical wand which could be used to change anything to scale seagrass restoration—what would they change?

The most consistent magic wand request was improved water quality and reduced/elimination of dredging (n=12). Other common requests included: investment in nurseries and seagrass infrastructure (n=8), the ability to allow seagrass to adapt to climate change (n=5), long term funding for seagrass restoration (n=5), labor automation (n=4), and increased community awareness (n=4;Table 9). Other requests highlighted by individual respondents included: cultivating more species of seagrass beyond the most popular, government advocacy, breaking silos to learn from adjacent and relevant sectors (i.e., bring non-seagrass restoration practitioners to the table), focusing on small test plots first for large scale restoration, and a "fabulously" annotated genome of seagrass.

TABLE 9. "Magic Wand" responses. Seagrass expert responses to the question: If you were to suspend reality, and imagine that you have a magical wand which could be used to change anything to scale seagrass restoration, what would you change?

Magic Wand Theme	Number of respondents	Select responses
Water quality	12	"Find ways to fix turbidity or just have turbidity be fixed." —ACA-2 "Connecting the dots between watershed and watershed stressors and downstream eelgrass." —GOV-2
Establish nurseries and infrastructure	8	"I would pour in 100s of millions of dollars into the field to 1) produce professional-scale nurseries for the 10 most commonly restored seagrass species that can produce large amounts of viable seeds."—ACA-17 "Invest in upscaling nurseries to make seeds commercially available to unlimited amounts." —PRV-4 "One thing is a miracle tree facility for a donor population. So like instead of harvesting from meadows to be able to just grab seagrass from a lab that is growing seagrass ... And so, if we could eliminate the barrier that is you can only harvest this many shoots from the donor meadows by having that material already ready to go, that would be amazing. A nursery for eelgrass would be really great."—ACA-1
Adapt species to climate change	5	"But at some point we're going to have to start looking at whether we do some facilitated migration of warmer water species or looking at particular brood stocks that seem to be more heat tolerant and using them for restoration elsewhere. I think that's going to be a big piece of the puzzle someday." —LNP-1 "I would think towards the future - integrate plans with sea level rise and think about where we can begin to restore meadows and plan for future meadows that don't exist yet. The shoreline itself is changing, so if we are thinking about 'long term' health of seagrass meadows, we will take a 10, 20, 50 year view of where to plan restoration projects."—ACA-13
Longer term engagement and funding	5	"Coordinate distribution of long-term funding (e.g., not grant-based 2-3 year projects) to organizations and partnerships with the best plans in the highest priority areas. Wetland restoration can sometimes take 20 years to plan at a large-scale and then another 20 years before real successes and functions are returned." —ACA-13 "It would be nice to have there be an understanding [how to] assess restoration and how effective it is. We actually have to monitor it over time. There's not always money [for long term monitoring], at least locally. How do you determine if it's successful after five years, 10 years, when the money's gone." —ACA-2
Labor automation	4	"In an ideal world, there would be a machine that goes out and picks all your flowers." —LNP-2 "Automate it a little bit more. So we've got ... the aerial drones, but I think there's also mechanisms to use underwater robotics as well. And especially because the direct injection system seems to work really well in a lot of places. But you can't [currently] do it on a massive scale." —ACA-7
Community engagement	4	"1. In the first instance, do a single, spectacular large scale restoration near an urban area, 2. use imagery to show animals returning to the area, especially charismatic animals or valuable (fisheries) animals." —ACA-10 "Invest in training and engaging (especially young) people from local communities to conduct on the ground restoration activities (planting, monitoring, seed/shoot harvesting and processing)." —ACA-17



6.3 CONSENSUS OPPORTUNITY: SEED-BASED RESTORATION

From insufficient funding, labor, infrastructure, and general scientific knowledge to cumbersome permitting and bad PR, myriad challenges stand in the way of scaling seagrass restoration efforts to meet the conservation need. Though no single solution is likely to address each of these challenges, seed-based restoration was consistently identified as a promising restoration method with the potential to provide unprecedented scaling opportunity.

