Restoring and valuing global kelp forest ecosystems

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Publication Date:
2023

DOI:
https://doi.org/10.26190/unsworks/24671

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Publication Details #1

Full Title:	Global kelp forest restoration: past lessons, present status, and future directions
Authors:	Aaron M Eger, Ezequiel M Marzinelli, Hartvig Christie, Camilla W Fagerli, Daisuke Fujita, Alejandra P Gonzalez, Seok Woo Hong, Jeong Ha Kim, Lynn C Lee, Tristin Anoush McHugh, Gregory N Nishihara, Masayuki Tatsumi, Peter D Steinberg, Adriana Vergés

Journal or Book Name:	Biological Reviews
Volume/Page Numbers:	97/1449–1475
Date Accepted/Published:	2022/3/7
Status:	published
The Candidate's Contribution to the Work:	Mr. Eger devised the research paper, coordinated the co-authors, led the literature review, extracted all the English data, coordinated the data collection outside of English, performed the analysis, interpreted the results, wrote the first draft of the manuscript, revised the manuscript, approved the final manuscript, submitted it for publication, addressed all the reviewer's comments, and resubmitted the work for publication.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 2: This work forms the foundation of this thesis. It is an extensive review of the scientific and non-scientific literature, collecting information from English, Japanese, Korean, Spanish, and Norwegian sources. It summarizes how the field of kelp restoration has developed, how successful it has been, what lessons can be applied to current projects, and makes recommendations for how to advance the field.

Publication Details #2

Full Title:	The need, opportunities, and challenges for creating a standardized framework for marine restoration monitoring and reporting
Authors:	Aaron M Eger, Hannah S Earp, Kim Friedman, Yasmine Gatt, Valerie Hagger, Boze Hancock, Ratchanee Kaewsrikhaw, Elizabeth Mcleod, Abigail Mary Moore, Holly J Niner, Frida Razafinaivo, Ana I Sousa, Milica Stankovic, Thomas A Worthington, Elisa Bayraktarov, Megan Saunders, Adriana Vergés, Simon Reeves
Journal or Book Name:	Biological Conservation
Volume/Page Numbers:	266/109429
Date Accepted/Published:	2022/2/1
Status:	published

The Candidate's Contribution to the Work:	Mr. Eger devised the project concept, hosted the initial working group, coordinated the survey responses, collated the responses, summarized the responses into the text, directed the co-author revisions, approved and submitted the work for publication, addressed the reviewer's concerns, and resubmitted the work for publication.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 3: Collecting the information for Chapter 2 was a substantial effort, information was not well recorded, stored in a central location, and the content and quality of the data related to restoration projects was highly variable. In discussing this issue with my colleagues working in other marine restoration fields, we realized that this problem also occurred in other marine restoration fields such as coral reefs, seagrasses, mangroves, oyster reefs, and tidal marshes. I therefore organized and hosted a workshop at the 6th International Marine Conservation Congress. This workshop brought together experts from all areas of marine restoration and initiated the work for Chapter 3, a roadmap of why need a monitoring and reporting framework, how we can achieve it, and what barriers we will face in doing so.

Publication Details #3

Full Title:	Playing to the positives: Using synergies to enhance kelp forest restoration
Authors:	Aaron M Eger, Ezequiel Marzinelli, Paul Gribben, Craig R Johnson, Cayne Layton, Peter D Steinberg, Georgina Wood, Brian R Silliman, Adriana Vergés
Journal or Book Name:	Frontiers in Marine Science
Volume/Page Numbers:	7/544
Date Accepted/Published:	2020/7/10
Status:	published
The Candidate's Contribution to the Work:	Mr. Eger contrived the study idea, brought together the co-author team, conducted the initial poll, conducted the literature review, created the first draft, led the co-author revision process, approved and submitted the work for publication, addressed the reviewer's concerns, and resubmitted the work for publication.

Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 4: The implicit goal of any restoration project is to restore a fully functioning ecosystem and along with it, all the species interactions and synergies that have evolved over the years. In Chapters 2 and 3, I saw that while this was often stated as the goal, it was not executed and projects most often only considered the habitat forming kelp species in their restoration projects. Chapter 4 thus explores potential ecosystem and human interactions that can not only be included in kelp restoration projects but also increase the probability that the project restores a fully functioning ecosystem.

Publication Details #4

Full Title:	The value of fisheries, blue carbon, and nutrient cycling ecosystem services in global marine kelp forests
Authors:	Aaron Eger, Ezequiel Marzinelli, Rodrigo Baes, Caitlin Blain, Laura Blamey, Jarrett Byrnes, Paul Carnell, Chang Geun Choi, Margot Hessing-Lewis, Kwang Young Kim, Julio Lorda, Pippa Moore, Yohei Nakamura, Ondine Pontier, Dan Smale, Peter Steinberg, Adriana Verges
Journal or Book Name:	Nature Communications
Volume/Page Numbers:	
Date Accepted/Published:	
Status:	submitted
The Candidate's Contribution to the Work:	Mr. Eger devised the study and data collection protocol, conducted the published literature search, directed the co-authors for any subsequent data collection, cleaned and formatted the data, did the analysis, interpreted the results, wrote the first draft, addressed co-author comments, approved and submitted the paper for publication, addressed two rounds of reviewer's comments, and submitted the paper for a third round of review.

Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 5: Ecosystem restoration is a value laden decision, society only performs restoration because there is the perception that it will be beneficial to society or the natural world. None of the restoration works outlined in Chapters 2, 3, or 4 are possible if society does not choose to do the restoration. While there is a strong ethical argument for protecting and enhancing the natural world based on its intrinsic value and right to exist outside of human society, decisions about restoration are often based on the perceived benefits for humans. I wrote Chapter 5 to inform this perspective and in it, I seek to quantify the ecological and economic benefits that kelp forests provide to society. The work does not intend to wholly commodify the unique interconnected existence that is a kelp forest but rather highlight the benefits and encourage greater recognition of those benefits.

Candidate's Declaration

I confirm that where I have used a publication in lieu of a chapter, the listed publication(s) above meet(s) the requirements to be included in the thesis. I also declare that I have complied with the Thesis Examination Procedure.

Restoring and valuing global kelp forest ecosystems

Aaron M. Eger

A thesis in fulfilment of the requirements for the degree of Doctor of Philosophy

School of Biological, Earth, and Environmental Sciences

Faculty of Science

August 2022

UNSW SYDNEY

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Originality Statement

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

Date: 27/08/2022

Acknowledgements

"We are drowning in information, while starving for wisdom. *To tackle the wicked issues facing our planet, we need* synthesizers, people able to put together the right information at the right time, think critically about it, and make important choices wisely." – E. O. Wilson (*modified*)

Research is a lot like an ecosystem, they both depend on connections and interactions to flourish. Behind every thesis, publication, and report is an interconnected web of collaborations and assistance, without which, the work would not be possible. This thesis is a little ecosystem compared to something as grand as a kelp forest, but it has matured and grown over the last four years and has perhaps finally arrived at its "climax community". From other scientists, to administration staff, to family, to ecologically minded businesses, to friends, to all the people working on kelp forests around the world, I owe a great deal of gratitude and appreciation for your support of this work as well as of myself.

The choice to move to Australia was not made easily and I have to acknowledge the encouragement from the Canadian support network. Mathis, Lauriane, Lia, Kieran, Laura, Caitlin, Tao, Tara, and the Bamily, thank you for turning me away from the safe option and getting on one more flight (with special thanks to Holly for making sure I got to the airport time and time again).

To my parents, I can only say thank you, I love you, and I'm sorry. Thank you for the endless support. The list is exceptionally long but a few thesis related titbits... Thank you for reading my papers (or at least the figures), thank you for telling your friends all about my research and learning the funny words and terms, eventually. Thank you for always trying to fit my world into yours. You always cared enough to ask questions and showered me with support as I moved from institution to institution, province to province, and across the sea, figuring out how I might help protect that beautiful bit of earth and ocean we call home. Mom, you are the most caring person I know and the world needs more of you. Dad, I hope to keep up the pioneer spirit, just perhaps with more sea salt. I love you both because I know you will always love me. It’s hard to communicate how important having that immutable stability and trust in me to find my own way has allowed me to set out and take risks, always knowing that I can always come home. And I’m sorry that I’ve had to move so far away to make all of this happen. The Pacific is a very big ocean and phone calls are tricky over 17 time zones. Still, we made it work and no matter where I end up, I will always make my way back home to give you my thanks one more time.

I originally thought I might want to do things a little differently than normal when I started my PhD, but I could not imagine how this project would grow. Nor could I imagine the support and assistance I would get from my supervisory team, Adriana, Peter, and Ziggy in making the ideas a reality. The end product is the result of many dead ends and ideas that may or may not have worked and their guidance in honing the questions and guiding the outputs has been essential. In particular, Adriana, you supported me as I developed a million different ideas, many of them having absolutely nothing to do with my thesis. For the training in storytelling, entrepreneurship, fundraising, filmmaking, book writing, workshop organizing, chairing meetings, and lots and lots of career advice, I cannot thank you enough. I know most (*all)* of that stuff doesn’t fit squarely in this thesis document, but the PhD was a vibrantly richer experience because of it and it’s hard to imagine having done all of this any place else. Science does not only live in textbooks, and I hope to keep these lessons with me.

Going into this thesis, we weren’t sure that people would want to collaborate, share their data, or their ideas. I can happily say that almost without exception, every single person I have spoken to in the kelp world has been open, warm, and receptive and I owe them immense gratitude. This fluid knowledge exchange helped drive this thesis forward and produce some hopefully useful products for kelp forest restoration and conservation. The Kelp Forest Alliance, the Kelp Restoration guidebook, and our Restoration Database all grew from this work in some way and there really is an enormous list of people to thank. First, Norah Eddy and Mary Gleason from The Nature Conservancy in California, thank you for driving the vision to make this thesis into an actionable conservation outcome forward. To all the wonderful co-authors, thank you, muchas gracias, 감사합니다, Takk skal du ha, ありがとうございました, for your contributions, passion, and insights and helping share this information with the world. In no particular order, my thanks to: Schery Umanzor, Bill Heath, Nancy Caruso, James Ray, Mike Esgrow, Jae-Hyeon Lee Jeong, Miyadi Minoru, Jess Nguyen, Pal Bakken, Doug MacMillan, John Merril, Max Calloway, Stephen Whitaker, Brian Takeda, Katie Nichols, Simonetta Fraschetti, Lee-Ann Ennis, Josh Russo, Norishige Yotsukura, Byung-Hee Jeon, Sean Ashworth, David Schiel, Tom Ford, Chang Geun Choi, Laura Tamburello, Greg Finn, John Smythe, Stephen Bunney, Dan Reed, Neil Andrew, Chris Solek, Karen Gray, George Wood, Ines Louro, Jan Verbeek, Duncan Worthington, Brian Allen, Jodie Toft, Emma Melis, Simon Reeves, Seokwoo Hong, Alejandro Buschmann, Ik Kyo Chung, Molly French, Rietta Hollman, Pike Spector, Gwangbok Kim, George Bloomberg, and Masatoshi Hasegawa.

My last four years have contained much more than the contents of this thesis and I would like to express my gratitude to all the Sydneysiders, temporary or permanent who helped make the last four years a wonderful spot of adventure that I still can’t believe was reality. Some of you have left and some are still here, some are from uni, some from away. But thank you to Claudia, Tom, Fabian, Katrina, Josh, Charlie, Iris, for many trips away, boat rides, scuba

dives, dinner parties, and adventures. We may not stay in Sydney together, but the time here was exceptional.

Thank you to the UNSW team Paula, Giulia, Clay, Chris, Shannen, Erin, Steph, Will, Derrick, Maddy, Zee, Orla, Rick, Mark, Dan, Connor, Fernando, Aline, Seb, Rosh, Charlotte, and Julie for being funny BEES and making the office a welcome place to come into and learn together. To the admin team at BEES, the CMSI, and the Scientia team, Jono, Jess, Su, Belinda, Rochelle, Alex, Paul, Greg, Aga, and Louise. The level of technical, logistic, and financial support you have given me has been phenomenal and unlocked a world of opportunities without which much of this work would not have been possible.

I'm still not entirely convinced there are many better places to live than Coogee/Maroubra (the postman still doesn't know which suburb we are). I owe a special gratitude to 3 Liguria street, my only home in Sydney and a place where I can spot whales from the balcony, hop down to Lurline for a swim, or have everyone over for a dinner party. So, thank you to Ed, Alicia, Maxime, Megan, Misha, Jordan, Robin, Marlin, Simone, Andre, Dan, Charlotte, and Lauren for helping make Liguria my home.

Then there is the one housemate who only lasted about three weeks… Three weeks strictly as a housemate that is. Danni, thank you for a world of endless distractions, challenges, and sojourns. There are those who need the wild and I am so happy to share that with you. Perhaps too much… After 12 weekends away in a row I finally succumbed to fatigue (and glandular – thanks for that as well..) and we had to move out of the fast lane for a little while. Still, our "wellness retreats" would still involve snorkelling, long day hikes, and criss-crossing the country in droopy. You are a truly unique blend of a scientist, artist, adventurer, and pun smith. You kept me going as the world at large threatened to unravel while my personal world became increasingly full. Day after day, we kept wondering if we would get tired of each other and I'm still waiting for that day. I don't think you ever expected to hear the word "kelp" so many times in your life, yet you have been endlessly supportive, encouraging, and loving of me in work and life. My life in Sydney would never have been the same without you, so thank you for replying to that Facebook ad.

And lastly. You may have been Dr. Eger a full seven years younger (more? *probably*) than I will be, but you will always be my little sister. Richelle, I cannot think of a greater supporter or cheerleader whose patient advice and sympathetic ear has been with me through every one of life's major outflows. I still remember myself, a bit lost after 1 year of uni, Skyping you (yes Skype), and you suggested I give marine science a try. Well, that seems to have been pretty good advice. I honestly think I would be lost without you to turn to. So, thank you for always being there with an open ear, charming wit, an increasingly crass vocabulary, and blunt integrity to help me figure out what path I should strike down next. I count myself as exceptionally lucky to have such a beautiful person as a sister and hope that you know that a bit of this thesis belongs you.

So long and thanks for all the kelp…

Abstract

Kelp forests cover ~30% of the world's coastline and are the largest biogenic marine habitat on earth. Across their distribution, kelp forests are essential for the healthy functioning of marine ecosystems and consequently underpin many of the benefits coastal societies receive from the ocean. Concurrently, rising sea temperatures, overgrazing by marine herbivores, sedimentation, and water pollution have caused kelp forests populations to decline in most regions across the world. Effectively managing the response to these declines will be pivotal to maintaining healthy marine ecosystems and ensuring the benefits they provide are equitably distributed to coastal societies.

In **Chapter 1**, I review how the marine management paradigm has shifted from protection to restoration as well as the consequences of this shift. **Chapter 2** introduces the field of kelp forest restoration and provides a quantitative and qualitative review of 300 years of kelp forest restoration, exploring the genesis of restoration efforts, the lessons we have learned about restoration, and how we can develop the field for the future. **Chapter 3** is a direct answer to the question faced while completing **Chapter 2**. This chapter details the need for a standardized marine restoration reporting framework, the benefits that it would provide, the challenges presented by creating one, and the solutions to these problems. Similarly, **Chapter 4** is a response to the gaps discovered in **Chapter 2**. **Chapter 4** explores how we can use naturally occurring positive species interactions and synergies with human activities to not only increase the benefits from ecosystem restoration but increase the probability that restoration is successful. The decision to restore an ecosystem or not is informed by the values and priorities of the society living in or managing that ecosystem. **Chapter 5** quantifies the fisheries production, nutrient cycling, and carbon sequestration potential of five key genera of globally distributed kelp forests.

