Scaling Seagrass Restoration

APPLYING LESSONS LEARNED
FROM INTERNATIONAL SEED-BASED
RESTORATION EFFORTS TO CALIFORNIA

The Nature Conservancy

CONTENTS

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PART

I

WORKSHOP OVERVIEW

Executive Summary

Seagrasses provide the foundation for one of the most biodiverse, productive, and ecologically important habitats on earth (Unsworth et al. 2020; Unsworth et al. 2018). They support thriving coastal ecosystems through sediment stabilization and augment the production of diverse and abundant juvenile and adult fish species, including those that comprise the backbone of recreational and commercial fisheries (Unsworth et al. 2018). However, coastal development, pollution, and anthropogenic climate change are rapidly destroying these keystone coastal species and the ecosystems that rely on them to survive and thrive (Waycott et al. 2009). Across California, *Zostera marina* (narrow-leaved eelgrass), the dominant seagrass species, is consistently exposed to acute (e.g., dredging, dyking, pollution) and sustained (e.g., wasting disease, erosion, sedimentation, climate change) threats from human activities (Merrifield et al., 2011; Ward & Beheshti 2023). Given the extent of these threats, actions to protect and restore seagrass along the US West Coast have proliferated, but existing efforts are falling short, with between 30-60% of existing restoration projects failing to achieve stated objectives (Ward & Beheshti 2023).

In 2014, NOAA Fisheries published the California Eelgrass Mitigation Policy and Implementing Guidelines which mandates no net loss of eelgrass habitat function in California (NOAA 2014). To date, this requirement for compensatory mitigation has largely resulted in eelgrass restoration efforts for compliance centered around urban areas with outsized development impacts (73% of existing restoration projects along the US West Coast were conducted for mitigation purposes; Ward & Beheshti 2023). California's Ocean Protection Council has a Strategic Plan Target (3.1.4) to both preserve the existing, known 15,000 acres (~6,070 ha) of eelgrass in California and create (i.e., restore) an additional 1,000 acres (~405 ha) by 2025. However, that target itself likely falls short of the total restoration area required to promote eelgrass recovery across the state (Fletcher et. al. 2023), and the state is not on track to achieve it.

In late 2023, TNC California launched a series of expert interviews and a survey to understand the barriers to scaling seagrass restoration. Through conversations with interviewees and survey responses, a clear consensus to advance restoration via seed-based restoration methods emerged. On 23-24 May 2024, we convened 20 seagrass restoration experts, including NGO and for profit practitioners, academics, researchers, and government agency staff from across the coastal United States, Australia, and the European Union, to develop a strategic action plan to explore opportunities to advance seagrass restoration via seeding in California. Here, we summarize the TNC California Seagrass Seeding Workshop outcomes, discussion, and identify next steps.

CRITICAL QUESTIONS GUIDING THE WORKSHOP

What decisions do we need to make to increase the pace and scale of seagrass restoration? How do we balance the need for both?

What are the critical bottlenecks in enhancing or restoring seagrass beds using seed-based restoration methods in California?

If money was no object, what restoration practices could benefit seagrass habitats (e.g., are there high risk / high reward activities)?

Key Takeaways & Themes

- **The need for action:** the cost of inaction is very high. Workshop participants highlighted the need for long-term baseline data and experimentation to be certain of an intervention's impact. However, there was general agreement that despite the lack of existing data required to improve our understanding of California's eelgrass populations, given rapid climate change, the cost of not acting is too high.
- **Priority research needs:** in water and lab-based research is needed to understand (*i*) flowering phenology and drivers within and across California bays, (*ii*) the importance of genotypic diversity across environmental and latitudinal gradients, (*iii*) the optimal method for seed storage and production to maximize viability, and (*iv*) how to optimize outplanting timing and method.
- **Genetics:** we need to support research in order to advance best management practices around genetic considerations for restoration.
- **Monitoring and long term data:** eelgrass beds can be patchy, ephemeral, and exist at seascape scales. To track the impact of our interventions, there is a need for reliable long term data collected in restored and reference sites year over year.

Background

Workshop Objective

The goal of the workshop was to gather lessons learned from participants to identify a path forward for trialing seagrass seed-based restoration across California, with considerations around experimental design, seed collection and production, infrastructure requirements, and planting methods. Our assumption is that identifying and unlocking the key bottlenecks across each step of the restoration process will allow us to uncover solutions that increase seagrass restoration pace and scale. We designed the workshop to identify tactical next steps to advance the potential for several rapid, concurrent, multi-site experiments to increase seagrass presence in California.

Structure & Schedule

Workshop participants gathered in person in San Francisco, CA on 23–24 May 2024 to tackle scaling seagrass restoration using seed-based methods through two sessions:

- **Session 1 (23 May 2024):** Bottlenecks and solutions to scale seagrass restoration using seed based methods across the restoration life cycle
- **Session 2 (24 May 2024):** California seeding experiment planning exercise and expanding learning opportunities

Full workshop agenda provided in Appendix I.

Participants

There were 20 workshop participants identified from a series of interviews conducted by The Nature Conservancy's California Oceans team. Participants had complementary expertise across the seagrass restoration life cycle and included academics (n=6), government agency staff (n=3), for-profit restoration practitioners and consultants (n=3), conservation foundation members (n=2), and a non-profit practitioner (n=1) from across the coastal US, Australia, and the EU as well as TNC CA staff (n=5) (Table 1).

Table 1. Workshop participants and affiliations.

Name	Affiliation & Title
Arn Aarreberg	California Department of Fish and Wildlife, Environmental Scientist
Darcy Bradley	The Nature Conservancy, California Oceans Program, Lead Scientist
Bryan DeAngelis	The Nature Conservancy, California Oceans Program, Lead Scientist
Norah Eddy	The Nature Conservancy, California Oceans Program, Associate Director
Bryce Goodman	Oceankind, Consultant
Laura Govers	University of Groningen & Royal Netherlands Institute for Sea Research, Associate Professor
Ben Grime	The Nature Conservancy, California Oceans Program, Scientist
Randall Hughes	Northeastern University, Marine and Environmental Sciences & Marine Science Center, Professor
Emma Jackson	Central Queensland University, Professor & Director of the Coastal Marine Ecosystems Research Centre
Lloyd Lee	Oceankind, Program Manager
Jon Lefcheck	University of Maryland, Center for Environmental Science, Research Scientist
Bo Lusk	The Nature Conservancy, Virginia Program, Coastal Scientist
Keith Merkel	Merkel and Associates, Principal Consultant
Phoebe Racine	The Nature Conservancy, California Oceans Program, Estuarine Project Director
Jay Stachowicz	University of California Davis, Professor & Interim Director of the Coastal and Marine Sciences Institute
Mirta Teichberg	Marine Biological Laboratory, UChicago, Associate Scientist & Director, Semester in Environmental Science
Melissa Ward	San Diego State University, Adjunct Faculty
Andrew Weltz	California Department of Fish and Wildlife, Marine Environmental Scientist
Eric Wilkins	California Department of Fish and Wildlife, Senior Environmental Scientist
Roosmarijn van Zummeren	Van Oord, Marine Ecologist