Seed-based restoration is a multi-stage process involving the field-based collection of flowering shoots (i.e., harvesting seeds), storing seeds to maintain viability, germinating based on timing or environmental cues (e.g., freshwater or water temperature), and dispersing seeds via hand broadcasting, dispersal buoys, or other planting methods (Marion and Orth, 2010). Compared to transplant-based approaches, seeds are generally thought to provide easier scaling opportunities and have less impact on donor populations (Orth et al., 2020). However, seed-based methods must also overcome key bottlenecks and may have more site suitability considerations than shoot-based methods (Cronau et al., 2023). In particular, seeds and small seedlings may be transported out of desired restoration sites due to wave action, substrate transport, or other local hydrodynamic factors (Marion and Orth, 2012; Yu et al., 2019), predated upon before they can establish (Infantes et al., 2016), or succumb to disease (Govers et al., 2017). But under the right conditions, seed-based restoration is considered a "big risk, big reward" (ACA-4) approach. Advancing seed-based seagrass restoration depends on (i) seed availability, (ii) infrastructure development to maintain seed viability, (iii) effectively disseminating seeds and establishing seedlings, and (iv) permitting and regulatory pathways, each of which we discuss below.

6.3.1 Seed availability

Seed availability is a critical bottleneck for restoration. Harvesting seeds depends on a team's ability to effectively track and forecast the optimal harvest time and then mobilize a team for efficient collection. ACA-3 elucidated this challenge, stating, "When to collect, how to collect a lot of seeds for a lot of shoots…that was something that I think took a lot of time and effort to understand that seeds are only produced at a time of year [and] that we have to really focus the effort when seeds are ready...to harvest. That's something that people still have to grasp—there's a very short time period as well when seeds are on the plants and can be harvested without losing them. Because once the seeds are lost, ... it's very difficult to collect enough seeds for any large scale restoration effort." Echoing this sentiment, LNP-1 highlighted the intricacies of the process: "It's tricky when you're collecting these flowering shoots with the seeds developing in them. Timing is everything and you've got a window of a couple of weeks so you don't want to pick too early, because the seeds won't finish developing. But if we wait too long, the seeds will be released into the system and we can't get them. So a big challenge then is keeping an eye on things."

The complexity of harvesting seeds at scale is compounded by substantial knowledge gaps in seagrass biology, particularly related to flowering timing and frequency and understanding what triggers multiple flowering events within a year. ACA-8 notes the discovery of a signal molecule in Arabidopsis, which appears to be a consistent factor in all flowering pathways, potentially offering insights into these aspects of seagrass seeding biology.

6.3.2 Infrastructure development

The facilities and infrastructure needed to support expansive seed-based restoration initiatives do not yet exist. Practitioners have employed seed-based methods in small-scale operations, such as seed bags and buoy-deployed seeding systems, and in single-site operations including for large restoration efforts. However, there is consensus that increased investment in infrastructure is required to facilitate large-scale, multi-site restoration efforts. PRV-1 articulated this perspective, stating, "It's crossed my mind multiple times [that we should] get a group together and write a proposal and see if we can get somebody to fund development of a nursery probably associated with some marine lab who already has the facilities. You have to choose your nursery location really wisely in terms of proximity to where you can have a large enough nursery and where seagrass restoration is needed and where it is likely to be successful with a nursery based approach. And to answer all of those questions, you might need to do a bit of science and scoping..." In addition to how to fund and site nursery infrastructure, seed mortality in storage is a concern that warrants further investigation and more effective storage methodologies will need to be developed to increase and optimize seed viability.

6.3.3 Seed dissemination and environmental conditions

Environmental factors, like oceanographic and sediment dynamics, critically influence the efficacy of seed-based restoration efforts. These geographically variable conditions may limit the suitability of seed-based restoration. ACA-2 highlighted this challenge: "And the problem with seeding is that, at least for us, seedlings are coming up January early February and we're almost always in the midst of storms. And so turbidity is high and turbidity is already a problem in [our] Bay. And then you add storms to that. So the time that eelgrass establishes naturally by seed is almost always coincident with storms. So I think that's our hypothesis why we've had some years that have worked really well and mostly years that have been complete failures with seeding."