I conclude the thesis by reviewing the lessons learned and the steps required to advance the field kelp forest restoration and conservation.

Publications arising from this candidature

Eger A. M. & Vergés, A. (2022). Restoring kelp forests in Into the Blue: Securing a Sustainable Future for Kelp Forests. United Nations Environment Programme, Nairobi.

Eger, A. M., Layton, C., McHugh, T. A, Gleason, M., and Eddy, N. (2022). Kelp Restoration Guidebook: Lessons Learned from Kelp Projects Around the World. The Nature Conservancy, Arlington, VA, USA.

Eger, A.M., Marzinelli, E.M., Christie, H., Fagerli, C.W., Fujita, D., Gonzalez, A.P., Hong, S.W., Kim, J.H., Lee, L.C. & McHugh, T.A. (2022). Global kelp forest restoration: past lessons, present status, and future directions. Biological Reviews. Wiley Online Library.

Eger, A.M., Earp, H.S., Kim, F., Gatt, Y., Hagger, V., Hancock, B.T., Kaewsrikhaw, R., McLeod, E., Moore, A.M., Niner, H.J., Razafinaivo, F., Sousa, A.I., Stankovic, M., Worthington, T.A., Bayraktarov, E., et al. (2022). The need, opportunities, and challenges for creating a standardized framework for marine restoration monitoring and reporting. Biological Conservation.

Eger, A.M., Marzinelli, E., Baes, R., Blain, C., Blamey, L., Carnell, P., Choi, C.G., Hessing-Lewis, M., Kim, K.Y. & Lorda, J. (2021). The value of fisheries, blue carbon, and nutrient cycling ecosystem services in global marine kelp forests. EcoEvoRxiv.

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Saunders, M.I., Doropoulos, C., Babcock, R.C., Bayraktarov, E., Bustamante, R.H., **Eger, A.M**., Gilles, C., Gorman, D., Steven, A., Vanderklift, M.A., Vozzo, M. & Silliman, B.R. (2020). Bright spots in the emerging field of coastal marine ecosystem restoration. Current Biology 30.

Vergés, A., Campbell, A.H., Wood, G., Kajlich, L., **Eger, A.M**., Cruz, D.O., Langley, M., Bolton, D., Coleman, M.A., Turpin, J., Crawford, M., Coombes, N., Camilleri, A., Steinberg, P.D. & Marzinelli, E.M. (2020). Operation Crayweed – ecological and sociocultural aspects of restoring Sydney's underwater forests. Ecological Management & Restoration 21, 74–85.

Ward-Paige, C.A., White, E.R., Madin, E.M.P., Osgood, G.J., Bailes, L.K., Bateman, R.L., Belonje, E., Burns, K. V, Cullain, N., Darbyshire-Jenkins, P., de Waegh, R.S., **Eger, A.M**., Fola-Matthews, L., Ford, B.M., Gonson, C., et al. (2022). A framework for mapping and monitoring human-ocean interactions in near real-time during COVID-19 and beyond. Marine Policy, 105054.

Presentations

Eger, A. M., et al. 2022 *Taking Kelp Forest Restoration From Local to Global.* United Nations Ocean Conference, Lisbon, Portugal, June 26 – July 1, 2022.

Eger, A. M., et al. 2022 *Taking Kelp Forest Restoration From Local to Global.* Greater Farrallones Kelp Restoration Network Workshop, San Francisco, July 28th, 2022.

Eger, A. M., et al. 2022 *Taking Kelp Forest Restoration From Local to Global.* Deep Dive, The Nature Conservancy Australia, Melbourne, August 15th, 2022.

Eger, A. M., et al. 2021 *Worldwide Synthesis of Kelp Forest Reforestation*. Australian Marine Science Association Conference, Sydney, Australia, June 27 – July 2, 2021.

Eger, A.M., et al. 2021. The Kelp Forest Alliance: *A Global Network for Kelp Ecosystem Restoration.* Society for Ecological Restoration of Australia Conference, Darwin, Australia, May 10-13, 2021.

Eger, A.M., et al. 2021. *Global value of kelp forests and the case for restoration*. Society for Ecological Restoration of Australia Conference, Darwin, Australia, May 10-13, 2021.

Eger, A.M., et al. 2020 *Global Kelp Forest Restoration: Past Lessons, Current Status, and Future Goals* Western Society of Naturalists 101st Meeting, Monterey Bay, USA, November 5th-8th, 2020.

Eger, A.M., et al. 2020, *Creating a standardized monitoring and reporting framework for marine restoration* (Workshop). 6th International Congress on Marine Conservation, Kiel, Germany, August 16th- 27th, 2020**.**

Eger, A.M., et al., 2020, *Worldwide Synthesis of Kelp Forest Restoration*. 6th International Congress on Marine Conservation, Kiel, Germany, August 16th- 27th, 2020**.**

Eddy, N**., …, Eger, A.M.,** 2020, *Assessing global kelp forest decline and management opportunities for restoring kelp ecosystems.* 6th International Congress on Marine Conservation, Kiel, Germany, August 16th- 27th, 2020**.**

Eger, A. M., Marzinelli, E., Steinberg, P., Vergés, A. *Worldwide Synthesis of Kelp Forest Restoration.* International Congress on Conservation Biology, Kuala Lumpur, Malaysia, July 23-27th, 2019

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List of Abbreviations

AUD: Australian Dollars

BC: British Columbia, Canada

BCA: Benefit-Cost Analysis

BCE: Before Common Era

CDFW: California Department of Fish and Wildlife

EEZ: Exclusive Economic Zone

ENSO: El Nino Southern Oscillation

EU: European Union

FAIR: Findable, Accessible, Interoperable and Reusable

FIRA: Fishery Resource Agency of Korea

FMDP: Fisheries Multiple-function Demonstration Project

GDP: Gross Domestic Product

ha: Hectares

IMR: Institute of Marine Resources, Norway

INTL: International Dollars

kg: kilograms

MERCES: Marine Ecosystem Restoration in Changing European Seas

MPA: Marine Protected Area

NDC: Nationally Determined Contribution

NGO: Non-Governmental Organization

NIFS National Institute of Fisheries Science

NIVA: Norwegian Water Resources Institute

NPP: Net Primary Production

QA/QC: Quality Assurance/Quality Control

ROI: Return on Investment

RRF: Restoration Reporting Framework

SEEA: System of Environmental-Economic Accounts

UN: United Nations

UNDER: United Nations Decade of Ecosystem Restoration

UNDOSSD: United Nations Decade of Ocean Science for Sustainable Development

UNSW: University of New South Wales

US: United States

USA: United States of America

USD: United States Dollar

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Chapter 1 - Introduction

Marine kelp forests in the orders Laminariales and Fucales, are one of the ecological wonders of the world. Their distribution spans much of the world's coastlines (Jayathilake & Costello 2020), their net primary production parallels that of the amazon rainforest (Duarte et al. 2022), they range in size from centimetres to 10s of meters (Cole & Sheath 1990, Leliaert et al. 2012, Wernberg et al. 2019), can grow by meters in a week (Sargent & Lantrip 1952), have multiple modes of reproduction (Schiel & Foster 2006), have helped push forward human exploration millennia ago (Erlandson et al. 2007), support multi-billion dollar fisheries (Bennett et al. 2016, Frimodig & Buck 2017, Eger et al. 2021), are themselves consumed (Mabeau & Fleurence 1993), have life supporting compounds (Holdt & Kraan 2011), and are the inspiration for artistic creations, myths, legends, and storytelling (Thornton 2015, Thurstan et al. 2018).

While adaptable, kelp forests have several key requirements for survival. As photosynthetic organisms they are restricted to places where light is able to penetrate, typically less than 40 meters (Steneck et al. 2002) but in some rare exceptions, they can reach depths of 236 meters (Graham et al. 2007). Most kelp species have a holdfast to anchor themselves to the seafloor and thus require hard substrate to secure themselves and grow upon (Anderson et al. 2005). Nutrients such as nitrates and phosphates may be a limiting factor in kelp growth (Dayton 1985) and many kelp forests thrive in nutrient rich upwelling regions (Fernandez et al. 2000, Schiel & Foster 2015). Kelp forests occur mainly along our polar, temperate, and subtropical coasts (Jayathilake & Costello 2020), and thus high water temperature is a common limiting factor in their distribution (Smale 2020). Finally, kelp forests exist within rich ecological food webs with many species interactions (Steneck et al. 2002). Grazing by herbivores is perhaps the most important of these interactions as overgrazing can easily remove a kelp forest ecosystem from a location where it would otherwise persist (Ling et al. 2015).

Alterations to any of the above key factors can cause the decline or disappearance of a kelp forest. Indeed, local decreases in light availability, loss of suitable substrate for growth (Connell et al. 2008), decreases in nutrient concentrations (Tegner & Dayton 1991), increased sea water temperatures (McPherson et al. 2021), and increased grazing by herbivores (Filbee-Dexter & Scheibling 2014), have all caused kelp forest declines in different regions around the world. Perhaps the largest two threats, increased sea temperature, and increased grazing, often act synergistically. As sea temperatures rise new, warm adapted species are able to migrate poleward and exist in regions that were previously too cold (Johnson et al. 2011, Vergés et al. 2016). Kelp forests in these areas are then faced with physiological stress from higher temperatures as well as new grazing pressures and can disappear entirely. There are no reliable estimates of the area (i.e., km^2) of kelp forest habitat that has been lost over the last century, but regional losses of 10s of thousands of hectares have been reported, many times leading to near complete local extirpation (Rogers-Bennett & Catton 2019, Hwang et al. 2020, Layton & Johnson 2021).

The loss of kelp forest habitat has had direct impacts on the marine ecosystems and communities that they support. Biodiversity and animal biomass is reduced in barren rocky habitat compared to kelp forests (Dean et al. 2000, Edgar et al. 2017). Notably, the loss of kelp is associated with declines in key species such as abalone (Marzinelli et al. 2014), lobster (Hinojosa et al. 2015, Shelamoff et al. 2022), and other fishes (Kingsford & Carlson 2010). Fisheries closures often follow from these declines and fisheries in California, Japan, Canada, and Korea have been impacted. No kelp forests, also means less dive tourism in areas where kelp diving is popular. As stressors on kelp populations continue to mount, these benefits and the kelp forests are increasingly at risk.

1.1 Marine conservation paradigms

For much of human history, the bounty of the ocean was too big to fail. It was inconceivable that human activity could irreparably harm marine habitats and animals (Huxley 1883). This paradigm slowly changed as overexploitation of certain resources led to population collapses of sea otters, sea cows, lobsters, and cod fish (Roberts 2007, Duarte et al. 2020). Pollution and physical damages also caused the decline of marine habitats such of oyster reefs (McAfee et al. 2020) and seagrass meadows (Orth et al. 2006). The natural reaction to these collapses was to cease the exploitation or pollution and hope that populations rebounded on their own (Reed & Brzezinski 2009, Jordan & Lubick 2011). A concept that has now given raise to the proliferation of marine reserves and protected areas (Agardy 1994). While this approach has resulted in recovery of marine animals (Côté et al. 2001) and in some instances, marine habitats (Edgar et al. 2017), there is a growing consensus that simply stopping the damage may not be enough. Rather, if we want to have healthy marine ecosystems and the benefits they provide, additional actions may be required.

Marine restoration is largely confined to the 20th and 21st centuries and has mainly focused on intertidal habitats such as mangroves, oyster reefs, and saltmarsh (Saunders et al. 2020). Subtidal restoration is even more recent, with many activities not starting until the 21st century. As a result, the field is truly in its infancy with people still researching the best ways to do restoration and there is a general lack of public awareness about the possibility and the need for marine restoration. Still, the field is gathering strength and interest is growing (Basconi et al. 2020). Notably the concept is being championed at the highest levels with the UN sustainable development goal 14 and the UN Decades for Ecosystem Restoration and Ocean Science for Sustainable Development. Groups are also searching for ways to incorporate marine restoration into the growth of the "Blue Economy", a field worth 2.5 trillion dollars per year (Hoegh-Guldberg 2015). With so much growing interest, it is important that we understand where the field has come from, what we have learned to date, and what we can work on in the future.

1.2 Kelp Forest restoration

Compared to other coastal habitats, there has been relatively little interest in kelp forest restoration (Saunders et al. 2020). In many countries, concerted kelp restoration efforts did not start until the 21st century, though the history in Japan dates back to the 1700s (Fujita 2011). Therefore, there are many important questions about kelp forest restoration that need to be answered. Foremost is a basic understanding of what has been done to date. Much of what has been published about kelp forest restoration is published in the scientific literature in English, despite extensive restoration projects in Japan (Fujita 2011), Korea (Lee 2019), Chile (Westermeier et al. 2016), and Norway (Verbeek et al. 2021). Of that literature in English, the focus is further narrowed on scientific publications and often excludes government, NGO, and community run projects (Morris et al. 2020). What is known about kelp restoration is therefore only a limited snapshot of the true picture and our understanding is thus incomplete.

Publications have highlighted the basic techniques for restoration. These include transplanting live juvenile and adult kelp to the seafloor, adding propagules to the water (i.e., seeding), removing herbivores such as sea urchins, and adding artificial substrates for kelp forests to grow on (Morris et al. 2020). The identified projects have been small in scale (< 1 ha), often run by scientific institutions, and occurred mostly in the United States of America, namely in California (Morris et al. 2020). We understand that it is important to remove or mitigate the stressor that originally caused the kelp to disappear but there has been no analysis of the best approaches for restoration. As with other marine restoration projects, the number of kelp forest restoration projects is expected to increase and require millions of dollars. Before we advance any further, now is the time to truly assess the field, identify the important lessons learned from past projects, and highlight the remaining barriers to success.

1.3 Synthesizing information on restoration outcomes

Many conservation actions and initiatives are hindered by poor record keeping of the intervention and the outcome (Adams & Sandbrook 2013). Projects often run with limited budgets and the available funds are typically spent on the action itself, e.g., hiring rangers, removing invasive species, or restoring a habitat. There are usually not enough resources to fund proper monitoring, recording, and analysis of the conservation action. Valuable information about what does and does not work in conservation is therefore often lost and the lessons are not shared with other projects (Sutherland et al. 2015). When project data is recorded, it is done in an uncoordinated fashion. Different variables are recorded using different methods and stored in different units (Bayraktarov et al. 2020). This discoordination further complicates attempts to synthesize information on the efficacy of conservation interventions and prevents knowledge sharing between projects as well as well global tracking of conservation outcomes.

Recently, this problem has begun to be addressed by an initiative called "Conservation Evidence" (Conservation Evidence 2022). This program is run from Cambridge University and tracks the outcomes of conservation interventions, ranging from establishing protected areas to increasing soil fertility (Conservation Evidence 2022). Though this work analyses an impressive 3510 actions, only 262 are related to marine habitats, and only 26 are related to any type of marine restoration. There is a clear need to address the issues of monitoring and reporting outcomes in marine restoration.