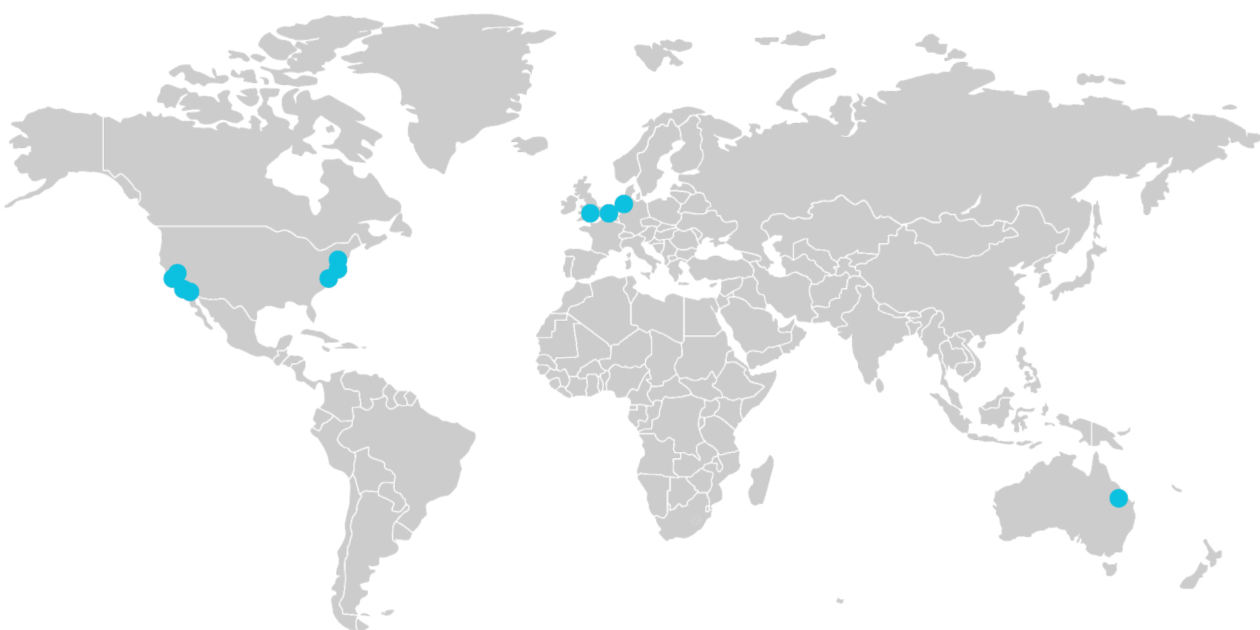


Figure 1. Home geographies of workshop participants convening in San Francisco, California, USA on 23-24 May 2024.

PART

II SCALING CHALLENGES & EMERGING SOLUTIONS

Workshop participants were asked to present on the challenges faced and solutions identified across each component of a seagrass restoration project: (i) site identification and planning, (ii) genetics and provenance, (iii) seed collection, production, and storage, (iv) site preparation, and (v) planting. A version of the following prompt was sent to each participant:

> *Our goal is to come away from the two days together with an understanding of whether seed-based restoration is a viable option in California. To achieve this, we are proposing using our time together to design a hypothetical project to conduct a series of concurrent experiments focused on the key and most critical questions preventing application of seed-based restoration in the state. We are looking to your experience and expertise to help us design this experiment to accelerate learning and ultimately determine the conditions and approaches under which seeding could be an effective and scalable restoration strategy.*
>
> *To this end, we are asking that you share your expertise related to seagrass restoration [restoration life cycle part (i)-(v)], specifically [presenter's topic of expertise], to highlight unique considerations for seed-based restoration relevant to achieving this learning goal via a 10 min presentation on day one of the workshop.*
>
> *As we look to design this experiment together, we want to hear your thoughts on what we should prioritize testing to achieve a learning objective (i.e., within our experimental design, what are we holding constant and what are we varying?). We hope you can highlight unique considerations around [restoration life cycle part (i)-(v)] as it relates to seagrass restoration using seeding approaches. We are also interested in understanding where significant knowledge gaps or critical enabling conditions need to be addressed before such an experiment can be considered. However, in the spirit of ambition, we ask that you not constrain your thinking to the realities of regulatory (e.g. permitting; regulatory provenance constraints; the protected status of seagrass in CA) and related barriers; our team has parallel efforts to tackle these hurdles.*

In this section, we provide a summary of key considerations shared by participants via presentations and discussions centered on scaling seed-based restoration methods.

Site Identification & Planning

Presenters: Melissa Ward, Keith Merkel, Jon Lefcheck

Presentations covered topics related to where seagrass restoration should occur, how much seagrass restoration is sufficient, how to plan a restoration project to effectively learn, and what restoration success looks like. To prepare the group for the day two planning exercise, we were also provided with an overview of the state of eelgrass restoration in California to identify the key challenges and opportunities for scaling seagrass restoration in the state (presented in Part III below).

Target setting

- Targets vary in their scale and focal ecosystem function (e.g., carbon reduction targets, protection targets, restoration acreage targets).
- Setting realistic targets requires answering key questions: *(i)* How much area can support seagrass? *(ii)* How much of this area currently supports seagrass? *(iii)* At what pace can we restore?

Example presented ➔ ***San Francisco Bay, CA, USA. Site suitability estimates ~23,000 acres (~9300 ha) of possible habitat. Currently, there are ~3,000 acres (~1215 ha) of eelgrass. However, historic rates of restoration are <100 acres (<40 ha) in 13 years.***

Planning for seed-based restoration projects

Challenges: it may be hard to learn from failures from seed-based restoration programs because seeding is timing dependent, seeding in areas of prior seagrass may lead to a false perception of success, and few failed restoration attempts are published.

Opportunities: seeding enhances genetic diversity; unparalleled upside potential when conditions are right; tremendous opportunity for community-engagement.

Site selection tools: ecological models including habitat suitability models; natural distribution pattern mimicry; test plots to test variation (e.g., across tidal elevations).

Informing seed deployment with transplanting

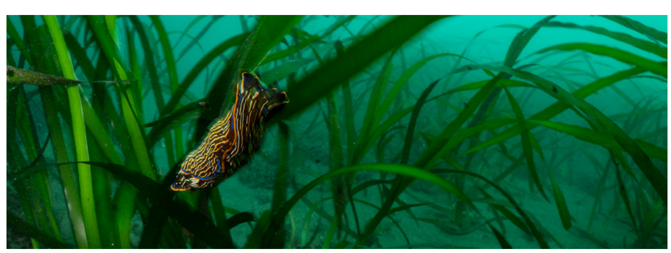
The primary method in seagrass restoration and mitigation projects is to transplant shoots from donor beds. Donor bed selection must be made with care to avoid potential impacts to both the donor bed and the transplant location/restoration bed. Given that there can be substantial genetic variation of seagrasses within the same bay, the genetics of transplanted material may not be ideal for use in a chosen restoration site. Moreover, the impetus for this meeting's focus on seeding is that transplanting can risk the health of the donor bed if not done correctly, is labor intensive, difficult to scale, and expensive. And, despite these substantial costs, transplanting often has a relatively high failure rate compared to other marine habitat restoration. However, practitioners felt that transplanting has many upsides including the substantial potential to be paired with seeding efforts; it is also generally considered a "safer" option than seed-based restoration (e.g., see review by van Katwijk et al. 2016). Before seeding, transplants could be used to test whether a site can support seagrass growth. Mixed seeding and transplanting efforts are also worth testing as transplants could hold more sediment in place, allowing for greater residence time of seeds and potentially increasing the likelihood of growth.

Planning for learning and scaling

- An important role for common gardens to integrate resilience into large-scale seagrass restoration: efforts are exploring opportunities to source warm adapted plants from the south and move them to the north and vice versa to test if genotypes can persist and confer thermal adaptations to local communities.

Example presented ➔ ***HEAT, Helping Eelgrass Adapt to Temperature. A multi-regional, seed-based approach to common gardens to address climate threats (using Zostera seeds, which are easy to collect and can be treated for pathogens to overcome logistics and regulatory hurdles).***

- Current general success standard is five years for projects. Note: success is inconsistently defined, monitoring plans are non-standardized, and requisite data to evaluate success are not always available.
    - » Success definitions can vary widely across projects; Ward & Beheshti (2023) used: (1) Practitioner-defined shoot density success, (2) Practitioner-defined areal coverage success, (3) Shoot density in the last monitoring period ≥ transplanted shoot density, (4) Plot area in the last monitoring period ≥ transplanted plot area.
- Area targeted is a function of risk, with marginal sites being planned over much larger areas than what is required (e.g., for mitigation) given the higher potential for failure.



KEY QUESTIONS & CONSIDERATIONS

- Isolating the restoration effect via reference meadows: when restoring seagrass after a dieoff, there is a need to determine the extent to which seagrass growth is due to restoration vs. natural recovery.
  - » Although assisted regeneration is also a form of restoration, it is crucial to contextualize any restoration 'success' (and 'failure') with reference meadows or plots in order to ensure we are not ascribing success or failure to restoration methods when broader ecosystem processes or environmental phenomena are main drivers.
  - » Establish monitoring protocols relevant to timing of the intervention.
- Restoration does not always scale in the way we would expect, because we start with the easy areas first and then move on to more difficult areas to restore (i.e., a product life cycle bell curve).