6.3.4 Permitting and regulations

Seed-based seagrass restoration requires its own set of permitting and regulatory considerations covering seed collection, nursery operations, and seed distribution which may not exist. In Florida, the shift from traditional methods of donor bed transplanting to more contemporary approaches in seagrass cultivation has introduced new challenges. GOV-3 articulated this transition: "We [are] shifting from a donor bed paradigm to a nursery paradigm and that is entirely new to the industry here in Florida. The science behind it is struggling to catch up, as [is] the permitting, so there's been a lot of conversations lately about how to better oversee the number of seagrass nurseries that are popping up around the state of Florida, and how best to manage permitting for broodstock collection, and what sort of genetic and other considerations need to be put in place for outplanting."

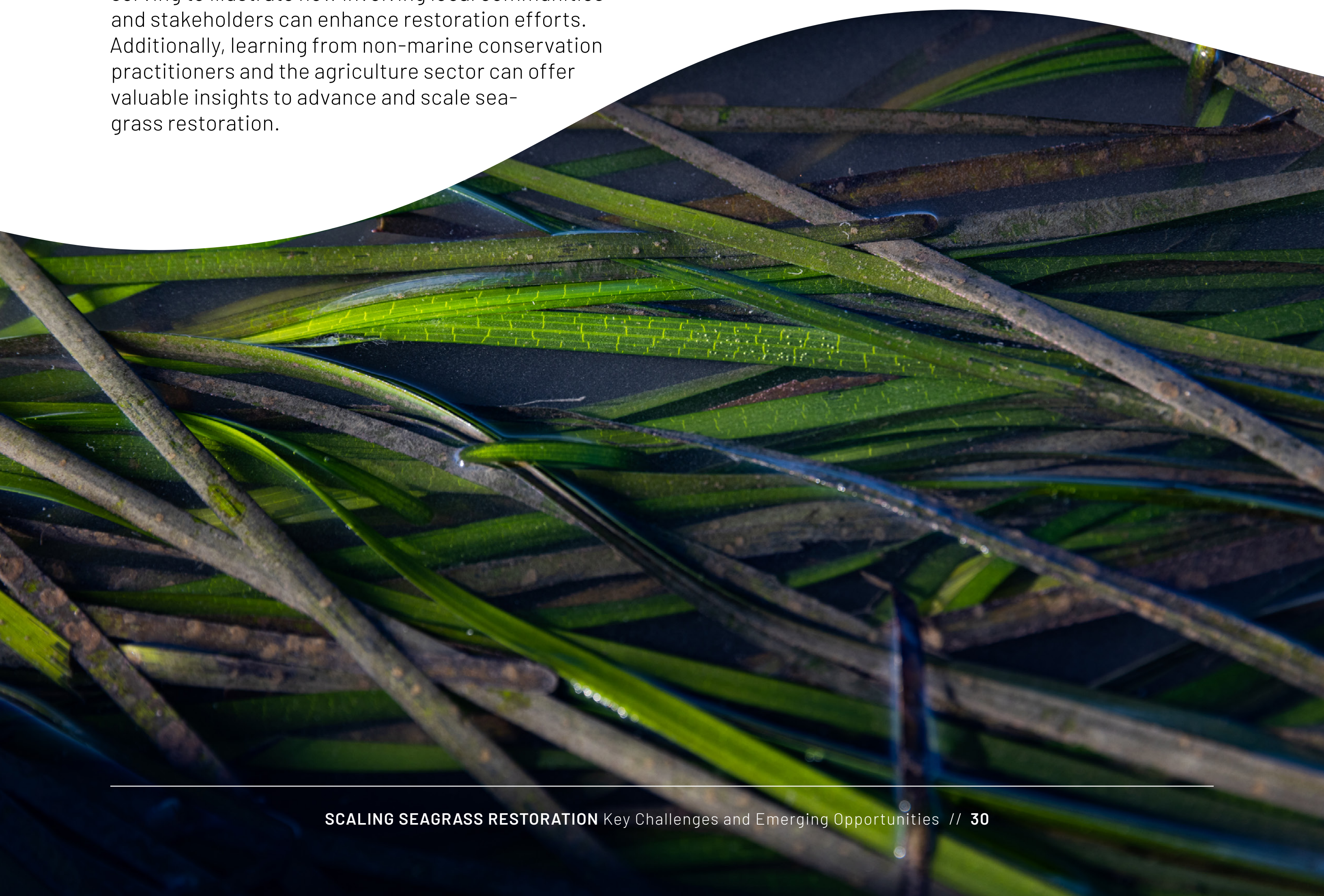
Similarly, in Australia, new permitting concerns are emerging at the intersection of research and commercialization: "One of our main challenges around permitting is we're a research facility but to actually start to produce seeds and flowers and do that in collaboration with traditional allies...they will take on the management to provide proper tools for large scale seagrass restoration. Then it becomes money exchanging hands for the seeds rather than it being research" (ACA-7). This example illustrates the regulatory considerations that are emerging globally due to the rapidly evolving nature of seagrass restoration.