1.4 Synergies for restoration

Marine ecosystems are highly biodiverse (Bouchet 2006), often have high population connectivity (Cowen et al. 2007), exist in a mosaic of habitats (Nagelkerken et al. 2015), and are heavily influenced by human populations (Crain et al. 2009). Despite these attributes, restoration efforts typically only focus on the target species being restored, usually a habitat former such as a kelp (Morris et al. 2020), seagrass (van Katwijk et al. 2009), or coral (Boström-Einarsson et al. 2018). This focus is likely because restorationists have yet to master the ability to do single species restoration and have not had the capacity to attempt multi-species restoration. Nevertheless, emerging evidence shows that taking advantage of the positive links between species, known as synergies, can aid restoration efforts and increase the chances of success (Halpern et al. 2007, Gedan & Silliman 2009). The ultimate goal of a restoration project is most often full ecosystem restoration (Gann et al. 2019) and restoring habitat forming species is viewed as the starting point to achieve this outcome. Together, these points highlight the need to expand our view of single species restoration and consider how we can restore multiple species together and even consider how human activities, usually viewed as negative, can perhaps aid restoration efforts (Zhang et al. 2018).

There are well known and well demonstrated examples of synergies and positive interactions between species in kelp forests. The sea otter-sea urchin-kelp forest interaction is now a textbook example of a trophic cascade, an indirect positive interaction between two species at different trophic levels, in this case the sea otter and the kelp forest (Watson & Estes 2011). While these types of trophic cascades have been shown with other urchin predators such as lobsters (Edgar et al. 2017) and fishes (Hamilton & Caselle 2015), the concept has not been integrated into kelp restoration practices. There has also been scant consideration of how different species of kelp or seaweeds maybe restored together, how competition between herbivores may alleviate grazing pressure on kelp species, or how human activities such as aquaculture can benefit kelp forest restoration. As we work to restore kelp forests, it is imperative that we consider how we can use these interactions to increase the probability of restoring the kelp itself, but also how we can better restore entire ecosystems.

1.5 Valuing marine ecosystems

Ecosystem conservation and subsequently, restoration are inherently value driven fields of practice. Society only works to conserve or restore an ecosystem if their morals or values deems that system worth protecting (Odenbaugh 2003, Choi 2007). Reasons for valuing an ecosystem are varied and range from a purely altruistic belief that ecosystems have a right to exist outside of the human experience (Soulé 1985) to more utilitarian beliefs that ecosystems provide benefits to people and are worth preserving because they benefit society (Kareiva & Marvier 2007). Altruistic motivations for conserving an ecosystem require little further exploration as ecosystems are valued simply in their own right. Conversely, valuing nature for its benefits creates multitudes of new questions about how we place those values and how we prioritize what we can save.

The fields of ecological economics and natural capital evaluation have grown at a rapid pace since the late 1990’s. Broadly, ecosystem benefits or services are categorized as either provisioning services such as fisheries and timber, regulating services such as oxygen production and water purification, and cultural services such as recreation and spiritual importance (United Nations 2014). These services may be evaluated using the market value, people's willingness to pay for a service, or substitution cost which is based on how much it would cost to artificially replace a service such as water purification (Ninan 2014). There have now been complete economic evaluation analyses of most major ecosystems (de Groot et al. 2012, Costanza et al. 2014) at the global level as well as thousands of regional and local studies (Ecosystem Services Valuation Database 2022). These values are used to highlight the importance of nature to people (Potschin & Haines-Young 2016), to make management decisions (Martinez-Harms et al. 2015), for accounting programs (Chen et al. 2009), and to advocate for restoration and conservation (Canning et al. 2021).

There have been evaluation studies for most major ecosystems, except for kelp forests (Costanza et al. 2014). The global examination of kelp forest services to date has grouped macroalgae habitats together with seagrass and does not provide an accurate assessment of the average value of a kelp forest or the intricacies involved in arriving at that value. People may then perceive kelp forests to have lower value than other ecosystems and thus de-prioritize their conservation and management (Bennett et al. 2016, Hynes et al. 2021). Regional studies have attributed place based values to kelp forests in Chile (Vásquez et al. 2014), the Falkland Islands (Bayley et al. 2021), South Africa (Blamey & Bolton 2018), Korea (Kang 2018), and Southern Australia (Bennett et al. 2016) but only one used marginal, area based values (i.e. per m^2), a key requirement for management decisions. A new, kelp specific analysis which combines marginal value estimates and kelp forest distribution estimates to generate regional and global estimates of the value of kelp forests is thus needed.

1.6 Research aims

The overall objective of my thesis is to advance the conservation and restoration of kelp forest ecosystems by targeting some of the knowledge gaps identified above. Once a knowledge gap was identified, the aim was to provide actionable recommendations or information that could lead to actionable recommendations. In particular, the research seeks to answer:

1) What is the current state of kelp forest restoration (**Chapter 2**)
2) What makes some restoration projects more successful than others (**Chapter 2 & 4**)
3) How can we increase knowledge sharing and understanding of restoration outcomes (**Chapter 3**)
4) How can we improve kelp restoration methods (**Chapter 2 & 4**)
5) What are the ecological and economic values of kelp forests (**Chapter 5**)

1.7 Overview of this thesis

Through the introduction and discussion, I use the first-person singular pronoun “I” to reflect that these sections only reflect my own thoughts and opinions. This usage changes to the first-person plural pronoun “we” in **Chapters 2-5**. While I organized, collated, analysed, and wrote the first drafts for all of these chapters, they are undoubtably group efforts and reflect the efforts and contributions of my valued collaborators. I think such intensive collaborations are indeed a positive for any scientific field as they have brought in new ways of thinking that have crossed countries, cultures, languages, and bacrounds. No one person could have completed this thesis alone and I am humbled to have been able to bring together the relevant information so that it may be used to inform kelp forest management.

As alluded to throughout this thesis, information about kelp forest restoration around the world was disjointed and difficult to access when I started my PhD. Many people had the perception that there were a few projects around the world and that not a lot of research or practice was available to learn from (Bayraktarov et al. 2016). Further, the available information was largely from California and Australia, each focusing mostly on *Macrocystis* restoration (Schiel & Foster 1992, Carney et al. 2005, Layton et al. 2020). People were aware that projects had occurred in Japan, Korea, Norway, and Chile but the extent of those projects and their outcomes represented a black box (Pers. Obs.). Therefore, I made accessing this information and connecting with restorationists in these countries a major goal of my PhD. Together we would create the world's first comprehensive review of kelp forest restoration. **Chapter 2** is the result of this effort and formed the basis for the rest of my PhD. In this chapter I work to detail the story of kelp restoration, how it started, where it has happened, how it was done, what motivated it, who did it, how much did it cost, and what were the outcomes. Each of these questions needed answering to give us a proper understanding of where the field has come from and where it is today. I was also motivated to use this opportunity to build a database of restoration projects around the world. Not only would the database answer the above questions, but it would also provide the opportunity to synthesize the outcomes of restoration and look for factors that made some projects more successful than others. While I was unable to collect every factor for every project, I was able to build a database with information from 269 restoration attempts across 16 countries. I then combined these quantitative results with a literature review in each region and put together a detailed understanding of the field to date. Pulling together so much information also highlighted the areas that needed future research and I was able to explore future barriers and opportunities to advance kelp forest restoration.

As I built the database and experienced the disparate ways that project data was recorded, I came to understand just how much the lack of a standardized reporting framework was holding back the field. Further, this problem was not limited to kelp forests but was a consistent issue across ecosystems. **Chapter 3** was informed by a workshop at The 6th International Marine Conservation Congress, hosted virtually from Kiel, Germany in August 2020. Here, I brought together marine restorationists from around the world and polled them on the needs, barriers, and opportunities for creating a global marine restoration reporting framework. I then collated the responses to this survey, categorized the responses and drafted the pathway to a framework presented in **Chapter 3**. This framework focuses on standardized data collection, centralized data repositories, enhanced information sharing, greater inclusivity outside of English, and continued collaborations between groups and institutions in the field. I present this framework as a pathway to help solve some of the issues I faced in my own data collection.

While most projects implicitly seek to restore a functioning ecosystem, the project focus is usually set on the habitat former (Cristescu et al. 2013, Cross et al. 2019), in this case kelp. There was additional evidence to suggest that considering multiple species or interactions in restoration could actually enhance restoration success (Halpern et al. 2007, Gedan et al. 2009). But as before, this information was unavailable for kelp forests. Therefore, in **Chapter 4,** I quantify the established synergies for kelp forests, draw parallels from similar ecosystems, and discuss unexplored but plausible synergies that might aid restoration efforts. **Chapter 4** brings these ideas together and provides concrete steps for how restoration projects may use these synergies.

Chapter 5 quantifies the ecological and economic value of kelp forests across all the continents. Bringing together all this information involved collecting information on thousands of biodiversity surveys, species sizes, their productivity, fisheries market values, growth rates of different kelp species, kelp tissue compositions, carbon sequestration rates, the market price of carbon, nitrogen, and phosphorus, as well as the spatial distribution of the kelp itself. As with **Chapter 2,** this work would not be possible without the insights of my collaborators around the world. Bringing it all together, I was able to provide the first area-based ecological and economic estimates of the value of kelp forests, estimate how much carbon they sequester each year, and make an estimate of the yearly economic contribution of kelp forests to society. This work situates the importance kelp forests alongside other marine habitats and demonstrates their value to society.

The work does not stop here, I see a bright future for kelp forest conservation and restoration. In **Chapter 6**, I discuss the implications of the work contained in this thesis as well as discuss how this work can be built upon for the future.

1.8 Addressing the research gap

I worked to address the largest data gaps preventing the successful management and restoration of kelp forest ecosystems. In **Chapter 2**, I led a global, multi-language qualitative and quantitative review of kelp forest restoration projects. This works provides a thorough systematic review of our understanding of how kelp restoration has evolved as a practice, how successful projects have been, the reasons for restoration, the methods that groups are using, as well as the costs of restoration. Inconsistent data records were a persistent problem in collating the information for this project and prevented a more robust analysis of the data. In **Chapter 3**, I worked to remedy this problem by bringing together experts in all areas of marine restoration to create a framework for how to record the outcomes of marine ecosystem restoration. I then focused on how we can expand kelp forest restoration beyond a single kelp species of interest and work to conduct more holistic restoration which creates synergies between kelps, other seaweeds, animals, and even humans (**Chapter 4**). If restoration is not deemed worthwhile, it may never be attempted. Therefore, in **Chapter 5**, I sought to evaluate the value of the services provided by kelp forests and went a step further to assign an economic value to that estimate.

I hope that my research contributes to facilitating a more global conversation about kelp forest restoration, improves the efficacy of restoration projects, highlights the feasibility and value of kelp forest restoration, and informs the novel management scenarios facing marine conservationists today.

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Chapter 2 - Global kelp forest restoration: past lessons, present status, and future directions

Link to thesis

In **Chapter 1**, I outlined the growing demand for, and practice of, marine and specifically kelp forest restoration across the world. Despite its potential, there had been very little work that consolidated the history of kelp forest restoration, why it happened, how it was done, what the outcomes were, and what lessons could be learned. In **Chapter 2** I sought to bring this information together for the first time and ensure that this included information from non-English speaking countries. This chapter thus provides an extensive overview of the field of restoration, an assessment of what has worked well to date, and how the field can grow in the future. It also forms the basis for the kelp forest restoration database which is now hosted at the Kelp Forest Alliance website (kelpforestalliance.com).

I have published this work: **Eger AM**, Marzinelli EM, Christie H, Fagerli CW, Fujita D, Gonzalez AP, Hong SW, Kim JH, Lee LC, McHugh TA (2022) Global kelp forest restoration: past lessons, present status, and future directions. Biol Rev. 97/1449–1475

I have presented this work at several conferences:

1. **Eger, A. M.**, et al. 2021 Worldwide Synthesis of Kelp Forest Reforestation. Australian Marine Science Association Conference, Sydney, Australia, June 27 – July 2, 2021.
2. **Eger, A.M.,** et al. 2020 Global Kelp Forest Restoration: Past Lessons, Current Status, and Future Goals Western Society of Naturalists 101st Meeting, Monterey Bay, USA, November 5th-8th, 2020.

3. **Eger, A.M.,** et al., 2020, Worldwide Synthesis of Kelp Forest Restoration. 6th International Congress on Marine Conservation, Kiel, Germany, August 16th- 27th, 2020.
4. **Eger, A. M.,** Marzinelli, E., Steinberg, P., Vergés, A. Worldwide Synthesis of Kelp Forest Restoration. International Congress on Conservation Biology, Kuala Lumpur, Malaysia, July 23-27th, 2019.

Abstract

Kelp forest ecosystems and their associated ecosystem services are declining around the world. In response, marine managers are working to restore and counteract these declines. Kelp restoration first started in the 1700s in Japan and since then has spread across the globe. Restoration efforts, however, have been largely disconnected, with varying methodologies trialled by different actors in different countries. Moreover, a small subset of these efforts are "afforestation", which focuses on creating new kelp habitat, as opposed to restoring kelp where it previously existed. To distil lessons learned over the last 300 years of kelp restoration, we review the history of kelp restoration (including afforestation) around the world and synthesize the results of 259 documented restoration attempts spanning 1957 to 2020, across 16 countries, five languages, and multiple user groups. Our results show that kelp restoration projects have increased in frequency, have employed 10 different methodologies, and targeted 17 different kelp genera. Of these projects, the majority have been led by academics (62%), have been conducted at sizes of less than 1 hectare (80%) and over time spans of less than 2 years. We show that projects are most successful when they are located near existing kelp forests. Further, disturbance events such as sea-urchin grazing are identified as regular causes of project failure. Costs for restoration are historically high, averaging hundreds of thousands of dollars per hectare, therefore we explore avenues to

reduce these costs and suggest financial and legal pathways for scaling-up future restoration efforts. One key suggestion is the creation of a living database which serves as a platform for recording restoration projects, showcasing and/or re-analyzing existing data, and providing updated information. Our work establishes the groundwork to provide adaptive and relevant recommendations on best practices for kelp restoration projects today and into the future.

2.1 Introduction

2.1.1 The need to restore kelp forests

Kelp forests, defined here as habitat forming brown algae in the Orders Laminariales, Fucales, and Desmarestiales (Wernberg & Filbee-Dexter, 2019) are globally distributed habitats which have declined around the world (Thibaut et al. 2005, Fujita 2011, Johnson et al. 2011, Vasquez et al. 2014, Blamey & Bolton 2018, Rogers-Bennett & Catton 2019). The causes of these declines range from local stressors such as pollution to global impacts, such as climate change (Wernberg et al. 2019). Early and persistent declines of kelp forests in the 1800s were linked to population expansion of sea urchins, most often facilitated by the removal of urchin predators from the ecosystem (Roberts 2007). Subsequent kelp population declines in the 20th century were driven by threats such as direct harvest of kelp or high levels of water pollution from urban areas (Wilson & North 1983, Vogt & Schramm 1991, Coleman et al. 2008, Connell et al. 2008).