Seed Supply: Genetics & Provenance

Presenters: Mirta Teichberg and Randall Hughes

Presentations covered seagrass genetics, in-lab and in-field methods, and considerations for genetic requirements relevant to planning, doing, and evaluating restoration.

Preparing for seagrass genetic studies

- Restoration success hinges on an in-depth understanding of seagrass phenology as it relates to the local system, particularly the timing and conditions under which flowering occurs.
- Seagrass phenology can be highly variable across populations, so building a timeline of flowering stages is critical to inform when to prepare for seed collection.

Genetic considerations for restoration and mitigation

- There is not a "best" source population; there is no one population that is good at all things:
  - » It is likely too risky to choose seagrass genetics based on one characteristic.
  - » There are trade-offs to consider when choosing seeds. For example, if we are targeting seagrass genetics that can withstand warming waters, we may select for genetics that perform poorly when faced with other common stressors such as grazing, nutrient limitation, or light competition.
- Genetic divergence across small spatial scales suggests local adaptation could be common:
  - » Depth and light gradients could be targeted as sources of genetic variation in seeds within a site rather than needing to collect and transfer seeds across sites/regions.
  - » Common gardens can help clarify whether or not we need to be moving seeds on large scales.
- Source environment may be able to predict traits and resilience; however, this is not a guarantee, especially in the context of climate change, because plants may not be adapted. However, the plant genome can signal if they are, for example, warm water adapted, which can be used to curtail the need for complicated field experiments (i.e., with enough data relating genomic markers to temperature, you could go to a novel site, collect plants, and predict temperature tolerance just by sequencing).

Biosecurity risk

- Biomaterial is difficult to sterilize in general, and while seagrass seeds are easier to sterilize than other parts of the plant, it is difficult to sterilize beyond the surface of the seed.
- Seagrass can introduce pathogens for other species (e.g., shellfish).
- Disease risk needs to be considered carefully, because we do not understand all drivers of disease in seagrass. Seagrass diseases noted of concern:
    - » Wasting disease (caused by *Labyrinthula zosterae*) can be particularly prevalent in some areas.
    - » *Phytophthora spp.*: seed pathogen, highly variable but present across Massachusetts, Rhode Island, and Connecticut, USA sites.

KEY QUESTIONS & CONSIDERATIONS

- Climate change is altering the germination window in some geographies.
- There is a need to develop research and best management practices to understand the genetic requirements for restoration: it is critical to determine what currently limits seagrass in a given location in order to identify appropriate source populations for restoration (which may be informed via environmental niche modeling). Note, there may be regulatory barriers preventing optimal sourcing.

Example presented → ***Wadden Sea, Netherlands. Seagrass can be transported from Germany and Denmark but not from countries to the south due to biosecurity risk, even though southern genotypes that are better adapted to warmer climates may be better donor material for warming seas. But in the SW Delta, Netherlands, all European genotypes can be imported (i.e., there are no constraints on moving material due to biosecurity concerns or otherwise).***

- In-vitro germination could help scale nursery production.
- Seed production is thought to be very different on the East and West Coasts of the US, and East Coast populations are thought to produce more seed. If East Coast seagrasses do produce more seed, why? Is it a fixed difference or is it due to growing conditions? What does this mean for the use of seeding for restoration in California?
- In nurseries, *Z. muelleri* flower for 3-5 years and then stop flowering. Is there a genetic basis for the *end* of flowering? (underlying logic: there is a genetic basis to flowering caused by a repressor system, with flowering starting when an organism stops producing floral repressors, so presumably there could be a genetic basis to the end of flowering too).
- Can seagrass genes be manipulated for desired outcomes? Transgenesis, used in agriculture, may prove feasible.

Seed Supply: Collection, Production, Storage

Presenters: Bo Lusk and Emma Jackson

Presentations included seagrass collection in two-different contexts, one limited by safety in-water due to saltwater crocodiles, and the other limited by labor. Storage and handling of seagrass, including innovations in seagrass seed production in nurseries, was also discussed.

Collection

- Though many programs target peak seeding for collection, there could be genetic/resilience advantage to collecting seeds across temporal and spatial ranges: both across the range of flowering, from early flowerers to later flowerers, and from different parts of the meadow, ensuring the seeds taken are within safe collection limits for the meadow.
- Target high density patches. High density areas can be identified using drones, with high density areas observable as dark patches relative to surrounding waters.
- Seed collection via volunteer / community-based programs:
    - » Many seed collection and dispersal efforts across the world rely on significant volunteer programs, some as a result of funding mandates for community involvement and others due to limited funding.
    - » Seagrass restoration volunteer opportunities are meaningful, build community, experience, and often get media attention.
    - » Volunteer programs can be limited by volunteer training, ability, and gear.
    - » Volunteer activities may be limited by geographic and site-specific requirements (e.g., shore-based vs. in-water activities; threats from local wildlife [in parts of Queensland, Australia, saltwater crocodiles make in-water work unsafe]).

Seed production via nurseries

- Nurseries have significant upside for seagrass seed production and also improve our understanding of seagrass biology.
- Results from pilot nursery efforts are promising, but there are very few working/producing seagrass nurseries in the world; many are in early stages of development, but only a few produce at scale (globally).
- "A pot" of Z. *muelleri* in a nursery can create 2,000 seeds in a season due to dense flowering in tanks.
- Production can be expanded by use of raceways.
- Tools and approaches from the aquaculture industry, e.g., Swirl separators used on fish farms to separate food from fish waste, are being tested to funnel seeds to the bottom of the tank for easier collection.
- Nurseries can be used for seed production only and/or to grow out seagrass for transplants.
- Nurseries may produce plants with different phenology and morphology than in the wild. For example, in Queensland, Australia dugongs graze seagrass; in the nursery, plants develop long, flowering shoots.
- Nursery techniques haven't been fully developed; but we shouldn't wait to build nurseries until we have perfected growing methods (i.e., build now while improving production methods).
- Limited application of seed enhancement technologies (e.g., seed priming, seed coating), despite potential (see *Planting* section below).
- If seed sourcing is highly bespoke, smaller scale, and relatively low cost, nurseries that can be regionally deployed (e.g., via shipping containers or equivalent) can be used. If generalities in terms of optimizing sourcing emerge, centralized, larger-scale nurseries may be preferred. The limiting factors here will be access to high-quality, flow through seawater.

Scaling challenges

- Seed harvesting and sorting:
  - » Collection from donor beds is laborious and tedious;
  - » Reliance on volunteer labor;
  - » Hard to identify when to collect;
  - » Uncertainty in identifying appropriate donor beds (i.e., where to collect);
  - » May be permitting constraints on how much donor material can be collected;
  - » Need methods to effectively sort organic matter from seeds post harvesting (e.g., elution);
  - » Important to design in a way that minimizes damage from volunteers (e.g., trampling for intertidal beds).
- Nursery production and seed storage:
  - » Understanding flowering and germination triggers are key to optimizing nursery production and storage; effectively triggering flowering could unlock production potential;
  - » Long storage times may be required: some seeds need to be stored for ~7 months before planting;
  - » Limited viability window (seeds stored longer than 9 months tend to lose viability);
  - » Optimizing seeds selected for storage (e.g., to avoid storing recalcitrant seeds);
  - » Pathogens, algae, slime molds; can be addressed by increasing biosecurity requirements (e.g., sorting and removing animals, using chemical dips, copper treatment, increasing CO_2);
  - » Capacity considerations;
  - » Different business models can be considered to optimize nursery operation, e.g., contract growing, wholesale supplier, vertical integration (retail nursery with tmodel, etc.