SECTION 7

CONCLUSIONS AND FUTURE WORK

Through interviews and surveys with a diversity of professionals in the seagrass restoration space, we identify six key barriers to effectively scaling seagrass restoration and reveal forward-looking strategies to address these challenges. Currently, large-scale restoration is limited by (i) a lack of stable long-term funding, (ii) complex and/or ill-suited permitting processes, (iii) limited public awareness, (iv) critical knowledge gaps in seagrass ecology, biology, and genetics, (v) labor shortages, and (vi) inadequate infrastructure. Key, actionable solutions will require improved information sharing and collaboration both within the seagrass restoration community but also outside of it to engage other habitat restoration networks and relevant members of adjacent sectors. Community engagement and improved public perception and awareness emerged as pivotal elements in the restoration process, with success stories from Virginia, Florida, Central Queensland, and Mozambique serving to illustrate how involving local communities and stakeholders can enhance restoration efforts. Additionally, learning from non-marine conservation practitioners and the agriculture sector can offer valuable insights to advance and scale seagrass restoration.

A shift in approach, favoring seeding over or in combination with shoot transplanting, was highlighted as a promising pathway to broaden the scale of restoration. However, to be successful, this approach requires a deeper scientific understanding of seagrass, including aspects like flowering timing to aid seed collection and production, seed storage, and genetic diversity. To advance this, TNC is hosting a workshop to bring together seagrass restoration practitioners and scientists working on key aspects of seed-based restoration methods in May 2024. Specifically, the goal of the workshop is to gather lessons learned to identify a path forward for trialing eelgrass seed-based restoration across California, with considerations around experimental design, seed collection and production, infrastructure requirements, and planting methods to ultimately unlock scaling opportunities for seagrass restoration both within and outside of the state.



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APPENDICES

APPENDIX A. Interview guide

Introduction

We are investigating and exploring the scaling of seagrass restoration. Our ultimate goal is to expand the footprint of seagrass restoration by using California as a test site to advance learning and rapid experimentation. This will be a two part study; the first consisting of interviews and surveys, and the second part a convening in 2024. Your responses today will be anonymized for any external sharing. We do have an auto transcription service for taking notes, but please let us know if you want to opt out of it. We anticipate finishing up this first phase in late 2024, and at that point we will share our findings with you. Please reach out to us in the interim if you have questions.

There has been some great work through a series of recent workshops identifying key learning and considerations around site selection, environmental quality, genetics, and defining success through continuous monitoring. We are hoping to build on top of this knowledge for situations where the ideal site has been selected and the ideal species has been chosen in order to understand what else needs to improve or change in order for us to implement seagrass restoration at scale.

To give a quick example, this could be flagging to us that current shoot transplantation methods are very labor intensive and require specialized skills in diving, and this is what has prevented operations from scaling today. The obstacles for scaling could include time, cost, labor, competing interests, or permitting to name a few things. **The question you will hear us pose often is why was the restoration project a few acres, what is preventing it from expanding to 100x in magnitude?**

Seagrass restoration background

- Five minute overview of your experience?
- [if this is not publicly available] What sized area were you aiming to restore? What is the total area restored to date? Approximate time frame this took from planning to transplantation? General breakdown on how long each step took? What about costs? How many shoots/seeds did you transplant? How big was the team?
- At TNC, we are also dedicated to ecosystem restoration as a whole. Was this something your study looked at? What were the metrics that you used?
- Do you feel these restoration efforts were successful? Were there follow on efforts? Why or why not?

Identifying challenges/threats

One big emphasis of this study is that we want to identify what's preventing organizations from scaling seagrass restoration.

- What were challenging factors preventing widespread success? How would you rank them in severity? [goal is to get specifics beyond baseline challenges for general restoration to understand if this was a site specific challenge or something that would impact scale-wise restoration].