These stressors are still relevant to contemporary kelp ecosystem management but now interact with climate change, a phenomenon that has multiple consequences for kelp forests (Smale 2020). Increasing water temperatures and marine heatwaves have resulted in large contractions of kelp populations as they are pushed past their physiological preferences and limits (Tegner & Dayton 1991, Kang 2010, Wernberg et al. 2016a, Rogers-Bennett & Catton 2019, Arafeh-Dalmau et al. 2019). Warmer sea water temperatures have also facilitated the range expansion of herbivorous sea urchins which can overgraze entire forests and create urchin barrens, a phenomenon identified in most countries that contain kelp (Fujita 2010, Filbee-Dexter & Scheibling 2014, Ling et al. 2014). More recently, temperature-driven shifts in the ranges of herbivorous fishes are also causing similar declines in kelp forests near the warm edge of their distribution (Vergés et al. 2014, Zarco-Perello et al. 2017). Such extensive losses have dramatic ecological and economic impacts. For instance, kelp losses have caused the closure of lobster, abalone, sea urchin, and kelp fisheries in several regions around the globe (Steneck et al. 2013, Bajjouk et al. 2015, Rogers-Bennett & Catton 2019).

2.1.2 History of kelp forest management

Managing kelp forests and their declines has a lengthy global history. Traditionally, kelp forest management has been a passive activity whereby managers focused on improving environmental or physical conditions, for instance, by improving water quality (Foster & Schiel 2010), limiting kelp harvest (Fujita 2011, Frangoudes & Garineaud 2015), or protecting species that facilitate kelp forests (Caselle et al. 2015). These methods can be successful, and low level exploitation in Chile, Norway, Ireland, and France have ensured that sustainable kelp harvesting continues to exist in those countries (Werner & Kraan 2004, Lorentsen et al. 2010, Buschmann et al. 2014, Frangoudes & Garineaud 2015). Marine protected areas (MPAs) have also worked to increase populations of species that facilitate kelp forests and reduce human pressures (Caselle et al. 2015). For example New Zealand created the Cape Rodney to Okakari Point Marine Reserve (i.e., “Leigh Reserve”) in 1976 and this MPA now maintains healthy kelp forests (*Ecklonia radiata,* J. Agardh 1848, and Fucales species) relative to areas outside the reserve, which are dominated by urchin barrens (Shears & Babcock 2003).

Despite successes with other conservation objectives such as restoring predator populations, (Lester et al. 2009), many passive measures (i.e., those that don’t manipulate kelp or their consumers) have failed to re-establish lost kelp populations (Wernberg et al. 2019). For instance, improvements in water quality in Sydney, Australia (Scanes & Philip 1995) did not lead to the re-establishment of the locally extinct fucoid, Crayweed (*Phyllospora comosa,* C. Agardh, 1839*)* (Coleman et al. 2008, Vergés et al. 2020a). Transplant experiments demonstrated that while the environment was now suitable for *P. comosa*, propagule supply and/or post-settlement survival was likely insufficient for the species to naturally re-establish populations (Campbell et al. 2014). While other passive approaches like MPAs can succeed in restoring predator species and kelp forests (Eger & Baum 2020), they can also fail to facilitate the re-establishment of a kelp forest (Leung et al. 2014). As a result, managers are increasingly considering active restoration approaches in combination with removing or mitigating the causes of decline (Layton et al. 2020b, Morris et al. 2020).

Restoration is defined by the Society for Ecological Restoration (SER) as “the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed” (SER 2004). Active restoration is attempted by introducing or removing biotic or abiotic materials from the environment. If kelp reproduction is limited, reproductive individuals are introduced, either by adding spores or gametophytes and/or by transplanting mature plants that act themselves as the spore source (Layton et al. 2021). If herbivory is an issue, it can be mitigated by culling, transporting, or harvesting grazers such as urchins or herbivorous fish (Fujita 2010, Watanuki et al. 2010, Tracey et al. 2015, Strand et al. 2020, Lee et al. 2021). Thus, restoration as defined by SER requires that the activity improves or brings back previously-existing species or habitats, regardless of the restoration methods used.

Restoration as defined above is distinguished from "afforestation" (e.g., habitat offsetting) which is the process of creating new kelp habitat in areas that did not previously have kelp forests and is therefore not considered "true" restoration. Artificial reefs deployment is the most common form of afforestation, which creates kelp habitat by adding new rocky reef substrate that can enhance the settlement and growth of existent kelp propagules or can act as a base for transplanting or seeding (Schroeter et al. 2018, Shelamoff et al. 2020).

2.1.3 Motivations for restoring kelp forests in the 21st Century

Restoring kelp forests provides society with many benefits. Healthy kelp forests directly support United Nations Sustainable Development Goals 2 (zero hunger), 8 (work and economic growth), 13 (climate action), and 14 (life under water; Cormier & Elliott, 2017). By conserving and restoring kelp ecosystems, we maintain a foundational marine habitat and ensure access to key ecosystem services such as habitat provisioning (Teagle et al. 2017), nutrient cycling (Kim et al. 2015) and carbon sequestration (Chung et al. 2013, Filbee-Dexter & Wernberg 2020). Kelp forests also underpin harvest services, for example, supporting direct kelp harvest (Buschmann et al. 2014) or fisheries through the species that they support (Smale et al. 2013). The services provided by these underwater forests are currently estimated at millions of dollars per km of coastline and billions of dollars per country (Smale et al. 2013, Vasquez et al. 2014, Bennett et al. 2016, Blamey & Bolton 2018, Eger et al. 2021), and provide livelihoods for coastal communities around the world. In addition to their economic values, kelp forests also hold significant cultural and aesthetic value to their local community (Thurstan et al. 2018, Turnbull et al. 2020).

International interest and recognition of marine ecosystem restoration is increasing, yet kelp forests are often excluded from these agendas despite their potential contributions to international goals and targets (Feehan et al. 2021). The largest initiatives are led by the

United Nations (UN), which has declared 2021-2030 as the “Decade of Ecosystem Restoration” as well as the “Decade of Ocean Science for Sustainable Development”. These independent but complementary initiatives are calling for a global focus on renewing marine and other ecosystems (Waltham et al. 2020), while also providing needed ecosystems services, helping combat climate change and safeguarding biodiversity and food security (Claudet et al. 2020). Kelp forest restoration has the potential to meet the objectives of both UN initiatives. If carbon credits are verified and established, kelp forest restoration also provides a means for countries to work toward their “Nationally Determined Contribution” (NDC) to mitigate carbon emissions under the Paris Agreement, in addition to European Union agreements to restore set amounts of habitat. These contributions could then also be commodified as carbon credits, while other services such as nutrient cycling could also be commodified and provide further incentives to restore kelp forests (Seddon et al. 2019, Vanderklift et al. 2019, Platjouw 2019).

While there are clear benefits from restoring kelp forests and global interest is accelerating, the path forward is uncertain. This uncertainty is in part because despite similarities in the causes of decline and restoration methodologies, very little information has been shared between projects within and among countries. The most recent analyses provide useful qualitative assessments of past restoration projects, but focus on work published in English-speaking countries and in the peer-reviewed literature (Layton et al. 2020b, Morris et al. 2020). Most restoration projects, however, are not formally published in peer-reviewed journals and occur in non-English speaking countries (Bayraktarov et al. 2020, Eger et al. 2020c). As a result, projects have typically learned and applied methodologies independently. Addressing this limitation will help ensure that lessons learned from 60-300 years of history in kelp restoration contribute to a more rapid rate of restoration successes.

2.1.4 Study objectives

This review aims to provide a comprehensive history of kelp forest restoration, assess the current state of the field, and provide recommendations for how the field can advance. We achieve this by reviewing the global history of kelp restoration, analysing past projects, examining the determinants of success, and describing solutions to barriers to future restoration projects. This comprehensive, multi-language project first reviews the history of kelp restoration in independent geographic clusters around the world. Following this qualitative overview, we present the results of a new kelp restoration project database (kelpforestalliance.com) and describe the global state of the field, what factors have resulted in success, and which in failure. Finally, we discuss the methodologies, costs, motivations, and legal frameworks currently related to kelp restoration and how we can enhance the factors that can lead to success in restoration and mitigate potential barriers in future.

2.2 Materials and methods

2.2.1 Literature searches

To find published literature on kelp restoration, we conducted a search using the Web of Science on December 7th, 2018 using the following terms: "restor* OR rehabilitat* OR green engineering OR ecoengineering OR ecological engineering OR return* OR recov* OR afforest*" AND kelp* OR seaweed* OR macroalga* OR Laminariales OR Fucales OR Desmarestiales". The search returned 1431 results (Appendix 1.1). We reviewed the titles and abstracts of the returned results and selected 156 publications that appeared to reference a kelp restoration project for additional screening. These 156 publications were reviewed to determine if they met our study's inclusion criteria. These criteria were to ensure studies 1) focusing on canopy forming algae from either the Laminariales, Fucales, or Desmarestiales order, and 2) working to enhance kelp ecosystems, in-situ, for non-commercial purposes (e.g., not aquaculture or mariculture). Relevant methods included transplanting, seeding, grazer control, installing artificial reefs, and others. Of these initial 156 publications, 51 were determined to meet the criteria for data extraction. After the first literature search, a publication alert with the same terms was set up to collect new records up until March 29th, 2021.

We collected data on both restoration and afforestation projects and tested (see section 2.3, Factor analysis) for differences in project success but found none between these two approaches (see Results). Thus, we combined restoration and afforestation approaches in subsequent analyses. Individual projects are specifically referred to as restoration or afforestation, while collective projects (e.g., across a country or across years) are referred to under the umbrella term restoration.

To find kelp restoration projects that may not be in the scientific literature, we conducted similar searches by country or geographic region in English, Spanish, or French search terms as relevant, using the Google Search engine with simplified terms to query only "kelp restor*" and a location (e.g., Norway or California). We included all countries where kelp is known to occur (Wernberg et al. 2019) and ran searches between 11/10/2019 and 12/12/2019 (Appendix 1.1). We reviewed between 30 and 100 search results per regional search and compiled a list of groups potentially conducting kelp restoration. We then contacted each group individually to inquire if they could contribute information on their restoration efforts. We supplied each group with a data template for them to complete (Appendix 1.2).

To find Japanese kelp restoration literature, we conducted an internet search using JStage on November 27th, 2019, and returned 616 results, 150 of which were identified for further screening. The search term was 磯焼け – the Japanese word "isoyake" – a commonly used term for kelp forest degradation in Japan. A fluent Japanese speaker (MT) then reviewed the documents to assess their eligibility. If a paper met the criteria described above, the relevant information was extracted and translated into English. We also translated the database used to inform the 2nd Isoyake Guidelines (Fujita 2019) and obtained descriptive information about restoration projects. This database was compiled with studies from the Tokyo University of Marine Science and Technology Library and covered the years 1970-2014. Ultimately, the Isoyake Guidelines database contained no information about the outcomes of the restoration projects and our published Japanese literature search found few studies with quantitative or semi-quantitative data. We therefore considered the Japanese studies from a qualitative perspective only and did not use them in the quantitative analyses.

To find Korean kelp restoration literature, we conducted the Korean literature search using Google Scholar and RISS on November 27th, 2019, and returned 600 results for Google Scholar and 60 for RISS. The search terms were회복, 복원, 해조류–, the Korean words for “recovery,” “restoration”, and “marine algae”. A fluent Korean speaker (HSW) then reviewed the papers to assess their eligibility. If the paper met the previously described selection criteria, the relevant information was extracted and translated into English.

2.2.2 Data collection

We extracted data from each paper using the *metaDigitise* package (Pick et al. 2018) in the R programming language (R Core Team 2019). If the required data was not included in the paper, we contacted the corresponding author to provide any missing information. See the data template (Appendix 1.2) for the full suite of parameters that were collected.

We used snowball sampling (Biernacki & Waldorf 1981) in all languages to accumulate contacts for other reports, persons, or groups conducting kelp restoration across the world.

We compiled two language specific project lists using this method in Norway and Chile. A personal contact list is maintained but will not be published for privacy reasons.

Data identifier: We assigned each study a reference number, event number, and an observation number. The reference number was unique to each report or reported project. The event number was unique to a restoration event or action. For example, entries for two artificial reefs contained in the same report but set in different locations would have the same reference number and different event numbers. The same observation number indicated different measurements of the same event, for example, if two species were transplanted together but recorded individually. We used different unique identifiers related to the reference level, event level, and project level when creating the different graphs (Appendix 1.3).

Cost data: We collected cost information either directly from the publication or report, or through personal communications with the authors. As best as possible, we divided costs into capital, operating, construction, in-kind, and monitoring categories, and recorded the year currency of the value. To allow for accurate cost comparisons between currencies and years, we converted all dollars into USD for the year 2010. First, using the Penn Table (Feenstra et al. 2015), we converted the local currency to USD based on the exchange rates during the year of reporting. Afterwards, we indexed costs for inflation to year 2020 using the Consumer Price Index (The World Bank 2019). These values only consider the costs of the restoration actions, not of planning or monitoring.

Area extent: While most studies that reported area typically gave only the starting size, when possible, we recorded size (area) as the largest measurement recorded for the project, including expansion after restoration. Therefore, if a study transplanted kelps over 10 m^2 and after monitoring for 2 years discovered the patch had grown to 100 m^2, we recorded 100 m^2

as the area extent. Conversely, if a patch shrank from 10 m^2 to 1 m^2, we recorded 10 m^2 in our database. Methods used to measure area extent differed depending on the study, and included aerial surveys, vessel-based monitoring, and underwater video footage.

Duration: We recorded duration as the day from the first restoration action to the day of the last observation or action recorded. We always used the last available time point to record our data.

Year: We recorded the year in which the first restoration action was initiated, rather than the year of the publication.

Location: We either extracted the geographic coordinates from the reports themselves or obtained approximate coordinates from Google Earth Pro ®.

Group Involved: We classified the groups involved in the restoration process as being

1. Academic (university or research institute)
2. Government (municipal, indigenous, state, or federal management body)
3. Non-government organization (NGO; registered non-profit)
4. Industry (environmental consultants, aquaculture, energy development)
5. Community (organized local group, not registered as non-profit)

Motivation: While reading each report, we searched the text to determine the motivation for each restoration project and classified the primary, secondary, or tertiary motivation into one of the following seven categories (Bayraktarov et al. 2019):

1. Improve restoration approach, technology, methods
2. Restoration after environmental impact (e.g., ship-grounding, mining, oil spill, hurricane)

3. Biodiversity enhancement (e.g., native vegetation, habitat creation, ecosystem connectivity, ecological resilience)
4. Answer ecological research questions
5. Enhance ecosystem services (e.g., fisheries production)
6. Biodiversity offset (e.g., threatened species, threatened ecological community)
7. Social reasons (e.g., community involvement, job creation, nature education, environmental outreach)

Variables measured: We recorded the project outcomes in several formats (Appendix 1.2) and several different assessment structures depending on individual project design. Projects were either assessed as the same site over time, a restored site in comparison to a reference site(s), or a restored site in comparison to a degraded site(s). The end variables quantified were area, density, count, growth, survival (1/0), percent survival, percent cover, or growth measures. If a project reported on a site over time, we recorded the first measure at the beginning of the project and the last measure as the last available data point.