KEY QUESTIONS & CONSIDERATIONS

- **Peak flowering of seagrass seeds varies year to year within a site and varies among sites within a year and is also generally shifting with climate change in some geographies; this can make seed collection a challenge.**
- **Along the US East Coast there can be a high phenological variation, with some populations seeming to drop all their seeds very suddenly and rapidly, whereas others (e.g., north of Boston) hold on to them for sustained periods. Thus, there's a much greater risk of missing the seeding 'window' in some areas than others.**
- **In some places, for example, North Carolina, some populations are transitioning from primarily perennial to primarily annual.**
- **Collecting seed across the season, when possible, may serve to enhance resilience of a system.**
- **Best practice guidelines to determine how much of a source population can be sustainably collected would be useful for planning and navigating permitting processes.**

Site Preparation Considerations

Presenters: Roosmarijn van Zummeren and Jay Stachowicz

Various themes in site preparation and site-specific considerations were presented, including lessons learned from planting seagrass sods and transplants, new methods being tested across European populations, and new research on the seagrass microbiome and its role in restoring seagrass meadows.

Informing field deployments with lab experiments

Lab testing can be used to identify optimal field characteristics for planting:

- Environmental characteristics: sediment/water concentration, settling velocity as a function of seed size.
- Germination considerations: seed damage, planting depth, perennial vs. annual sourcing.

Coupling coastal engineering with seagrass restoration: what works and what may not

Examples presented from restoration efforts across Europe:

- **Loch Craighnish, Scotland:** Sand nourishment with seagrass seeding: enhance anchoring capacity and reduce/prevent seed erosion by applying a 10 cm sandy sediment layer mixed with seeds on muddy seabed.
- **Kattegat Strait, Denmark:** Coastal protection (breakwater construction and sand nourishment) with seagrass sod transplanting and seeding: sod transplantation was somewhat successful but survivorship was negatively affected by sediment (suggesting longer waiting time between sand nourishment and transplanting may be necessary); seeding did not result in germination (wave activity in area was relatively high). Oyster reef reinstatement may have negatively impacted transplant survival in this effort.
- In general, it can be beneficial to leverage other mitigation efforts (e.g., marsh) to improve local conditions for seagrass.

Seagrass microbiome

- Seagrasses removed and transplanted to their original site fare better (i.e., there is a homesite advantage), which is thought to be due to 1) seagrass genome, and 2) seagrass microbiome.
- Seagrass response to heat waves may be mediated by microbes—how might this affect restoration planning?
  - » Plants that perform well in the face of heat stress are associated with lower variance in microbiome over time (i.e., "good performers" have relatively constant root microbiomes but more variable leaf microbiomes).
  - » This opens up the potential to imagine culturing a resilient microbiome and inoculating less resilient plants.
- The importance of seagrass microbiomes has inspired testing of seagrass sods or cores, rather than transplanting with popsicle sticks, staples, or similar methods.

KEY QUESTIONS & CONSIDERATIONS

- **Harnessing the microbiome to improve restoration outcomes will require running seed microbiome inoculation experiments, determining how to inoculate plants at large scales, and understanding the drivers of changes to the microbial community (and why it changes so rapidly).**

Planting

Presenters: Laura Govers and Emma Jackson

Presenters outlined key considerations for planting seeds, drawing on their unique experiences working in diverse locations, which, for different reasons, have required innovation in using seeds to restore or enhance seagrass beds.

Case studies in seagrass seed-based restoration

- **The Netherlands:** A country with a long history of seagrass restoration across intertidal and subtidal habitat, which has been spurred in part by the heavy modification of the coastline to historically manage tidelands and now to combat sea level rise. Seascapes have been highly altered, with some systems transformed into marine lakes or lagoons. In general, there is a broad alteration of local hydrodynamics. As a result, there is minimal to no access to natural donor materials, either shoots or seeds, because seagrass beds have become fragmented and connectivity has been lost in some locations. Despite sufficient data to create well parameterized site suitability models, project success is often decoupled from what would be expected from these modeling activities. However, after more than a decade of effort, the Wadden Sea seagrass beds have now grown to 1,250 ha.

RESTORING SEAGRASS IN A CHANGING CLIMATE

Climate change is altering seagrasses' germination window in some geographies.

In many places, temperatures are too hot for seagrasses during certain times of year.

Several species graze on seagrass, e.g., crabs, birds, dugongs, which may influence the site or timing of seeding. Climate change is altering population dynamics of some key seagrass grazers, disincentivizing some practitioners from trying to restore seagrass beds.

A restoration-wide concern is whether we are working fast enough to keep pace with climate change?

In June 2022, TNC hosted a workshop to answer the question: *What interventions can increase the pace and effectiveness of climate adaptation in eelgrass to maintain its presence and associated services along the Mid-Atlantic/ New England coast?* (Peterson et al. 2023).

- **Queensland, Australia:** Seeding is often a preferred restoration method due to challenges associated with in-water transplanting (e.g., the presence of saltwater crocodiles) and threats to local wildlife posed by some shoot-based transplant methods (e.g., staples and stakes pose risks to dugongs, who graze on seagrass and could potentially swallow transplanting materials). Queensland has developed multiple seagrass nurseries, providing space for testing materials in a controlled environment. Because Queensland's primary seagrass species targeted for restoration, *Z. muelleri*, has small seeds, <2mm, additional innovation has been required to effectively deploy seeds.

Seed-based planting methods

- Seed characteristics are key to determine planting methods. For instance, some *Zostera* species have such small seeds that they do not have enough weight to break surface tension.
- Key methods:
  - Hand cast;
  - Direct injection / Dispenser Injection Seeding ("DIS"): using a sealant gun with seed-containing sediment paste; optimized over injection density, injection depth, number of seeds per single injection, and nozzle placement (bottom or side);
  - Buoy Deployed Seeding ("BuDS"): trials discussed resulted in huge seed losses;
  - Seed ball treatments: a seeded ball of sediment that can be launched or sunk from a boat; key challenges include seed balls needing to maintain a high moisture content and production being non-automated (vs. terrestrial systems using machines to make pellets);
  - Carrier slurry: slurry mix seeds, algae, and other liquids pumped down from boat; has been tested but unsure of efficacy;
  - Pairing seed with shoot-based transplant methods.
- Seed enhancement technologies:
  - Seed priming: seeds are hydrated under regulated conditions;
  - Seed coating: helps seeds drop to sediment so they stay.
- Considerations for seed (via injection) vs. shoot-based (via cores or anchored shoots) restoration:
  - Shoot-based cores may be more suitable for exposed locations, but all shoot-based methods are impactful to donor meadows; anchored shoots have a higher scaling potential than cores (they experience faster growth and have fewer permitting challenges, but work best in benign conditions).
  - Seeds can also have high survival and growth in benign conditions, and seed-based methods have a high scaling potential (but require substantial labor); seed collection can also be harmful to donor meadows, e.g., trampling in muddy meadows, collecting seeds from annual plants, and requires careful consideration when designing a seed-based restoration project.

KEY QUESTIONS & CONSIDERATIONS

- Seed loss and impacts to seed survival due to hydrodynamics, predation, disease, bioturbation; hydrodynamic modeling to identify high retention sites can be used to address this; hydrodynamics and sediment stabilization can also be addressed using in water structures (at relatively small spatial scales).
- Planting design can be improved by using bigger plots to avoid scale-dependent negative feedbacks.

BENEFITS OF SEED-BASED RESTORATION APPROACHES

- **Efficiency of collection:** seeds can be collected en masse.
- Likely, **lesser impact on donor bed:** less plant material collected.
- **Reduced labor:** methodologies for collecting and dispersing seeds can be less labor intensive than planting transplants.
- **Overcoming genetic and population bottlenecks:** seeds can be collected from a variety of donor beds and/or from different genetic strains within a bed.
- **Space efficient:** less material, time, care, cost while in storage.
- **Improved biosecurity:** the outside coating of seeds can be sterilized and are easier to sterilize than other parts of the plant, reducing the risk of transmitting disease.
- **Known successes:** several restoration efforts across the world have had high levels of success using seed-based methods.
- **Innovation and growth potential:** rapid advancements are happening in seed collection, storage, production, and dispersal.
- **Network formation:** a seagrass nursery network, the Global Seagrass Nursery Network (GSNN), has been developed to facilitate information sharing across the world.
- **Scaling potential is unparalleled.**

SEED-BASED RESTORATION CHALLENGES

- **Tracking success:** it can be difficult to track the success of seeding without long term monitoring and good baseline data; it can also be hard to learn from failure.
- **Tradeoff between quantity and precision:**
  - » Even if plants germinate, it does not mean the plant will survive or a bed will form.
  - » Low success rate: 5-10% success rate of seeds is considered successful.
- **Risk to donor bed:**
  - » Like transplanting, you need to be careful not to take too much from donor beds; there is risk of disrupting a stable bed.
- **Unknown relationship with microbiome:** soil microbiome around plants is critical to their survival, how then do we consider what this means for seeds?
- **Biosecurity risks:** beyond the surface of a seed they are difficult to sterilize, but are easier to sterilize than other parts of the plant; in spreading seed, you may risk spreading disease.
- **Significant topical knowledge required:** there are multiple points of failure in seeding.
  - » In order to be successful in seeding, there is a need to understand how plants produce seed, how to store seed, the environmental and ecological conditions appropriate for outplanting (e.g., hydrodynamic conditions, sediment stability, grazer/predation presence).
  - » A key gap currently exists in standardizing efforts to generalize learnings and support knowledge transfer.