Current solutions

- For your project [if practitioner] how were you able to circumvent these challenges? Were you able to circumvent these challenges?
- In hindsight, is there anything you would want to try differently?
- For the current solutions you listed, do you think any of these are scalable? Which ones? What are the risks associated with these solutions?

Future solutions

- Let's go back to your definition of success in seagrass restoration. Based on the current solutions we just spoke about, what's the gap? What do we need (funding, technical development, manpower) to get there?
- More specifically, what would we need to do in the next 3-5 years? Any risks we would need to mitigate?

Innovative solutions

- Have there been innovations in other industries (e.g., agriculture) or other seagrass locations you have heard about that you think could be applicable to seagrass restoration generally or your projects specifically?
- To suspend reality for a moment, if I had a magical wand and could change anything to unlock restoration potential, what would you like me to change?

[optional] Success definition/defining metrics

- What metrics do you think we should be using to evaluate success?
- How should we improve our standardized monitoring so we can evaluate success effectively?
- How does this relate to whole ecosystem restoration? Do you have any thoughts on this from a measurable success standpoint or a rapid experimentation standpoint?

APPENDIX B. Survey

Administered via TypeForm. *(Responses are anonymous)*

Hi, Thank you for your time and participation in our survey. Our objective is to determine what challenges exist today for scaling seagrass restoration through applied restoration efforts. Our ultimate goal is to expand the footprint of seagrass restoration by using California as a test site to advance learning and rapid experimentation.

We recognize there has been excellent studies on site and environmental selection. The focus of our study is once a suitable site and host media has been identified, what are the challenges of collecting and transplanting shoots/seeds and how we could scale the process. We are hoping this takes no more than 10 minutes of your time. We will share out the synthesis by the end of this year and anonymize all comments and responses.

Question 1

Please describe your experience with seagrass? (select one)

a. Smaller nonprofit (n<50)

b. Larger nonprofit (n>=50)

c. Consultant and/or private sector

d. Academic researcher in seagrass

e. Policymaker or government scientist working on seagrass restoration

f. Other ____________________

Question 2

What is the magnitude of seagrass restoration you have done (please specify in approximate acres and number of restoration sites)

Question 3

[long form] What do you think has prevented you (or others) from engaging in 10x this magnitude?

Question 4

What geography do you work in? (please specify region + country or global if you are involved in multiple efforts)

Question 5

Could you select what you believe are the top three pain points for *scaling* seagrass restoration? (Please keep in mind the focus of our study is boots on the ground restoration and how to get it to scale; we recognize the important of site selection, environmental quality, and continuous monitoring, but we will not go as deeply into this content)

a. Funding

b. Permitting

c. Public perception and awareness of seagrass

d. Assembling and deploying seagrass infrastructure (nursery tanks, seed curing, etc.)

e. Labor

f. Availability of seeds

g. Availability of shoots

h. Curating genetic diversity and lineage of shoots

i. Other ____________________

Question 6

If [a. Funding] is selected:

- What sources of funding do you currently get or are aware of others getting?
- What specifically has been challenging about these sources of funding? [select all that apply]
  - » Not enough
  - » Constrains my site where I can operate
  - » Too time consuming to procure
  - » Too fragmented
  - » Require multi-year
  - » Other ______________________________
- What solutions do you have (or have witnessed) currently to combat funding challenges?
- People often request funding, but what will more money empower you (or others) to purchase/do?

If [b. Permitting]

- What aspects of permitting do you (or others) find challenging?
- What needs to change in order for permitting to be less challenging?
- How would you recommend TNC help with the permitting process?

If [c. Public perception and awareness of seagrass]

- What do you think is currently challenging about the public perception of seagrass?
- Which interest groups do you think are critical to engage with?
- What steps would you recommend to change this public perception?
- Any case studies you could give of good public engagement?

If [d. Seagrass infrastructure]

- What parts of seagrass infrastructure do you think are challenging to implement?
- Why do you think it is challenging to implement (select all that are relevant)
  - » Capital expenditure cost
  - » Operating cost
  - » Availability of tanks
  - » Proximity requirements to seawater
  - » Manual labor
  - » Other ______________________________
- What do you think can be done to lower the barriers of these infrastructure challenges?
- What are you (and/or your peers) hoping to achieve with more of this infrastructure?