Success Score: The information related to the outcome of the restoration attempt was reported in several different formats using a variety of values (Appendix 1.2). This mix of reporting standards and units made it difficult to uniformly analyse the success scores all together. We overcame this issue by using the simplest available metric, a binary survival score. The binary success score was set as 1 if any kelp remained at the time of the last report and a 0 if none remained. There were insufficient sample sizes for the other reporting styles (e.g., those with before-after-control-impact designs) to conduct additional analyses using these metrics as well.

2.2.3 Factor analysis

To evaluate the effect of each covariate (fixed effect) on binary success scores, we used generalized linear mixed effects models with a binomial distribution. Because very few projects had data for all the covariates, we evaluated each factor individually and were therefore not able to evaluate the relative importance of each covariate. We analysed the effects of the following covariates: publication type to test for publication bias; latitude to assess the role of biogeography; genera to determine if some species were easier to restore than others; the method used to test the efficacy of each method; the area of the project to see if larger projects were more successful; whether the restored site was in a protected area to assess potential benefits from that protection; the impacts of disturbances on restoration projects if a disturbance was reported; whether site selection criteria were in place to see if that selection contributed to success; how close the project was to a kelp bed of the same species to help determine if natural adjacent populations assisted to restore populations; whether the project specifically mitigated a stressor, the project duration to see if longer projects were more successful; and whether a project was restoration or afforestation.

To account for multiple data points contained in some reports (Appendix 1.3), we used mixed effects models with the study/project reference number as the random effect to account for the correlation between data points in the same study. The generalized mixed effects models were fitted in R using the *lme4* package (Bates et al. 2015) and we used the *lmerTest* package, which applies Satterthwaite's degrees of freedom estimations and the *F*-statistic to assess significance (Kuznetsova et al. 2017). We then used these models to predict the probability of success using the *predict* function in R, while the error was calculated using the *predictInterval* function in the *merTools* package in R. This function creates a sampling distribution for the fixed and random effects and then draws the range of values from that distribution.

All analyses and graphing were conducted using the R programming language (R Core Team 2013).

2.3 Regional histories of restoration

2.3.1 Overview of kelp forest restoration

Our review of the history of kelp forest restoration revealed a global field dating back decades to centuries. While many different species have been targeted for restoration, relatively similar approaches to restoration have been developed in each region. Despite their methodological similarities, the social contexts in which restoration has occurred have been very different. To better understand these contexts, we first qualitatively reviewed the regional histories of restoration individually and later evaluate the new global restoration database (Figs. 1 and 2). A few Korean and Japanese projects discussed in the regional review were not captured in the global database because they were not returned in the searches for those regions.

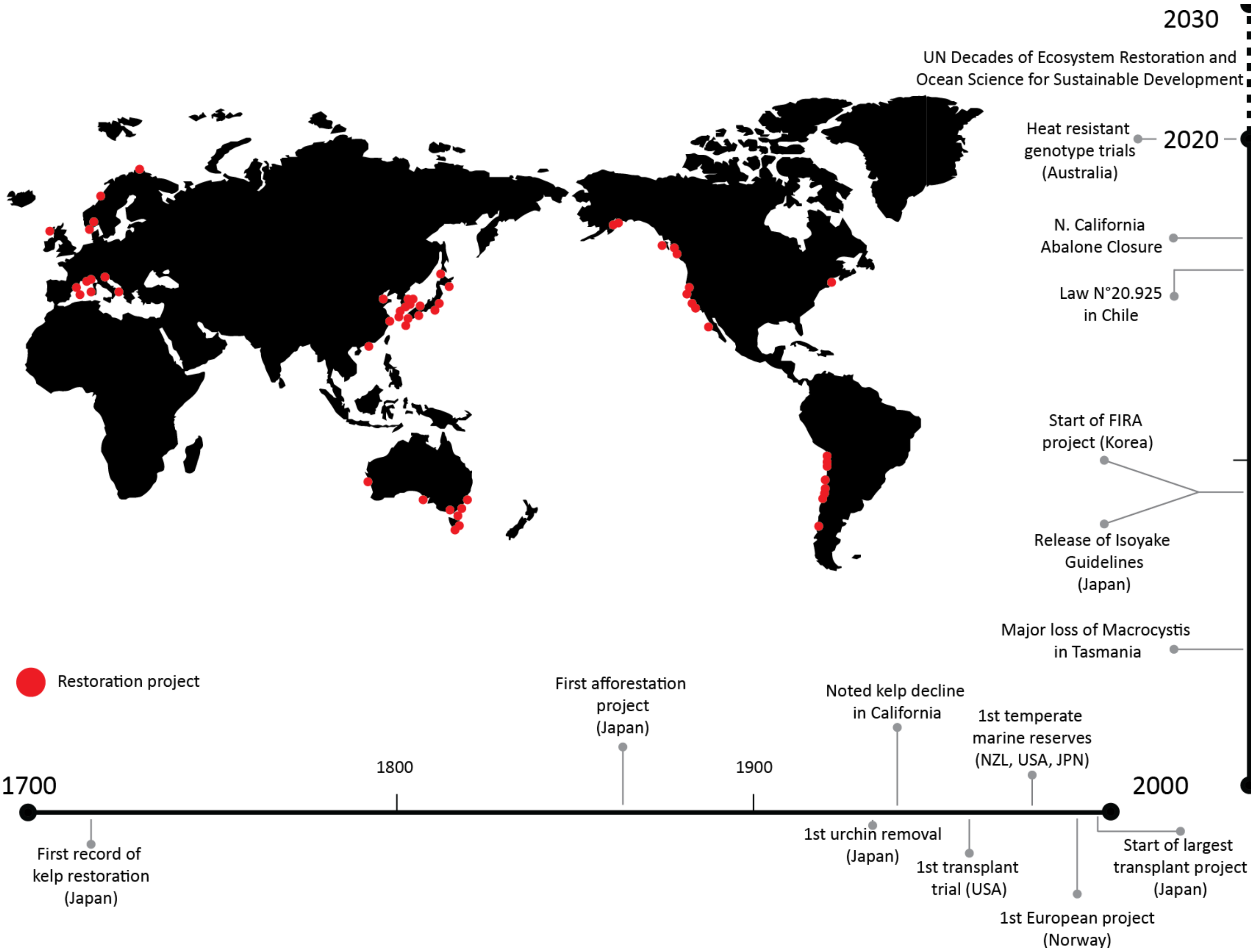

Figure 1 Location and timeline of important global kelp restoration-related events.

2.3.2 Japan

Japan has the world's longest and richest history of kelp forest management over hundreds of years, including over 700 recorded restoration projects since the 1970s. *Saccharina* species (Kombu in Japanese) are popular food items and are the most commercially important kelp. This genus is found in the cold temperate waters of Japan (Hokkaido to NE Honshu; Fujita, 2011). Starting in the 14^{th} century, Kombu was harvested by Hokkaidoan fishers and exported by ship to central and southern Japan, then later exported to China. The domestic market persists today, and Japan produced 79,000 metric tons in 2019 (FishstatJ 2020). While economically productive, this harvest has previously led to kelp population declines (Fujita 2011).

The early efforts in Japan fell were both restoration and afforestation. The first recorded restoration project was in 1718 when a monk, Saint Teiden, instructed fishers to throw stones into coralline barrens to encourage kelp regrowth in NW Honshu (Ueda et al. 1963). A local fisher then led a larger afforestation project and installed 317,000 stone blocks onto a sandy seabed off SE Hokkaido between 1863-68, increasing his yearly kelp yield from 7 tons to 20 tons (Ueda et al. 1963). Thereafter, afforestation via reef construction (tsuki-iso) became increasingly common in Northern Japan and an additional 300 ha of reefs were installed from 1921-50 (Kuroda et al. 1957). While these efforts were extensive, they were not always successful, and sedimentation commonly led to restoration failure (Kinoshita 1947). The second common method to enhance kelp populations during this time was the clearing of competitors such as turf algae from the benthos, either by hand or mechanical scrapers (170 ha from 1921-1950; Kuroda *et al.*, 1957).

Fishers in NW Hokkaido also noticed that sea urchins would graze on their kelp stocks and began to remove urchins to protect the kelp. A local cooperative first realized these "pests" could be of potential value and started to purchase the removed urchins, process them, and ship them to Honshu (main island of Japan) in 1932 (Kinoshita 1947). The demand for Kombu as a food and as a feedstock continued to increase and more structured fisheries management systems formed in the 1950s and 60s (Fujita 2011). National and prefectural governments continued to focus on deploying artificial reefs, now using manufactured concrete blocks (Tokuda *et al*., 1994). Concurrently, the urchin culling efforts also expanded to NE Honshu and SW Hokkaido, as did clearing the benthos of competitors (Fujita et al. 2008a). Sea urchin removal and artificial reef placements have had few changes to their approaches. Scraping the benthos, however, has advanced to include chains moved by wave action, boat operated rotators, and even remotely-controlled underwater excavators (Japanese Fisheries Agency 2021).

Restoration attempts for *Ecklonia* and *Eisenia* species in Japan's warmer central and southern waters started in the 1980s (Notoya et al. 2003). These genera are locally eaten by people and are important habitat for abalone and lobster populations that support major coastal fisheries in Japan. In contrast to Northern Japan, these restoration efforts have focused on transplantation and grazer control of not only urchins, but also herbivorous fishes (*Siganus fuscescens, Calotomus japonicus, Kyphosus* spp., (Fujita et al. 2008b, Fujita 2010). Managers in NE Kyushu (Southernmost main island) repeatedly found that consistent removal of these grazers was the key to kelp restoration success, as short-term control using cages or gillnets would result in a period of kelp regrowth, but eventually failed when managers removed the cages and the herbivores ate the transplants (Fujita 2011).

These lessons were all applied in what is now the largest successful kelp restoration project in Japan. Starting in 1999, the Shizuoka Prefectural Government placed small concrete blocks in healthy kelp forests, allowed spores to settle on them, and then transported them to barrens to restore *Ecklonia* forests in a deforested area (Izu Peninsula, Central-East Japan; Eger *et al.*, 2020c). Local fisheries cooperatives, municipal, and prefectural government groups joined these actions for a second phase that ran from 2002-2010. As of 2018, ~870 ha of *Ecklonia* has been restored, leading to such a marked recovery of abalone populations that managers are considering the re-opening of a closed abalone fishery (Eger et al. 2020c).

Given the numerous projects conducted in Japan, there have been many opportunities to learn from their outcomes. Indeed, these efforts were reviewed in 2009, 2015, and 2021 by the federal Fisheries Agency to provide detailed guidelines for future projects. The "Isoyake

Taisaku Guidelines" (Japanese Fisheries Agency 2009, 2015, 2021) were launched alongside a funding initiative to promote reforestation of algae forests. This initiative, known as the Fisheries Multiple-function Demonstration Project (FMDP), operated from 2009-to present and funds fishing cooperatives and NGOs to control herbivores, transplant kelp, maintain herbivore exclusions, clear the benthos, remove sediments, and improve upstream water quality (Sekine 2015). The national government provides half the requested funds, the prefectural government provides a quarter, and applicants fund the last quarter (Sekine 2015). In addition to funding, the project provides access to experts to guide the restoration process. Approximately 300 thousand yen (~$2,540 USD 2010) per hectare is invested in this process. Despite 288 groups accessing the funds and support, < 100 ha of algae has been restored since its inception (Sekine, pers., comm). The limited success of this initiative has been attributed to increased herbivory, increased water temperatures, reduced nutrients, increased frequency and strength of typhoons and flooding, increasingly armoured and industrialized coastlines, and the end of project funding (Fujita 2019).

2.3.3 Korea

The Korean peninsula is bounded by three seas and has a long history as a maritime nation that harvests fish, invertebrates, and seaweeds. The decline of over 10,000 ha of seaweed forests during the 20th century (Sondak & Chung 2015) has put this relationship at risk. Following the Korean War (1953), the South Korean government has worked to increase the availability and access to the marine resources within their own Exclusive Economic Zone (EEZ). Their management strategies focus on modifying the ocean with artificial materials while also working to enhance the biomass of harvestable species (Sánchez-Velasco et al. 2020). Construction of these artificial reefs started in 1971 and was targeted at enhancing coastal fisheries in depths of 20-40 meters. Under this initiative, the installation of eight different types of reefs continued until 1990 with a sum cost of $61 million USD (FIRA 2020).

These reefs gave rise to the concept of marine ranching, which cultures species in the ocean for consumption. A pilot ranching project took place from 1982-1989 and resulted in the Near-shore fisheries Marine Ranching Master plan in 1994 (Park et al. 1995). The National Institute of Fisheries Science (NIFS) ran this program from 1998-2010 and worked to enhance fisheries and create or restore kelp forests in multiple areas along the Korean coastline. NIFS worked with kelp genera that were amenable to cultivation, focusing on Dasima (*Saccharina japonica*, C.E. Lane, C. Mayes, Druehl & G.W. Saunders 2006*)*, *Ecklonia* spp., Miyeok (*Undaria pinnatifida*, Suringar 1873*)*, and *Sargassum* spp. Once the kelps were successfully cultivated, they were typically transplanted on the artificial reefs using ropes containing juveniles or seeded using spore bags (Park et al. 2019).

Following the initial NIFS projects, the Korea Fisheries Resource Agency (FIRA) was established in 2009 and took over marine ranching, kelp restoration, and afforestation projects in Korea. This date marked the start of the world's largest kelp forest afforestation and restoration program. The project is running until 2030 with a yearly budget of $29 USD 2019 million (FIRA 2020) and aims to create or restore 50,000 hectares of kelp forests, already installing >20, 000 hectares at 173 sites as of 2019 (Lee 2019).

At the beginning, FIRA followed similar protocols as previous work, using transplants or seeds on artificial reefs. However, they are now focusing on urchin control and the best ways to restore kelp on rocky reefs that once supported kelp forests (Yang et al. 2019). The projects in Korea have been largely led by the federal government with considerable input from local universities, which research different restoration techniques, provide historical baselines and targets, and advise ongoing management efforts (Hong et al. 2021). For the foreseeable future it appears that most kelp restoration work in Korea will occur under the FIRA program with input from university researchers. Though community groups do not themselves work to restore kelp forests in Korea, the government projects are generally well-supported by Koreans, who are indeed “seafood and seaweed lovers” (Han 2010). In some instances, projects were initiated in response to public pressure (Kang 2018). Within Korea, there are seaweed festivals and even a day known as “Marine Gardening Day” which celebrates the ties between people and the ocean and encourages responsible stewardship and restoration of the sea.

2.3.4 United States of America

Kelp in southern California, notably giant kelp (*Macrocystis pyrifera*, C.Agardh, herein *Macrocystis),* has been an important source of materials such as alginates, potash, and acetone since the early 1900s (Barksy et al. 2003), and has an extended management history. When kelp populations declined due to poor water quality and overharvesting (Wilson et al. 1977), the first restoration trials were motivated by a desire to restore these resources. The first recorded North American trials transplanted *Macrocystis* in Southern California in 1958 (North 1958). These efforts were soon combined with the manual or chemically-induced mortality of grazing fishes and urchins (Wilson & North 1983).

Academics, fishery managers, and industry groups soon led repeated initiatives to restore *Macrocystis* with transplants, seeding, and urchin culling during the 1960s and 70s (Wilson et al. 1977, Wilson & North 1983). Most commonly, projects succeeded in restoring 10s-100s of hectares of kelp while others failed due to heatwaves, urchin incursions, or storms (Wilson et al. 1977, Wilson & North 1983); following these efforts, the number of projects remained low until after the year 2000. During this decade, several community groups, notably those under the banner of the California Coast Keepers organization, became interested in restoring their local marine environment. Noticing correlations between increased urchins and decreased kelp forests, these groups led initiatives to remove urchins and transplant kelp individuals (House et al. 2018, Williams et al. 2021).