PART

III DESIGNING A SEEDING EXPERIMENT FOR SCALING SEAGRASS RESTORATION IN CALIFORNIA

On day two of the workshop, a breakout group format was used to organize participants into groups of four to six individuals to undertake a planning exercise to design an experiment to test seagrass seeding throughout the California coast. The objective of the planning exercise was to draft a complete outline of an experiment to determine the conditions under which seeding could be a viable and effective restoration approach in California and identify the enabling conditions to launch such a project.

During day one, several seagrass experts from California were asked to identify key challenges and opportunities to advance seagrass restoration via seeding in California specifically, and to more generally provide important context for designing an experiment in the state.

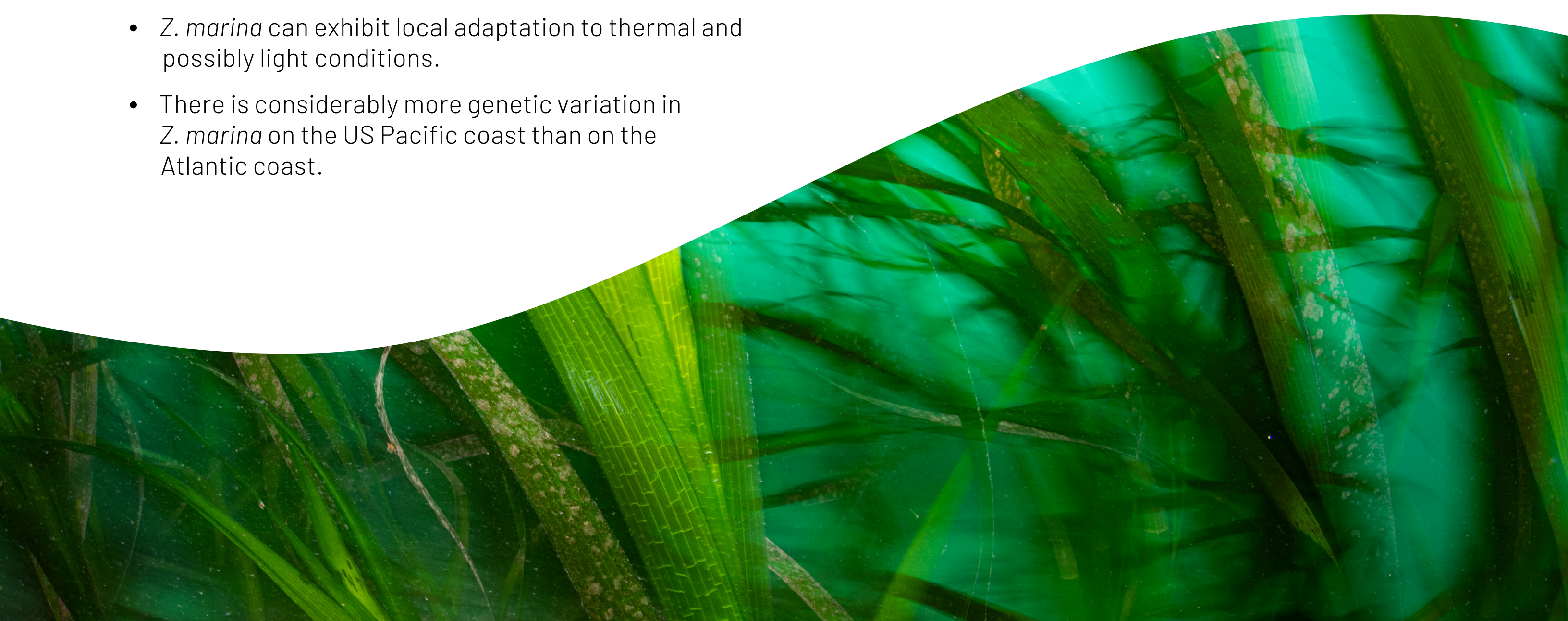
California context

General factbase

- The two most common seagrasses that occur on the West Coast are eelgrass (genus *Zostera*) and surfgrass (genus *Phyllospadix*); we focus on eelgrass, specifically *Z. marina*.
- The morphology of *Z. marina* in California is radically different, with short and stubby plants in San Diego Bay (far southern California) and long and flowing plants in Humboldt Bay (far northern California).
- In general, California bays and estuaries are tidal and known for strong thermal gradients.
- *Z. marina* can exhibit local adaptation to thermal and possibly light conditions.
- There is considerably more genetic variation in *Z. marina* on the US Pacific coast than on the Atlantic coast.

Challenges

- California lacks a statewide seagrass monitoring plan; there are currently inconsistencies between site suitability estimates, what practitioners think is possible, what data we have, etc.
- Restoration success rates across the West Coast are variable (Ward & Beheshti 2023): 32%-60% of restored plots across US West Coast have been unsuccessful; seagrass restoration failures are thought to be due to light availability, algal blooms, and sediment; most restoration is for mitigation (73%).

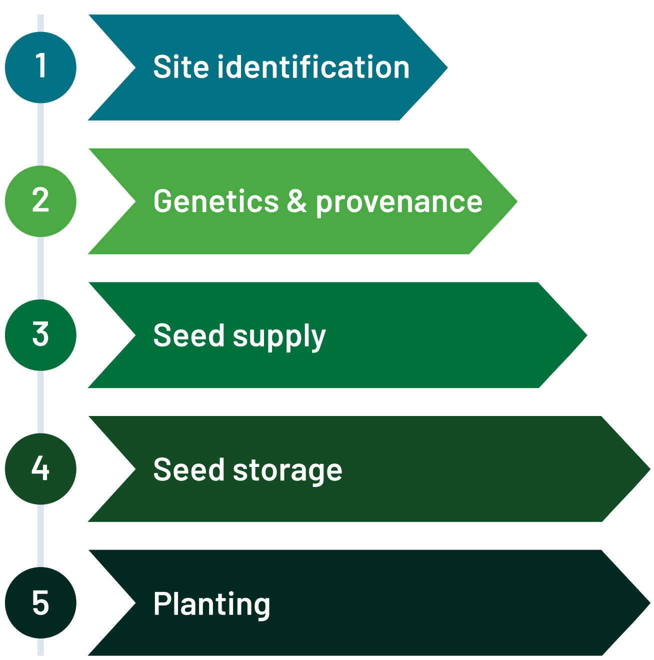


Opportunities

- All eelgrasses are protected species in California.
- 80% of *Z. marina* beds in California are contained within just five bays.
- Large latitudinal extent of the state provides a wide range of suitable habitat for *Z. marina*.
- The most common method of restoration/mitigation is via transplant using popsicle sticks, bamboo stakes (e.g., San Francisco Bay), and garden staples (e.g., Elkhorn Slough); seed-based methods have received less attention (and mostly via seed buoys) than bareroot restoration.
- Natural seeding is supporting recovery in restored areas across the state (particularly in high retention sites, e.g., the Eden Landing Ecological Reserve in Alameda County).