If [e. Labor]

- What aspect of labor do you (and/or your peers) find challenging for scaling seagrass restoration?
- What do you think can help with the labor challenges? (select all that apply)
  - » Additional volunteer mobilization (Quantity)
  - » Dedicated skilled labor (Quality)
  - » Mechanization/Automation (Substitution)
  - » Other ____________________
- Do you want to expand on what part of the restoration process would benefit from these changes in labor?

If [f/g. Availability of Seeds and/or shoots]

- What techniques do you (and/or others) currently use to harvest seeds (or shoots)?
- What constrains you (and/or others) from harvesting more seeds (or shoots)?
- If you (and/or others) were to receive funding for a solution, what would you invest in to help you with this problem?

If [h. Curating genetic diversity]

- How do you (and/or others) currently increase the genetic diversity of your restoration program?
  - » What is the most ideal situation in your mind of increasing genetic diversity?
  - » What currently prevents you (and/or others) from doing this?

If [i. Other]

- What is challenging about this?
- What have you done previously (or witnessed peers do) to circumvent this challenge? [long form]
- What would you suggest as a path forward to resolve this challenge to effectively scale restoration efforts? [long form]

Question 7

Let's suspend reality for a moment. If you had a magic wand, and you could accelerate seagrass restoration 100x, what would you do?

Question 8

Anything else you want to say about challenges and potential solutions to scaling seagrass restoration that you haven't had a chance to say yet?

Question 9

If you'd like to be contacted for future engagements or the findings of our report, please leave your email here.

APPENDIX C. Adjacent Sector Interview Findings

Executive Summary

The Nature Conservancy's California Ocean program conducted a study to identify challenges associated with scaling seagrass restoration. In Phase I, interviews with practitioners, academics, consultants, and government officials revealed funding, permitting, community awareness, knowledge gaps, labor, and infrastructure as major hurdles. Phase Ib of the project aimed to explore how seeding could alleviate these pressures by interviewing experts from adjacent sectors, including aquaculture, terrestrial restoration, rice cultivation, and agricultural technology.

Key findings from the expert interviews suggest that developing a seeding supply for seagrass restoration requires time and market forces, as seen in terrestrial restoration. Optimization of production protocols, inspired by aquaculture practices, could lead to efficiency and volume gains. While genetic diversity is crucial, it is rarely the primary consideration in restoration projects. Different business models, such as forward contracting, can encourage producers to participate in the seeding market. Seagrass restoration can draw inspiration from adjacent fields, such as rice paddy-inspired cultivation, agricultural technology applications for monitoring, and seed drill technology from mine removal.

This paper provides an analysis of the learnings from adjacent sectors and offers recommendations for applying these insights to scale seagrass restoration.

1. Objective: Broadening perspectives on seeding and scaling seagrass restoration

To explore how seeding could alleviate some of the pressures identified in Phase I, Phase 1b of the project focused on interviewing experts from adjacent sectors. The objective was to broaden the thinking around the challenges associated with seeding and scaling seagrass restoration by learning from solutions employed in fields such as aquaculture, terrestrial restoration, rice cultivation, and agtech.

2. Methodology

2.1. Expert selection criteria

The study cast a wide net among experts in terrestrial restoration, rice cultivation, and private aquaculture nursery owners. The research team reached out to 18 experts, including previous and current coworkers, authors of papers in terrestrial restoration and native seeding, and speakers at restoration and other relevant conferences and workshops, to gather insights from diverse perspectives.

2.2. Interviewee profiles

The study successfully conducted interviews with 13 experts from 10 different organizations/companies:

- Holdfast Aquaculture team: Diane Kim (CEO), Nathan Churches (CSO), Ian Jacobsen (COO)
- Sea and Shoreline: Heather Herold (CMO)
- Salarte and Aponiente: Juan Martin Bermudez (Environmental Manager), Sofia Rivaes (Biologist)
- Rhishi Pethe: Former chief product officer of Mineral.ai, current consultant for agtech
- International Rice Research Institute (IRRI): Linga Reddy Gutha (Head of IP/tech transfer department)
- The Nature Conservancy: Kevin Badik (Rangeland ecologist), Abigail Hart (Project director), Olga Kildisheva (Program manager)
- Bureau of Land Management: Lauren Svejcar (Project manager)
- Florasource: Tom Hawkins (CEO)

Responses are anonymized below using ADJ-1 through ADJ-10.