Afforestation through the installation of artificial reefs has been of notable interest in California. Early attempts used available materials (e.g., disused street cars) to establish kelp forests (Carlisle et al. 1964), but later developed into more robust strategies using rocky materials. In an attempt to increase the stock of sport fish during the mid-1980s and early 90s, the California Department of Fish and Wildlife (CDFW, (Carter et al. 1985) created a series of artificial reefs throughout California. Later in the 1990s, the California government mandated installation of what is now a 172 hectare artificial reef to offset a *Macrocystis* forest that was destroyed by warm water outflow from a nuclear power plant (Reed et al. 2006). Similarly, municipal governments in Seattle, Washington, and Vancouver, British Columbia, have led efforts to build new reefs to offset industrial projects which destroyed kelp forest habitat (Cheney et al. 1994, Fehr et al. 2011).

In northern California, recent restoration efforts for bull kelp, *Nereocystis luetkeana*, have ensued due to their rapid and extensive losses (McHugh et al. 2018, Hohman et al. 2019). In just under a decade, Multiple stressors, such as the loss of apex predators, high urchin grazer recruitment, and prolonged warm water events have resulted in a net loss of >95% of *N. luekeana* forests, and subsequent lack of recovery, along 350 km of coastline in just under a decade (Rogers-Bennett & Catton 2019, McPherson et al. 2021). Thus, kelp forest collapse ensued which negatively impacted ecosystem, economic, and social health of northern California coastal communities.

As a consequence, interest is growing in California ocean users to safeguard the iconic and vitally important ecosystem via monitoring, and if appropriate, through restorative actions.

Further, California policy makers plan to develop a comprehensive ecosystem-based management and restoration strategies moving forward to protect coastal and marine biodiversity and ensure the continued delivery of ecosystem services (Ocean Protection Council 2021). The involvement of the State has provided fiscal, regulatory, and institutional support for research and pilot kelp restoration projects being led by key community members, NGOs (e.g., Reef Check California, Greater Farallones Association, and The Nature Conservancy) and academics (Ocean Protection Council 2021). Some of the projects currently being explored in northern California include: developing regulatory pathways and methods to reduce urchin grazing pressure through recreational and commercial diver efforts; using occupied and unoccupied aircraft imagery to understand *N. luetkeana* canopy coverage over time; evaluating a variety of *N. luetkeana* culturing and out-planting procedures, leveraging conservation genomics and gametophyte banking to preserve the genetic diversity of *N. luetkeana*; investigating the dynamics of urchin recruitment and reproduction; kelp farming; developing *N. luetkeana* spore dispersal model; exploring the feasibility of predator (sunflower sea star *Pycnopodia helianthoides)* restoration; and outreach and education (Ocean Protection Council 2021). An increase in frequency and duration of conditions that are stressful to kelp will likely result in localized and regional future kelp forest degradation, reinforcing the necessity of developing climate-resilient solutions to ensure ecosystem health (Hohman et al. 2019, Gleason et al. 2021).

Elsewhere, kelp restoration efforts in Washington and Oregon are now emerging through groups such as The Northwest Straits Commission (nwstraits.org/our-work/kelp-recovery), the Oregon Kelp Alliance (oregonkelp.com), and the Elakha Alliance (elakhaalliance.org/). These groups are trialling and exploring transplantation, urchin culling, and sea otter reintroduction as restoration strategies.

2.3.5 Canada

Kelp restoration projects have taken place on a limited scale in recent decades in British Columbia (BC), although the anticipated negative impacts of climate change (Krumhansl et al. 2017) and urchin barrens have increased interest in the subject. In response to extensive urchin barrens limiting kelp distribution, the A-Tlegay Fisheries Society, Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site (hereafter Gwaii Haanas; cooperatively managed by the Haida Nation and Government of Canada), and the Pacific Urchin Harvesters Association are trialling increased quotas and/or opening closed areas for commercial fishing of red sea urchins (*Mesocentrotus franciscanus*; Department of Fisheries and Oceans Canada, 2020). Elsewhere, interest is growing in restoring or farming kelp as a climate solution on Vancouver Island (Ocean Wise Seaforestation Initiative – ocean.org). Prior small-scale *Nereocystis* restoration projects have taken place in southern BC (similar for northern Washington State), focused on seeding to start new populations in response to general declines (Heath et al. 2017).

In Gwaii Haanas in northern BC, cooperative management partners – Council of the Haida Nation, Parks Canada, and Fisheries and Oceans Canada – initiated a larger-scale kelp forest restoration project over 20-hectares of shallow subtidal rocky reef (Lee et al. 2021). This work was motivated to restore ecosystem balance by mimicking sea otter predation (historically extirpated, see Bodkin, 2015) on urchins where sea otters have not yet returned. Restoration work was initiated in 2018-19 with pre- and post-restoration monitoring and research funding over five years. This project involves close collaborations among Gwaii Haanas management partners as well as the commercial urchin fishing industry and multiple academic institutions. Due to this diverse partnership and engagement with Haida Gwaii communities, cultural and social considerations are as important to the project as ecological gains (Lee et al. 2021). Provision of urchin roe for food in the communities, working with Haida divers in monitoring and research, as well as employing Haida and commercial divers to remove, crush and maintain low urchin densities at the sites, are all key components of the project.

2.3.6 Australia

The focus on kelp restoration in Australia is recent, and efforts have focused on urchin culling and/or removal in *Ecklonia radiata* forests, on restoring giant kelp (*Macrocystis*) populations in Tasmania, or on restoring the locally-extinct fucoid, crayweed (*Phyllospora comosa*). Urchin removals have most often been done by abalone and urchin fishery organizations that are working to restore kelp habitat and create more biomass of abalone and/or urchin in the states of New South Wales, Victoria, South Australia, and Tasmania (Worthington & Blount 2003, Gorfine et al. 2012). The Tasmanian government subsidises the local urchin fishery to remove invasive urchins, which have expanded their range south from continental Australia (Ling et al. 2009), including for urchins that might not otherwise be profitable to harvest (Larby 2020).

There have been three main efforts to restore specific taxa via transplantation in Australia. First, SeaCare Inc. installed small patches of *Macrocystis* in Tasmania from 1997-2001. However, the efforts were not sustained and they did not achieve long-term success (Sanderson 2003). While currently in early development, researchers from the University of Tasmania are working to select thermally tolerant kelp from the remnant populations of *Macrocystis* and are trialling outplants back into the ocean (Layton & Johnson 2021). The other main project is Operation Crayweed which has been working since 2011 to restore *P. comosa* and associated biota along the coast of the Sydney metropolitan area (Campbell et al. 2014, Marzinelli et al. 2016). Operation Crayweed is notable for their work with community groups, schools, and artists to connect people to their restoration projects (Vergés et al. 2020a), as well as their work into genetic mixing of transplant populations and the identification of genotypes for future-proofing against climate change (Wood et al. 2021).

2.3.7 Europe

Kelp populations inhabit the coastlines of ~20 countries in the Europe-Mediterranean region, with records of kelp restoration focused on Norway, Spain, and Italy.

In Norway, urchin grazing has been a major driver of kelp declines since at least the 1970s (Sivertsen 1997, Norderhaug & Christie 2009). As an experimental study, scientific divers crushed urchins with hammers over 10 diver-days in Central Norway in 1988. While the reduction in urchins allowed the canopy (mainly sugar kelp, *Saccharina latissima*, Druehl & G.W.Saunders 2006) to recover rapidly (Leinaas & Christie 1996) and subsist for almost a decade, later surveys showed the urchins had returned and the kelp disappeared (Norderhaug & Christie 2009). Following these initial trials, researchers remained interested in restoration, but government bodies did not fund further projects due to perceived challenges and lack of interest. Kelp restoration work was not initiated again until 2003 when the “Sugar Kelp Project” (2003-2008) trialled different small scale methods, including scraping the benthos to remove competitors, transplanting adult and juvenile kelp on either hard substrate or ropes, and seeding (Moy et al. 2008, Moy & Christie 2012).

Though the project failed when turf algae outcompeted the kelps, this project marked the start of a renewed interest by the Norwegian Institute for Water Resources (NIVA) and similar groups to restore kelp. NIVA then trialled artificial reefs in Northern Norway in 2006 and was successful over a 5-year period, but ultimately failed as urchins overgrazed the kelps (Christie et al. 2019a). In 2011-18, both NIVA and the Institute of Marine Research (IMR) tested various restoration techniques, focused on either manually crushing and excluding urchins, outplanting or transplanting *Saccharina* and *Laminaria* (Fraschetti *et al.*, 2017; Fredriksen *et al.*, 2020) and chemically killing urchins using quicklime (Strand *et al.*, 2020). The fast-recovering species in these studies were both *Saccharina latissima*, *Alaria esculenta* and the arctic *Saccorhiza dermatodea*. The quicklime efforts are notable because they had lower co-mortality rates than the previous quicklime projects in the early 1960s in California (Wilson & North 1983) and 1980s in Eastern Canada (Weinstein 1983). Recently, researchers and entrepreneurs are collaborating to develop market-based solutions to overabundances of urchins. Starting with a small-scale pilot project in 2018-19, NIVA, a business (Urchinomics®), and a community group (www.tarevoktere.org) have been exploring either directly harvesting urchins or collecting them, transporting them on land, and growing them for the food market (Verbeek et al. 2021).

Interestingly, natural recovery of *L. hyperborea* and *S. latissima* populations in mid-Norway have been occurring without any intervention over the last couple of decades (Fagerli et al. 2013). Increases in sea surface temperature reduced the survivorship of the green urchin (*Strongylocentrotus droebachiensis*) and facilitated the expansion of the edible predatory crab (*Cancer pagarus*), which has reduced urchin populations (Christie et al. 2019b). Neither of these actions was intentional but they demonstrated that novel warmer conditions may enhance kelp recovery and/or restoration in some higher latitude reefs (Filbee-Dexter et al. 2019), while they may impede restoration and accelerate declines at lower latitudes (Wernberg et al. 2016a, Vergés et al. 2016, Qiu et al. 2019).

Restoration of kelp in the Mediterranean has largely focused on the fucoid genus *Cystoseria*. Anthropogenic pressures in the Mediterranean basin are intense with a long and sustained history of coastal development (Gibson et al. 2007). As a result, populations of *Cystoseria* have declined throughout the region (Thibaut et al. 2005). Universities and research institutes, primarily in Italy and Spain, worked on the initial restoration efforts. These projects focused on trialling small-scale culturing and outplanting (Verdura et al. 2018, De La Fuente et al. 2019, Tamburello et al. 2019), and have also considered urchin removal, which was identified as a barrier to success (Guarnieri et al. 2014). Following these initial trials, the Marine Ecosystem Restoration in Changing European Seas (MERCES) project was created with European Union funding and ran from 2016-20 (Fabbrizzi et al. 2020). This project included kelps among other marine habitats and expanded the scope of past restoration efforts; it has trialled methods to outplant *Cystoseira* in Italy, Albania, Tunisia, and Spain (Iveša et al. 2016, MERCES 2020).

2.3.8 Chile

Macrocystis and *Lessonia* are foundational species along the Chilean coastline and are important commodities and habitats for fisheries species. Wild harvest of *Macrocystis* has a long history in Chile and is now one of the few remaining wild kelp harvests in the world (Buschmann et al. 2014). The fishery annually harvests 400,000 dry tonnes and provides 10% of the world's alginate (Buschmann et al. 2014). This harvest has reduced portions of the wild kelp populations with an associated reduction in ecosystem services, currently valued at $54 USD million (Vasquez et al. 2014). To help manage the diminishing populations, the federal government established a management program (Law N°20.925) that provided funds to encourage the cultivation as well as restoration of seaweeds (Biblioteca del Congresso Nacional de Chile 2020). The primary focus of projects stemming from the program has been the long-line cultivation of *Macrocystis* with less work on restoring either genera or cultivating *Lessonia*.

Lessonia restoration projects in Chile are often supported by regional or national funding agencies. The projects are typically partnerships between academia and fishery cooperatives, and usually work with transplants. Transplantation methods include attaching juvenile plants onto existing holdfasts (Westermeier et al. 2016), or adding mature plants to artificial substrates, which are then secured onto the benthos (Correa et al. 2006). Though these projects have demonstrated that transplants can indeed survive and grow, considerable variation was shown in the density, biomass, and length of plants among projects, both by methodology and planting season.

Lessonia restoration projects have had limited success in Chile. The first restoration attempts for *L. berteroana* occurred in response to increased herbivory and enhanced ENSO cycles in 1990 (Vásquez & Tala 1995). These projects combined the outplanting of spores, juveniles, and reproductive adults, fixed to the substrate using epoxy and anchored boulders (Vásquez & Tala 1995, Correa et al. 2006, Westermeier et al. 2016). Early survival rates for these methods averaged around 50% and plants showed similar growth rates to natural populations. However, the projects were only maintained over short time scales and small spatial extents.

Building off this work, researchers are now testing whether increasing genetic diversity can increase restoration success rates. Researchers are grafting plants together, creating chimeric individuals of *L. berteroana* (Montagne 1842) and *L. spicata* (Santelices 2012), and transplanting them over larger areas than previously attempted. As a result, the transplanted individuals have the DNA of the two donor plants, ideally improving tolerance to stressors such as temperature. The work has been patented (Patent CL201701827) and conducted in collaboration with three universities, government funds, and a private company. If this method is successful, it will be an important step in Chilean kelp restoration, as local kelp forests are vulnerable to physiological stress caused by warmer sea temperatures (Vásquez et al. 2014).

2.4 Analysis of the global database

2.4.1 Project overviews

Our database collated 259 kelp restoration and afforestation efforts that provide quantitative insights into the characteristics of restoration projects and determinants of success. Recorded projects first started in 1959 and the number of projects per decade has consistently increased since then (Fig. 2; data in Appendix 1.4; Eger *et al.*, 2020b). Of these projects, most of the work has been done in Japan and the United States of America, particularly California (Fig. 1). As a result, efforts have been focused on the restoration or afforestation of the genera within these countries (*Macrocystis* and *Laminaria* spp; Fig. 2). While projects occurred in 12 other countries, many countries had with no recorded restoration or afforestation projects. Notably, the United Kingdom, Ireland, France, Russia, Iceland, and China have significant kelp populations and management histories, but we found no recorded projects. This result suggests that restoration and-or afforestation is not as needed in these countries, that local actors do not prioritize the restoration of kelp ecosystems, or that the information regarding previous restoration efforts is difficult to access. Given that restoration projects have not been conducted in many countries that provide kelp habitat, it is not surprising that kelp restoration projects are less common than those for other marine habitats (Saunders et al. 2020).