With that context in mind, break out groups met for 45 minutes to identify and consider key aspects of and considerations for designing an experiment to learn how to scale *Z. marina* restoration across the state across each of five stages of restoration: *(1) Site Identification, (2) Genetics and Provenance, (3) Seed Supply, (4) Seed Storage, (5) Planting.*

FIVE STAGES OF RESTORATION



A final group discussed considerations around how to scale the experiment itself and seagrass restoration more generally within and beyond California. A facilitator helped direct conversations towards answering a standardized list of key questions:

a. Rationale

- » *Why are we including this in the experiment?*
- » *What does success look like?*

b. Experimental design

- » *What are the key hypotheses?*
- » *What manipulations are we testing for?*
- » *What parameters are we varying? What are we holding constant?*
- » *How do we incorporate controls / identify reference sites?*
- » *At what scale does this experiment need to occur (how many replicates, geographic extent, area, etc.—not all of these will be equally important across restoration stages)?*

c. Analysis

- » *How do we analyze results?*
- » *What kind of results would confirm or refute our hypotheses?*

d. Impact and Dissemination

- » *Are the results only important/informative or useful to CA?*
- » *If no, what other geographies would find the results most impactful or useful and why?*
- » *Could the results of the experiment immediately inform restoration projects, or are there several other follow-on steps required to study before the information can be applied to restoration approaches?*

Break out session outcomes are shown in Table 2. From these discussions, we identified key areas requiring immediate attention and additional investment .

Table 2. Key parameters and considerations for advancing experiments to optimize seed-based seagrass restoration in California.

		Site identification / experimental design	Genetics & provenance	Seed supply	Seed storage	Planting
Rational	Why are we including this in the experiment?	Success rate of restoration is low. Eelgrass is a protected species in CA and the mitigation hierarchy calls for promoting natural recovery/reinforcement of populations.	Diversity is the driver of adaptation.	Seeds can be collected in mass with fewer impacts on the donor beds than those associated with transplanting methods.	If we can maximize seed viability, we can optimize planting density, and extending the shelf life of seeds will unlock restoration potential.	Seeds can be disbursed or planted in mass across large geographic areas to scale restoration effort, yet there is a need to understand if it is feasible in CA.
	What does success look like?	Maximizing our ability to respond to eelgrass losses with effective methods, to know which sources to use where, how, and when. Understanding why seagrass isn't in a place already.	Knowing which traits are important under which conditions and targeting them for restoration.	Maximizing restoration by understanding differences in seeds and which populations are creating the most viable seeds for outplanting.	Maximizing germination rates, increasing efficiency across all parts of the process, and increasing the viability window.	Optimizing restoration by identifying when seeding is the right approach and when it isn't.
Experimental Design	Key hypotheses	Taking plants across a range of conditions and putting them under common conditions will yield "winners" and "losers."	• Local adaptation is widespread and produces trait variation among and within populations; • If conditions vary, diversity will be maintained, and diversity is needed to maintain plant biomass. • We can maximize restoration success through informed selection among source populations.	Flowering can be predicted and collection can be optimized.	Storage length and method is predictably related to seed characteristics/traits and can be optimized for viability.	Optimal methods are a function of knowable characteristics.
	Approach	Testing sources of eelgrass within and across estuaries; Step 0-figure out where there is seagrass; Step 1- plant source material across varying conditions in target sites for restoration and see what persists to identify "winners"; Step 2—take the winners and scale up the restoration. Note, interannual variation will create challenges for this approach.	• Plant individual and mixed populations (using an equal proportion of traits): sample what you planted and sample what showed up and do this over time • Seed reciprocal transplants from the starting pool and track survivors.	Set up nurseries along the coast for controlled testing and monitoring. Perform pilot experiments to determine (i) where to collect seeds, (ii) whether harvesting seeds has a negative effect on donor meadows, (iii) flowering variability, and (iv) what is triggering seed release (environmental vs genetic).	• Test the effect of different storage conditions on seed viability, specifically isolating effects from manipulations listed below. • Test whether seed traits (such as size, shape/sinking rate, etc.) influence germination success and retention success.	• Due to high variability within and across bays in CA, planting should occur in as many sites as possible using multiple planting techniques. • Pair transplanting with seeding to control for site suitability. • Assess which methods perform best across the various site parameters.
	How to identify controls & reference sites?	Use within bay controls; monitor donor beds; use reciprocal donor beds	Same meadow dynamics between test and reference sites; same environmental parameters	Use within bay controls and monitor donor beds	Highly controlled storage facilities used to isolate effects	Select control meadows based on where donor material is being sourced to disentangle site suitability from planting methods. Planting plots of shoots can act as a control.

Continued on next page

		Site identification / experimental design	Genetics & provenance	Seed supply	Seed storage	Planting
Experimental Design	**Parameters—varied & constant**	• Varied: seed based vs. shoot transplants • Constant: parent sources; standardize with common garden experimental design	• Varied: traits; environmental conditions; meadow extent/density/condition. • Constant: flowering timing, planting methods	• Varied: biogeographic gradient, subtidal vs. intertidal; meadow extent/density/condition; seed collection methods; collection timing within flowering period • Constant: collection methods within a manipulation	• Varied: location; time; storage method (isolating populations vs. mixing; flow through vs. closed tanks); seed characteristics (and their relationship to germination rate tracked through time and across populations, depth gradients, environmental conditions); moving seeds (time, method) • Constant: controlled environment within facilities used to isolate manipulations	• Varied: seed disbursement in isolation vs. with transplants; planting density timing; depth gradients; hydrodynamic gradients; intertidal vs subtidal; planting methods (injection, broadcast, hessian bags, seed balls); plot size and configuration (many small vs. single large) • Constant: planting methods within a manipulation
	Experimental scale	Min 7–8 different estuaries (e.g., S.D. Bay, Mission Bay); ideally no less than 2 x 2 m plots (but overall bigger is better); should get results within a few years	Every bay in CA (all individual bays have a thermal gradient) that currently has eelgrass, focusing on the 5 bays that contain ~85% of current stock.	Start with understanding flowering chronology and seed collection within a single estuary with existing infrastructure. Extend to other bays that could benefit from seeding. ID-ing starting estuary will require balancing the need for restoration with a place that has optimal experimental conditions.	Having a central testing site would be beneficial; build out regional nursery system based on needs	Each location within a bay is variable so outplant using optimized methods in as many sites as possible. As methods are optimized, scale to every bay in CA.
	Key considerations	Identify opportunities to pair eelgrass projects with other landscape/estuarine projects (wetland, oysters)	• Disentangling interactions (below vs. above ground biomass); • Exploring tradeoffs (e.g. higher above ground biomass can increase disease transmission; plant size/density tradeoffs); • Being able to track success/failure: pair with lab experiments and pair seeds with shoots to really understand if seeding failures are mechanical (key questions include: what is the seed niche vs. shoot niche? are there predictable conditions where seeding will work)?	• We need to understand the link between flowering dynamics in different regions of CA to know if natural seed collection or seed production is necessary/optimal. Requires monitoring across multiple years and sites. Nurseries can be used to isolate flowering and seed production drivers. • Regulators need to understand if there are negative effects of harvesting seeds from donor beds on the beds themselves.	• The role of disease and sterilization. • Are there tradeoffs between viability / diversity? (as long as there is not convergence on specific traits then we can just start with different populations to overcome this)	Very few significant seeding experiments have been previously tested in CA. CA has dynamic and diverse bays characterized by variable hydrodynamic conditions and water clarity so numerous planting techniques will need to be tested to determine optimal methods. It is important to understand when outplanting should occur (i.e., do you outplant right after collection when loss will be high due to the overwintering period before germination, or do you store over winter and outplant at the beginning of the growing season to avoid losses during the stormier winter season?).