3. Key Findings

3.1. Development of seeding supply

- Current state of seeding in seagrass restoration
  - » Private sector seagrass aquaculturists confirmed that they did not use seeding in their seagrass restoration operations due to limitations related to seed availability (ADJ-2) and the lower survivability of seeds compared to shoots (ADJ-3).
- Learnings from terrestrial restoration: challenges and market mechanisms
  - » In contrast, seeding was found to be a more mature concept in terrestrial restoration projects in the Great Basin and San Joaquin Valley. Alfalfa farmers were incentivized to grow native plants to support terrestrial seed-based restoration efforts when provided with futures contracts, which helped them hedge against the uncertainty of growing an unfamiliar crop and the risk of growing a crop not backed by an insurance market (ADJ-7).
  - » Private seed companies have also entered the market to provide native seeds, although the quality can be inconsistent and they are often contaminated with invasive species (ADJ-9). There is a need to investigate different market mechanisms to incentivize more participants in seed programs, with early adopters tending to be sustainability-minded farmers or those facing water shortages that prevent them from growing their favored crops (ADJ-6).

3.2. Optimization of production protocols

- Adjacent sectors have successfully optimized aquaculture production protocols to enhance production of other marine species, e.g., mussels via seeding ropes at a density that prevents biofouling and timing transportation to maximize survival; ADJ-1). For seagrass, identifying key variables, conducting iterative experiments, and fine-tuning methods for collecting and storing seeds would almost certainly lead to similar efficiency and production gains (ADJ-1).

3.3. Genetic diversity considerations

- Balancing genetic diversity and restoration practicality
  - » Because specific ecotypes may not always be available for restoration, terrestrial restoration practitioners often have to work with what is available on the market, which is often a limiting factor (ADJ-7). Terrestrial practitioners working on grassland restoration are also centrally concerned with preserving adaptation and interspecies diversity, which in theory is less of a challenge in a monoculture like most seagrass meadows (ADJ-8).
- Insights from rice genebanks and commercial native grass cultivation
  - » Best practices for maintaining a genebank include regular growing out of stored samples and evaluating genetic material across multiple environments to ensure multiple lineages remain viable (ADJ-5). This approach contrasts with growing practices for purely commercial uses, which prefer genetic (and phenotypic) uniformity, and perform in situ cultivation and propagation of grass fragments within a network of specialty growers to maximize high volume, cost-effective production of a uniform product (ADJ-10).

3.4. Business models for growing seed supply and encouraging adoption of restoration practices

- Seagrass industry approaches
  - » A for profit successful seagrass business model involves applying for funding and permitting on behalf of clients, typically through government grants, mitigation banking, and carbon credits (ADJ-2). An alternative funding approach is to leverage interest from other markets, including the restaurant industry, which has shown some interest in domesticating seagrass as a food source (ADJ-3).
- Lessons from terrestrial restoration and ecotourism
  - » Forward contracting has been used to address uncertainty and risk and incentivize farmers to grow native species for terrestrial restoration (ADJ-7). Ecotourism funding model have been successfully applied in coral restoration (Goodridge).

3.5. Potential for cross-sector inspiration

- Learnings from aquaculture (network vs. hub model)
  - » Seagrass restoration may benefit from an optimized collection and holding process, similar to the network versus hub model used in mussel and oyster farming (ADJ-1). Identifying adjacent industries with infrastructure to host seed collection and holding is critical for this to succeed, as is figuring out how to set up a network to transport seagrass shoots and/or seeds (ADJ-1).
- Rice paddy-inspired seagrass cultivation
  - » Lessons from rice cultivation have already been successfully applied to seagrass production. In one effort, canals and salt pans were intentionally flooded to cultivate seagrass at consistent temperatures and depth in an identical method to that used in rice paddies. This method decreased transplanting costs and enhanced survivability of seagrass, while also enabling the growth of 127 different species (ADJ-3).
- Agricultural technology applications for monitoring and mapping
  - » Underwater drone technology currently used for detecting plastic could potentially be adapted to reduce costs in monitoring and mapping seagrass post-transplant (ADJ-4).
- Seed drill technology from mine removal
  - » A ball-shaped drill seeder, inspired by Serbian mine removal technology, can traverse different topographies more easily than expensive and ineffective aerial seeding methods, and could potentially be adapted for underwater use (ADJ-9).
- In vitro cultivation and specialty grower networks
  - » In vitro cultivation of shoots, which could then be sourced to specialty growers to mature and provide to the market is a practice used in propagating female sterile grass for commercial use and may be applicable for restoration purposes (ADJ-10).