2.4.2 Groups involved in restoration

Scientists and researchers have been most commonly involved in kelp ecosystem restoration (Appendix 1.5). Relatively few projects outside of Japan and Korea have been led by governments, NGOs, industry, or community groups. This imbalance perhaps reflects the nascent nature of kelp restoration as restoration practitioners are still working to research and refine methodologies as opposed to attempting restoration on a large-scale (Appendix 1.6). Further, restoration projects are currently expensive (see finances section 6.1) and these costs may prevent large-scale restoration initiatives (Eger et al. 2020c). While there are some partnerships between academics restoration practitioners and other sectors of society (such as the Gwaii Haanas initiative; Lee *et al.*, 2021), they are less common in the English-speaking world. Bridging this gap will be important for future restoration efforts. Academics can provide scientific knowledge on kelp ecosystem ecology and advice on the methodology whereas other sectors can provide local and ecological knowledge, funding, social license, and the people power required to complete the work at scale (Eger et al. 2020c, Lee et al. 2021). Such partnerships are already common in Japan and Korea, and it may be beneficial to replicate them elsewhere.

2.4.3 Project size

Perhaps because most restoration efforts have been experiments by academics, we found that 78% percent of projects were less than 1 hectare in size. Only 37 projects attempted kelp restoration at areas greater than 1 hectare, and only 3 of those were greater than 100 hectares. Of those 37 projects, 13 were afforestation projects. The one recorded afforestation project >100 ha failed, therein most of the few large-scale project successes are restoration projects, NB: the FIRA afforestation collective project is not recorded as a single entry in the database. Tellingly, the main motivation for restoration was to improve methodologies (41% of recorded responses; Appendix 1.6). We also recorded the largest area of kelp forest achieved for each project (e.g., a project that planted 100 m^2 of kelp forest which subsequently shrank to 10 m^2 was recorded as 100 m^2, see methods) and therefore the area size in the database may be an overestimation in some cases. While we found no relationship between project success and size, we expect this is because we only quantified success as the presence or absence of kelp. Analyses which categorize success more finely may find that larger projects are more likely to persist, as is speculated in **Chapter 4**.

These findings further show that kelp restoration is an emerging field that has mostly focused on experimental and theoretical approaches to restoration. We anticipate this status will change as interest in kelp restoration grows, providing the opportunity to use information gained from the previous small-scale projects to inform the larger-scale ecosystem restoration projects expected in future.

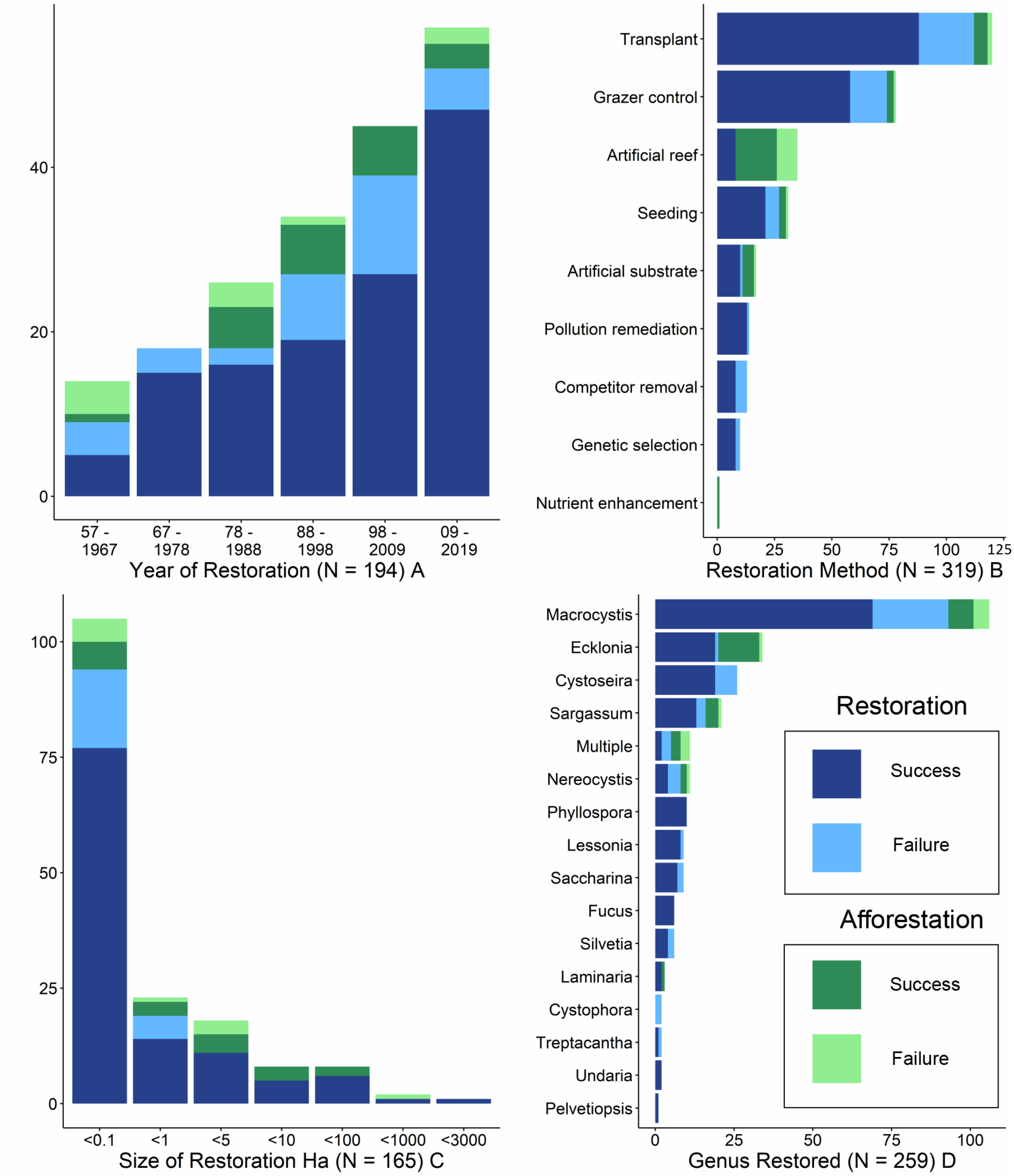

Figure 2 Descriptive results showing ecological success (darker shade) or failure (lighter shade) of kelp restoration (blue) and afforestation (green) projects completed to date (variable N) by: a) year the restoration project was commenced; b) main method used for restoration; c) size of restoration project; and d) genus restored. Sample sizes differ as per Appendix 1.3

2.4.4 Proximity to other kelp forests improves chances of project success

When we examined whether a kelp population survived at the end of the monitoring period, the key predictor of project success was the site's proximity to an existing kelp population (Fig. 3), suggesting that this factor is important to consider in future restoration efforts. The only other significant predictor was whether there was a disturbance during the project, with success being less common following a disturbance (e.g., heat wave, pollution, urchin ingression). The other covariates including kelp genus restored, year the project was conducted, project size, afforestation vs restoration, or the primary method of restoration did not significantly predict success. When more consistent metrics are available for projects in future, a more detailed multivariate assessment of success and varying definitions of success may yield differing results.

The significant result suggests that restoration projects may benefit from a supply of propagules from nearby populations, suitable environmental conditions for restoration, and/or existing populations that facilitate the establishment and survival of new generations (Eger et al. 2020a). Notably, this finding is consistent at the regional level as the projects which restored kelp at an ecologically meaningful scale were in locations where kelp has declined but not disappeared. For example, the large scale FIRA afforestation project in Korea has created ~ 18,000 ha of kelp through a combination of artificial reefs, transplants, and seeding, where kelp decline has been recorded at 10-30% (FIRA 2020). Although significant, the decline in Korea is much less than the 90-95% declines observed in Tasmania and Northern California. Other large scale projects have shown similar patterns: successful restoration projects in Eastern Japan, Northern Norway, and Southern California have all been in regions with remnant kelp populations (Eger et al. 2020c). Conversely, restoration projects in the Mediterranean, Australia, and Northern California without substantial healthy populations of the target species nearby have not resulted in large-scale success to date. Contrarily and while not a restoration project, there has been rapid unassisted recovery of kelp species in Norway following large scale declines (Leinaas & Christie, 1996; Christie *et al.*, 2019a; Strand *et al.*, 2020).

Future projects that work to restore areas near existing kelp populations of the target species, or of other co-occurring species which may facilitate recruitment (Eger et al. 2020a), or that work to enhance existing kelp populations before they decline (Coleman et al. 2020), may be more likely to succeed in restoring kelp. Past work has shown that once a kelp bed has shifted to an alternate state, it is difficult to reverse that shift (Filbee-Dexter & Wernberg 2018). Accordingly, enhancing declining but existing kelp populations maybe the most cost-effective approach and should be prioritized in future management plans. Managers could achieve this goal, for example, by managing urchin populations before they become barrens, or by transplanting or seeding kelp into or directly adjacent to existing kelp forests. In scenarios where kelp restoration is desired but no nearby populations exist, projects may be more likely to succeed if multiple areas are restored to support each other, or a single larger area is restored that can become self-sustaining. Such spatial approaches are already common in the design of MPA networks (Palumbi 2003, Almany et al. 2009) and could be mimicked for restoration.

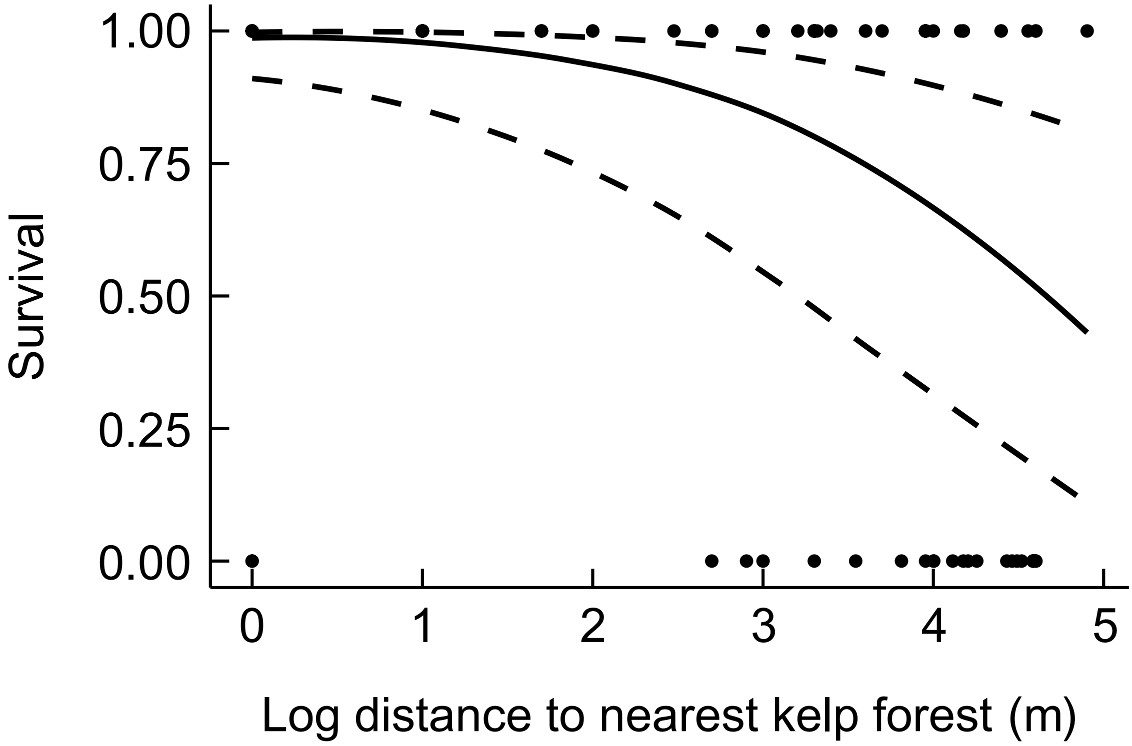

Figure 3 Relationship between kelp survival and project proximity to an existing kelp forest that includes the same species

2.4.5 Environmental barriers to restoration success

Across projects, we found several recurring ecological issues that prevented long-term success of kelp restoration. The most common barrier to restoration success was the incursion of grazing species such as sea urchins and herbivorous fishes. Grazing by urchins has hampered restoration projects in Norway, California, Australia, Japan, and Korea (Wilson & North 1983, Fujita 2019, Layton et al. 2020b). While fish grazing is a less common barrier globally, it has been problematic in Australia, Japan, and Korea (Lee et al. 2014, Yoon et al. 2014, Vergés et al. 2020b). Sedimentation and water pollution has caused problems in Southern California and Washington in the USA, and Japan and Korea (Wilson & North 1983, Carney et al. 2005, Kang 2010, Fujita 2011). Finally, extreme events such as storms, consistently warmer sea temperatures, and marine heat waves have caused transplants to die in Southern California, Chile, and Australia (Wilson & North 1983, Camus 1994, Sanderson

2003, Wernberg et al. 2016b). Finding ways to mitigate these barriers to success will be key to progressing the field of kelp restoration. Social barriers to restoration are not discussed in full in this review but see Section 2.6 "Socioeconomic considerations for restoration".

2.4.6 Ecological success in kelp forest restoration

Defining and predicting ecological success in ecosystem restoration projects is a consistent challenge and one that we encountered in our analysis. None of the categorical variables (genus, year, project size, restoration group, duration) were significant predictors of restoration success. The predictive ability of these models may become more resolved as more nuanced metrics are success are used, as opposed to the binary version we used in this analysis.

Indeed, the high instance of success masks the fact that most projects have been very small scale and have not corresponded to the scale of previous and on-going degradation. Therefore, while percentage survival of kelp is a potential metric to use for success, it can be misleading because of the scale issue. Other analyses (van Katwijk et al. 2016) have attempted to overcome these barriers by creating subjective metrics of success, or "success scores", but are limited by their qualitative cut offs and confound different variables by combining factors such as survival, size, and project duration, and typically ignore the specific goals of each project. A potential solution to this issue is using effect sizes from replicated, before-after control-impact research frameworks where goals are clearly defined (Underwood 1992). However, exceptionally few studies in our synthesis used these designs and thus we were unable to effectively use such analysis. For the field to progress further, future projects should include rigorous measurements of outcome and work to standardize recording approaches across projects.

2.4.7 Kelp restoration in Japan: a qualitative assessment

The Japanese literature database lacks quantitative information on restoration outcomes but provides insights into the state of restoration within the country (Fig. 4). Restoration and afforestation work in Japan focused on culturing programs, modifying the substrate with artificial materials, controlling sea urchins, and transplanting kelp (Fig. 4A). Several projects have also experimented with controlling grazing fish populations, a method that is not commonly used elsewhere in the world (Fig. 2B). Restoration in Japan (in addition to Korea) therefore appears to use more manipulative techniques than elsewhere in the world. Most projects outside of Japan relied on wild harvest of kelp plants, whereas Japan used culture or breeding programs to source plants, likely linked to the fact that Japan is one of the largest producers of seaweed in the world (Nayar & Bott 2014) and can adapt seaweed farming technology. Similarly, it appears much more common for projects to deploy artificial substrates in Japan (Tokuda et Al. 1994), a practice that while also common in Korea, is often opposed in other countries (Thierry 1988, Tickell et al. 2019). The Japanese coastline is heavily urbanized and artificial reefs are often used to offset these developments. As elsewhere (Benabou 2014), offsetting practices may not truly replace the biodiversity that has been lost and may give license to further detrimental development.