Continued on next page

		Site identification / experimental design	Genetics & provenance	Seed supply	Seed storage	Planting
Analysis	**How do we analyze results?**		Sample what you planted and sample what showed up and do this over time; do we get the same answer across bays (do up bay populations always do best in hot conditions; is it the same genes responsible for/ associated with that response)? This will tell us if predictability is at the local scale (i.e., within estuary) or if we need to be moving material from other bays.		Compare seed success across storage methods, sterilization procedures, and seed traits (size, color, shape, etc).	
	What kind of results would confirm or refute our hypotheses?	Some populations perform better than others.	• The same genes are associated with higher survival in similar environments across CA; • Selecting source popula-tions with high predicted tolerances to the target site will improve restoration outcomes.	If we identify key populations that create more viable seeds for outplanting, then those should be targeted for collection.	Key effects within our control are associated with seed viability.	If specific methods and locations of planting seeds are more successful than others, then those should be optimized for scaling efforts.
Impact	**Where are these results impactful or useful and why?**	The approach could be scalable, but the findings may be CA specific.	Everywhere: If there is generality that emerges, it would unlock scaling through cost savings; but if there is no generality, and we need site specific approaches, that is important to know so we aren't using doomed-to-fail approaches.	Flowering considerations are likely CA specific, but can be compared with known latitudinal gradients elsewhere: an alert network of collaborators could be developed to identify when flowering is occurring, duration, and how often in various regions of CA.	Everywhere: could inform ability to capitalize on ag extension agents and agricultural / aquaculture (e.g. coral/seaweed hatchery) sector more generally; could unlock potential for nurseries in shipping containers for mobility	Everywhere: results could be applicable to any geographies with similar environmental conditions (i.e., turbidity, currents, etc.) to CA.
	Could the results of the experiment immediately inform restoration projects?	Finding winners makes this immediately useful; if winners are not found, site-level work is needed. But this likely needs to be a multi-year effort to ensure that winner one year (or season) are not losers in other years/ seasons.	If there is generality, then immediately useful; if not, then we need site-level work.	Immediately useful.	Immediately useful.	Immediately useful.

Consensus impact opportunities

Develop statewide monitoring plan for California
Focus on the top 5-6 bays which account for 85% of California's *Z. marina* beds.

Establish a foundational understanding of eelgrass flowering and seeding
California lacks foundational understanding of when *Z. marina* flowers across the coast, lacks knowledge of basic seed phenology, genetics, and how long to store seeds and when to ideally outplant.

Test of seed-based restoration methods
Given the variety of seed phenologies and high variability of conditions, seeding methods should both be tested and potentially developed based on local needs.

Use common gardens
Plant populations collected from multiple distinct geographic locations or environmental conditions (within or across bays) together under shared conditions to identify key traits associated with restoration success.

Increase viability of a site
Site selection is a hard task, with key considerations around retention, sediment composition, water quality, and water clarity. Some of these features can likely be manipulated. For instance, increased retention gives seeds a higher chance of settling and germinating. Ways to increase residence time in California bays could include: adding transplants and/or planting in sites with specific natural features (e.g., rolling benthic environments). Restoration in conjunction with coastal development projects may consider engineering approaches such as building breakwalls or adding sediment plugs to spur seagrass growth.

Enhance public and community engagement
Community awareness and engagement is critical for restoration success. Many noted that working with volunteers is essential for scaling restoration activities in some locations. Everyone unanimously reported that volunteers loved the experience and that community engagement provided critical project visibility. Beyond mobilizing volunteers, participants largely felt that seagrass needed better public relations. Despite its critical importance as a habitat building species, there has been relatively little funding, attention, and public awareness of these systems (even relative to other key marine species and habitats).

Create a community of practice
"The biggest risk is poor communication." Participants nearly unanimously expressed a desire to have more connection and more sharing of information amongst seagrass restoration practitioners, researchers, and associated industry. In particular, there is a need for standardization across restoration trials to enable the identification of general patterns and results. Continuing to support seagrass restoration specific sessions at large, internationally attended conferences, promoting field-based learning tours, and providing a forum to facilitate knowledge exchanges could all serve to support the development of a seagrass restoration community of practice.

Engage state and federal agencies early and often
State and federal agencies are the primary actors responsible for managing and mitigating impacts on eelgrass across California. Early and regular engagement in restoration objective setting, planning, and monitoring and evaluation outside of required permitting processes is encouraged and appreciated by agency staff to collectively work towards shared restoration goals.

Research priorities to drive next generation experiments and knowledge of the California context

Top Research Priorities
- **Flowering:** determine flowering phenology and drivers for *Z. marina* within and across California beds.
- **Genetics:** identify which *Z. marina* traits are important and under which conditions to be able to target them for restoration, while also maintaining diversity.
- **Seed storage and production:** identify available and optimized infrastructure design for seed storage and production; understand the drivers of seed viability in storage and transport.
- **Outplanting timing and method:** understand when and how to outplant *Z. marina* to maximize success.

Other Research Needs
- Identifying where are we most likely to be successful;
- Optimizing seed collection;
- Understanding the relationship between site characteristics and suitable best practices (moving from general best practice guides to something that accounts for the features of specific sites);

A need to work with engineers and technologists to bridge understanding biological and ecological processes key for scaling with operational processes required to scale.

Scaling the experiment

Prior to launch, conduct stakeholder meetings to discuss early-stage plans:
- Invite tribes and communities to address concerns and questions.
- Work with the private sector to coordinate, train, and mobilize volunteer (or paid) labor force.

To address gaps in scaling and building successful restoration and enhancement projects, there is a need to establish a network of practitioners with regional nodes.
- Requires long term funding to enable planning, adaptation to unexpected events, and building redundancy into design and execution.
- Identify a role for the private and commercial sector, e.g., maximizing the role of existing infrastructure (intake and discharge facilities); maximizing commercial expertise.
- Create a state level steering committee/advisory council (a mix of academics, agency, and private sector) with regional leads (serving as the point of contact for the region).
- Each region should have paid staff member whose role would be:
  - » Establishing and ensuring soft and hard restoration targets;
  - » Organizing and facilitating local working groups to begin scoping community involvement and engagement.
- Ensure collaboration with aquaculture groups and key marine labs (e.g., Bodega Marine Lab, San Diego State University).

Physical infrastructure will be required to scale seagrass restoration in California:
- Build toward long-term ecological research stations for seagrass restoration.
- Create a network of restoration infrastructure along the coast.
- Existing infrastructure may be modified to fit restoration activities:
  - » Nuclear facilities
- Shipping containers can be modified at a low cost to create seagrass nurseries, "eelgrass on wheels" mobile units.
- Physical infrastructure can develop as we go if long term funding is available.
- Long-term: physical infrastructure can yield more long-term commitments and investments.

Ideally, lab-based experimentation is done in parallel with the field-based studies.

PART

IV EXPANDING LEARNING OPPORTUNITIES

Moderated by Jon Leftcheck

A CALL FOR INFORMATION SHARING

Poor knowledge sharing is one of the biggest risks to global seagrass health.

Seagrass has limited funding and attention and is actively threatened, making the risk of repeating experiments high.

Significant seagrass work in some locations has been done by private industry, which is confidential.

Work commissioned by governments, even if legally available, may not in practice be available due to opaque data management systems.

Seagrass Networks

- **Coordinated Global Research Assessment of Seagrass System (C-GRASS):** synthesizing seagrass science, producing standard protocols and best practices guidelines for data sharing on seagrass ecosystems, supporting integration with Ocean Data Standards and Ocean Biodiversity Information System.
- **European Seagrass Restoration Alliance (ESRA):** a recently founded platform for the European seagrass restoration community to collaborate and engage in knowledge exchange.
- **Global Seagrass Nursery Network (GSNN):** a global network to facilitate knowledge sharing on seagrass nurseries.
- **Indo-Pacific Seagrass Network:** building capacity, fostering learning exchange, and conducting collaborative research on seagrass and their associated fisheries across the Indo-Pacific
- **Pathways for connecting people and seagrasses (PATHGRASS):** supporting socio-ecological seagrass research across Europe.
- **Zostera Experimental Network (ZEN):** supporting a collaborative network of scientists addressing critical research gaps on the structure and function of *Zostera marina* ecosys
- **Project Seagrass**'s Network Cymru, increasing public awareness of seagrass meadows in Wales, UK, and Global Seagrass Nursery Network, collaboratively identifying knowledge gaps in the building, running and maintenance of seagrass nurseries around the world.
- **SeagrassNet:** long-running program to track status and trajectories of seagrasses globally. SoP has been adopted by many managements agencies (e.g., NOAA NERRS, EPA NEPs)
- **Seagrass Restoration Network (SRN):** linking scientists, industry practitioners, community and government policy makers to advance conservation, recovery, and restoration of seagrass meadows in Australasia.
- **The Seagrass Consortium:** advancing large-scale seagrass restoration in support of the UN Decade On Ecosystem Restoration in Europe.
- **World Seagrass Association:** providing training and information exchange and raising global awareness of seagrass science and environmental management issues.