4. Conclusion

4.1. Summary of key insights

Key learnings from discussing the relevance of adjacent sector approaches to overcoming bottlenecks associated with seed-based seagrass restoration include the development of seeding supply through market mechanisms, optimization of production protocols, balancing genetic diversity with practicality, and exploring different business models for adoption. Cross-sector inspiration, such as rice paddy-inspired cultivation, agricultural technology applications, and seed drill technology, could also contribute to scaling seagrass restoration efforts.

4.2. Recommendations for applying learnings to seagrass restoration

To effectively apply the learnings from adjacent sectors, there are opportunities for seagrass restoration practitioners to:

- Investigate market mechanisms to incentivize seed production and engage early adopters
- Collaborate with aquaculture experts to optimize production protocols and identify infrastructure for seed collection and holding
- Balance genetic diversity considerations with restoration practicality, drawing insights from rice genebanks and commercial native grass cultivation
- Explore diverse business models, such as forward contracting and ecotourism, to encourage adoption
- Adapt cross-sector innovations, like rice paddy-inspired cultivation, monitoring solutions from agricultural technology, and seed drill technology, to seagrass restoration contexts

APPENDIX D. Interviewee Names & Affiliations

Name	Title	Affiliation
Adriana Vergés	Professor	University of New South Wales; Operation Posidonia
Bo Lusk	Coastal Scientist	The Nature Conservancy
Brad Furman	Seagrass Research Lead	Florida Fish and Wildlife Commission
Bryant Chesney	Senior Marine Habitat Resource Specialist	NOAA
Carolyn Geraghty	Restoration Program Manager, Morro Bay NEP	Morro Bay NEP
Chris Gillies	Managing Director	SeaGen Aquaculture
Dana Clark	Restoration Ecology Team Leader	Cawthron Institute
Emma Jackson	Professor & Director, Coastal Marine Ecosystems Research Centre	University of Central Queensland
Holly Greening	Co-Founder (former Executive Director)	Coastwise Partnership (formerly Tampa Bay Estuary Program)
Jay Stachowicz	Professor	University of California Davis
Jennifer Ruesink	Professor	University of Washington
Jonathan Lefcheck	Research Scientist	University of Maryland
Judy Haner	Marine and Freshwater Programs Director, Alabama	The Nature Conservancy
Kathryn Beheshti	Assistant Researcher	University of California Santa Barbara
Kathy Boyer	Professor	San Francisco State University
Melissa Ward	Marine Scientist	San Diego State University
Phil Colarusso	Marine Biologist	US-Environmental Protection Agency
Richard Lilley	Director / Co-Founder	Project Seagrass
Robert Orth	Professor	Virginia Institute of Marine Science
Roosmarijn van Zummeren	Ecologist	Van Oord
Salomão Bandeira	Professor	Eduardo Mondlane University

APPENDIX E. Interviewee recommendations for TNC's role in seagrass restoration permitting

How would you recommend TNC help with the permitting process?

Liaise with government agencies who are the permitting authority

Assist in developing best practice guidance for harvesting donor materials, with considerations around protected areas, population structure, etc.

Work with coastal states to facilitate application process

Engage with policy makers

Create a fast-track permitting pathway for true habitat restoration efforts

Create a workflow / decision tree for locations that identifies who, how, and what has been permitted successfully. Create a public, opt-in database of people working on seagrass restoration looking for collaborators (academic, commercial, non-profit)

Compile regional information in one location that provides practitioners a checklist when going through the process

Use TNC's power, money, and influence to bring attention to broken aspects of the system to cut the red tape

Conduct assessments of the policy and permitting landscape and create best practice guides for how to navigate permitting

Support less developed countries in setting up permitting protocols for seagrass possible under water restoration works

Develop a 'White Paper' per State in collaboration with state agencies to identify pathways to improve permitting (for all parties involved)