How can TNC help provide value to seagrass restoration?

- Convene practitioners;
- Coordinate with the goal of information sharing and minimizing duplication of efforts;
- Make space for regulatory agencies;
- Political outreach: act as policy liaisons, push priorities, lobby;
- Community/public outreach;
- Identify global roadmap: understand and recalibrate what is possible;
- Play a role in protecting systems and addressing stressors.

What feels missing from existing networks?

- Statewide or national coordination on seagrass conservation—a document, advisory group to help determine scientific gaps and collaboration needs;
- Global connectivity, such as the mangrove and coral networks;
- There is an appetite to convene seagrass restoration practitioners, however, there is no network in place with this mandate.

Is there a need for another seagrass network?

- Convening meetings and workshops is labor intensive; however, there is a need for communities of practice.
- In order to bring the seagrass restoration space together, a session or day could be added to larger meetings (e.g. CERF or RAE), which may reduce some costs of gathering by linking to existing infrastructure.
- There is a long history of restoration of different key species that the seagrass space may take inspiration from; for example, in the early days of oyster restoration, Australia came to the US for weeks at a time, which rapidly changed the rate of learning and connection.
- Meeting fatigue may reduce if meetings are focused on an output.
- ZEN goes in and out as goals come up, they do not consistently meet.
    - » ZEN could be mobilized to learn about seeding.
    - » A call is placed out to members of ZEN, and whoever is interested in a topic can join the research group.
- Efforts to convene do not need to be permanent, but convening is needed in the very near term, whether that is through single day sessions, learning tours, or online workshops.
- Formalize field learning networks.

HIGH RISK / HIGH REWARD BRAINSTORM SESSION OUTCOMES

Agnostic of cost, what interventions and/or tools can radically scale seagrass restoration?

Widely improve water quality

Build markets: semi-commercialize seagrass to spur innovation (e.g. develop circular economies)

Understand the potential to connect seagrass to the carbon market

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Planning for the future: seagrass restoration with respect to 1) coastal development and 2) sea level rise

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Build infrastructure and programs for producing seeds in California

- » Seagrass nurseries can also provide ecosystem services by improving water quality

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Create top down, state-wide restoration targets, funding, and legislation for mitigation

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Grassroots: build public awareness of the importance of seagrass

- » Take inspiration from successful seagrass campaigns and communities with interest and awareness of seagrass

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Workforce development and training opportunities

PART

V NEXT STEPS

Based on the workshop discussions and outcomes, we identified the following key near-term implementation opportunities for the broader restoration community:

- **Advancing seagrass restoration in California** by developing local and regional level goals and a framework for why, when, where, and how to intervene. Ensure alignment and integration with ongoing state-led efforts for seagrass and other coastal habitat restoration (e.g., kelp and oysters).
- **Develop California specific tools and approaches for Z. marina restoration, particularly around advancing seeding** as a restoration method that can be implemented per a robust intervention framework with the ultimate goal of increasing the scaling ability, efficiency, and success rates, while lowering costs.
- **Network like-minded practitioners across the state and around the world to develop and share solutions**, increase learning opportunities, and develop shared data and monitoring platforms.
- **Advance the science, restoration practice, and promote the adoption of multi-species, multi-habitat restoration** for climate resilient California estuaries and coastal communities.

Key assumptions underlying these priority activities include:

- The problems we need to solve in California are highly similar to other places. Technical issues such as seed collection, storage, and outplanting, and strategic biological intervention approaches, such as genetic and thermotolerance solutions, are similar across the US and even globally.
- Our pace of success outpaces the impacts from threats.
- Optimizing seeding solves for scalability, efficiency, and success hurdles.

Tackling these implementation needs will require cross-coastline collaboration and information sharing. In the immediate future, TNC California is committed to investing to support the science gaps identified through this workshop by working alongside workshop participants and others.

ACKNOWLEDGEMENTS

We would like to thank the workshop participants, who, after traveling from near and far, showed up fully engaged, open to sharing, ready to problem solve, and enthusiastic about creating and deepening connections with a network of restoration scientists and practitioners to tackle the grand challenge of scaling seagrass restoration. The kindness, ambitious attitude, and deep expertise of this group led to informative presentations, highly productive conversations, and immediately actionable opportunities, which we have summarized here.

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APPENDICES

APPENDIX I. Workshop Agenda

SEAGRASS SEEDING WORKSHOP

23-24 MAY 2024

DAY 1: 09:30 - 16:00
DAY 2: 09:00 - 15:30

SAN FRANCISCO, CA

414 Mason St. 8th Floor, Suite 800
Harry M. Smith Conference Room
San Francisco, CA 94102

OBJECTIVE

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. We hope to come away from the workshop with tactical next steps to advance several rapid, concurrent, multi-site experiments for increasing eelgrass presence in California.

OVERVIEW

On the first day (9:30 - 16:00 PT), we will hear from workshop attendees about the challenges faced and solutions identified across each component of a seagrass restoration project, with a focus on seeding methods and unique considerations for seed-based restoration specifically: site identification, genetics and provenance, seed collection / seed supply production, seed storage / curing, site preparation, and planting.

On day two (9:00 - 15:30 PT), we will undertake a planning exercise to design an experiment to test eelgrass seeding throughout the CA coast. The objective of the planning exercise is to draft a complete outline of an experiment to determine the conditions under which seeding could be a viable and effective restoration approach in CA and identify the enabling conditions to launch such a project (what conditions should be varied to identify test sites / inform experimental design? what would seed collection or seed production need to look like? how much nursery infrastructure and where? how should planting methods be identified and tested given local conditions? etc.).

AGENDA

DAY 1: MAY 23

9:30 - 16:00, Dinner @ 18:00

9:15 - 9:30	**Arrival: coffee, tea, pastries**
9:30 - 10:15	**Overview & introductions** • Welcome • Overview • Objectives
10:15 - 11:00	**Site Identification & Planning** • Melissa Ward (10 min) • Keith Merkel (10 min) • Jon Lefcheck (10 min) • Discussion (10 min)
11:00 - 11:30	**Seed Supply Part 1: Genetics & Provenance** • Mirta Teichberg (10 min) • Randall Hughes (10 min) • Discussion (10 min)
11:30 - 11:45	**Break**
11:45 - 12:30	**Seed Supply Part 2: Collection, Production / Shoot storage, Curing** • Bo Lusk (15 min) • Emma Jackson (15 min) • Discussion (15 min)
12:30 - 13:30	**LUNCH**
13:30 - 14:00	**Site Preparation Considerations** • Jay Stachowicz (10 min) • Roosmarijn van Zummeren (10 min) • Discussion (10 min)
14:00 - 15:00	**Planting: Identifying Methods & Planting** • Laura Govers (15 min) • Emma Jackson (15 min) • Discussion (30 min)
15:00 - 15:30	**Other Considerations / Key Themes**
15:30 - 16:00	**Wrap Up and Review Lessons Learned**
18:00	**Dinner @ Ti Piacera Ristorante** 1507 Polk St, SF, CA 94109; 415-771-9946

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AGENDA

DAY 2: MAY 24

9:00 - 15:30

8:45 - 9:00	Arrival: coffee, tea, pastries
9:00 - 9:30	CA Seeding Planning Exercise Overview & Objective
9:30 - 10:15	**Break Out Groups Session #1** • Group 1: site identification / experimental design • Group 2: genetics & provenance • Group 3: seed supply
10:15 - 10:30	Break
10:30 - 11:15	**Break Out Groups Session #2** • Group 1: seed storage / seeding Infrastructure • Group 2: planting • Group 3: execution
11:15 - 12:00	Share Out (5 min per group + discussion)
12:00 - 13:00	Lunch
13:00 - 14:00	Planning Exercise: Putting Pen to Paper
14:00 - 14:30	Immediate Next Steps & Takeaways
14:30 - 15:00	Expanding Learning Opportunities
15:00 - 15:30	Wrap Up & Next Steps

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