Restoration projects increased between 2007 and 2014 (Fig. 4B), likely in response to the government program for incentivizing restoration (Fujita 2019). The most common cause of decline was grazing by sea urchins and fishes while increased water temperatures, sedimentation, nutrient deficiencies, and low salinity were also responsible for kelp decline in the database (Fig 4D). The greatest number of projects were conducted in Hokkaido, perhaps reflecting its large size and also its long history of marine and kelp management (Appendix 1.7). Across the rest of the country, no one area had significantly more restoration projects than another. Kelp restoration in Japan appears to have a globally unique trajectory where, in addition to having conducted the most restoration projects of any country, many different species and methods have been trialled. Given this broad experience, Japan can provide many lessons about the positive and negative aspects of different restoration techniques, including those that are less-practiced elsewhere around the world such as culture of kelps for restoration, fish control, and substrate manipulation.

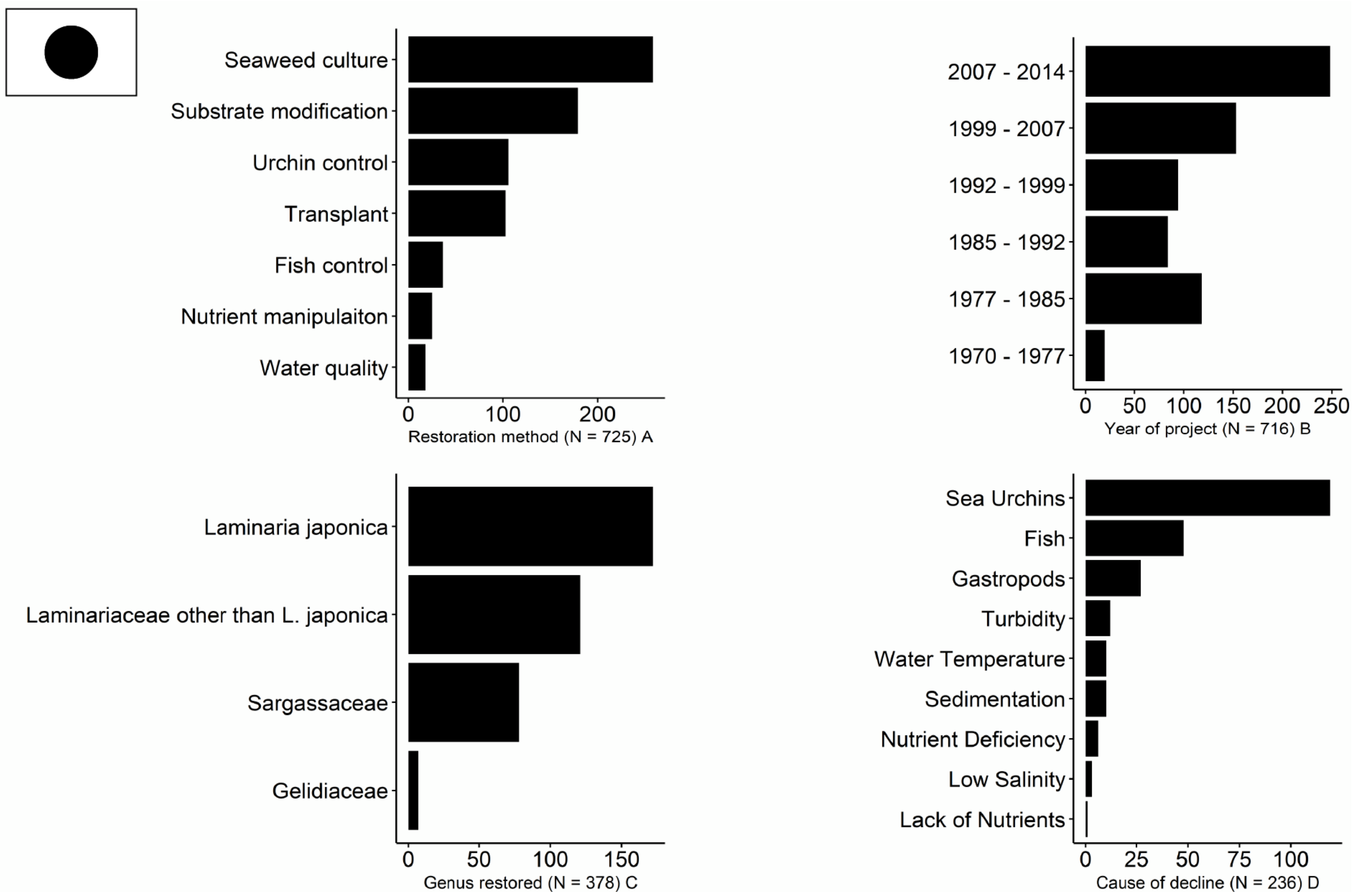

Figure 4 Descriptive results of projects identified in the Japanese literature search: a) Main method used for restoration; b) Year the restoration project commenced; c) Genus restored; and d) Initial cause of decline. No information about the project outcomes was available. Sample sizes differ as not all data was recorded for each entry.

2.5 Restoration methodologies

We found four main methods were used to actively restore kelp populations: transplanting, seeding, grazer management, and artificial reefs (Fig. 4 and 5), with the choice of method largely dictated by the cause of decline. Since the 20th century, the premise behind each method has not substantially changed but our review revealed different lessons learned from each method.

2.5.1 Transplanting

Transplanting kelp typically involves adhering the holdfast to some artificial material and then adding that to the sea floor with the intention that the holdfast migrates to the benthos or the plant acts as a seed source and provides a suitable environment for new plants. Restorationists have trialled many different methods, including gluing holdfasts to the rock (Susini et al. 2007), attaching them to small concrete blocks or stones (Oyamada et al. 2008, Fredriksen et al. 2020), tying them to ropes (North 1976), attaching them to existing holdfasts (Hernandez-Carmona et al. 2000), and attaching them to mesh mats, themselves anchored to the seafloor (Campbell et al. 2014) or to artificial substrata (Marzinelli et al. 2009).

The key limitation with each of these techniques is the scalability and how well the plant can attach to the seafloor. Physical transplantation of kelp is a laborious process and manual installation will likely prove cost prohibitive for large scale restoration projects. A new method termed “green gravel” is being developed that reduces deployment time by removing the need for divers and increases the scalability by using lab cultured gametophytes that are attached to small stones (i.e., gravel), grown in the lab and then dispersed into the ocean (Fredriksen et al. 2020). The method has demonstrated some success and a working group (greengravel.org) is trialling the approach in new locations and conditions (e.g., high wave exposure sites). The benefit of transplanting is that it immediately introduces plants into the environment and these plants can create conditions more suitable for new recruits (Layton et al. 2019, Japanese Fisheries Agency 2021). Transplanting may therefore be a necessary first step that can establish source populations that then self-propagate. However, our results show that these transplanted patches need to be close to other existing kelps to survive (Eger et al. 2020a, Layton et al. 2020a).

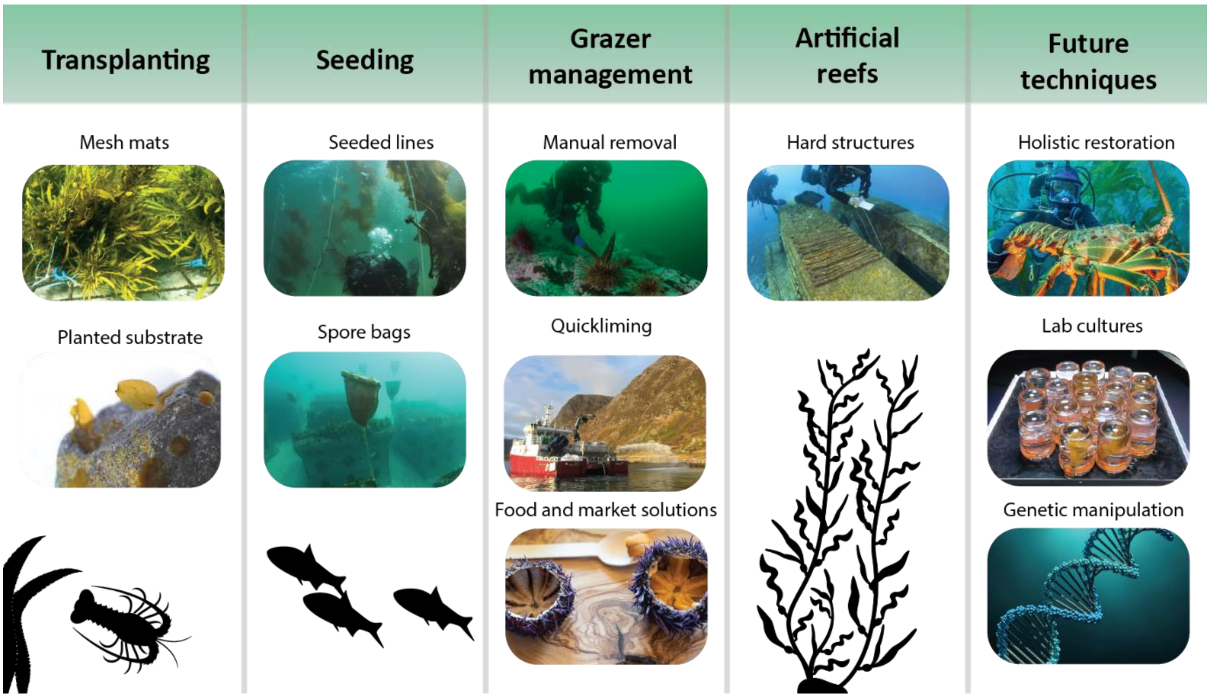

Figure 5 Methods used in kelp forest restoration (Credit left-right, top-bottom: Operation Crayweed, FIRA, Ryan Miller, FIRA, NOAA, Green Gravel, FIRA, NIVA, University of Tasmania, Urchinomics, Pixabay).

2.5.2 Seeding kelp populations

Broadly defined, seeding involves dispersing and/or growing the juvenile life stage (i.e., seeds, gametophytes, propagules, zoospores) of the kelp into the ocean. Seeding kelp populations has received much less attention than transplantation. This gap may be due to the extremely high mortality of kelp propagules (Schiel & Foster 2006) and the perceived advantage of focusing on sporophytes where survival is many orders of magnitude higher. The projects that have used seeding have usually weighted mesh bags filled with fertile kelp blades to the bottom on the sea floor and allowing the propagules to settle on the sea floor (Westermeier et al. 2014). Such projects have had limited success and remained time intensive as divers were used to install and remove the bags from the ocean. Restorationists in coral reef ecosystems are trialling the use of ships to disperse coral propagules into the ocean (Doropoulos et al. 2019) and a similar approach could be trialled for kelp that would likely more cost effective. Nevertheless, seeding methods have promise because if successful, they are applicable at a much larger-scale at relatively low cost, and allow genetic selection and manipulation to be more easily applied (Saunders et al. 2020, Vanderklift et al. 2020).

2.5.3 Removing competitors

Removing kelp competitors from the sea floor has received very little attention outside of Japan, where they have developed a suite of techniques for clearing the rock bare (Japanese Fisheries Agency 2015, 2021) . Some of these methods can be maintained without continued input, for example, a chain spun around by a wave, but others such as manual or mechanical removal are much more labour intensive. Regardless of the approach, large-scale scraping of the benthos is likely untenable in most countries and locations, thus this approach will likely be limited to small-scale transplant sites where removing competitors may help establish the desired kelp population.

2.5.4 Grazer control

Controlling grazers relies on manual removal or exclusion of the animal from the targeted restoration area. For sea urchins this can entail crushing them (Leinaas & Christie, 1996), relocating them (Mead 2021) , harvesting them (Piazzi & Ceccherelli, 2019), or killing them with quicklime (Bernstein & Welsford, 1982). These methods are also restricted by their labour costs (Fig. 6) and the feasibility varies by location. One cost-benefit analysis of

Centrostephanus rodgersii removals in Tasmania, Australia, by physically killing or removing the urchins estimated approximately 13 dive days per hectare per diver (Tracey et al. 2015), though the exact removal rate of urchins is dictated by the urchin density, depth, water conditions, and typography.

Though urchin management is more scalable than transplanting, it still requires substantial resources. Urchins have been successfully baited to help congregate their numbers and therefore make removal more efficient (Japanese Fisheries Agency 2015, 2021, James et al. 2017). Another solution to the scale issue is potentially addressed by using quicklime (CaO) over urchin barrens (Strand et al. 2020). In areas where urchin barrens are relatively depauperate of other species, the collateral damage may be minimal, although other echinoderms and juvenile abalone can be damaged or killed (Strand et al. 2020, Keane 2021) though local investigations into the ecosystem effects are warranted when applying it for the first time. The moral trade off of this approach is beyond the scope of this paper, but from a technical perspective, it can work over large areas (Strand et al. 2020).

Another challenge associated with urchin removals is to maintain the sites where they have been removed. Many projects have demonstrated that if sites are not maintained, urchins will often return and continue to graze kelp transplants or recruits (Carlisle et al. 1964, North 1978, Carney et al. 2005, Yoon et al. 2014). Current evidence suggests that sea urchin biomass needs to be <70 grams of urchins per m^2 and, in some cases, closer to 0 (Ling et al. 2015). The exact number of urchins able to sustain a barren will depend on the species and grazer type (e.g. scraper vs. grazer) and availability of alternative food (Byrne *et al.*, 2013). As an addition or an alternative to continual site maintenance, restoring healthy predator populations alongside kelp forests that can keep sea urchin numbers low may also help create self-sustaining ecosystems (Eger et al. 2020a). Regardless of the solution, restorationists will need to address this problem to ensure long-term viability.

Alternative solutions for managing grazer populations include the establishment of a fishery or ranching program which removes the animals from the ocean for food and/or profit (Lee et al. 2021, Verbeek et al. 2021). These market-based solutions have the added benefit of providing employment and increasing the perceived value of the kelp forests, hopefully spurring further conservation. A limited number of organizations are currently exploring these solutions in Norway, California, Australia, and Japan (Larby 2020, Urchinomics 2020). Restoration of natural sea urchin predators, either through marine reserves which may allow them to recover without further intervention (Eger & Baum 2020), or through planned reintroductions/range expansions where key predators are missing (Eger et al. 2020a). Managers could combine reserves and reintroductions with active restoration efforts to maximize chances of success.

Destructive grazing of kelps by fishes is less common than urchins but is a consistent issue in some areas such as Southern California, Southern Japan, and some regions of Australia (Vergés et al. 2019). There is likely to be an increase in these interactions between kelp and range-expanding herbivorous fishes as sea temperatures rise (Vergés et al. 2019). The same issues and potential solutions apply to controlling grazing fish populations as described above. In addition, increasing kelp abundance and density through successful restoration efforts could help mitigate the grazer damage by distributing fish grazing pressure over many plants as opposed to a few. Focusing restoration efforts during times of the year when herbivores are less active or less abundant can also enhance kelp survival (Carney et al. 2005). Future restoration projects should therefore aim to create large populations as opposed to small patches where grazing may be concentrated and they should also consider seasonal variations in herbivory.

2.4.5 Artificial reefs

Artificial reefs are the last major approach though they are more often used in afforestation rather than restoration projects. While they are often not well-documented, artificial reefs have an extensive history, and the materials used in a reef range from rocks, street trolley cars (Carlisle et al. 1964), bombs and ships (Tickell et al. 2019), to materials designed to enhance algal growth (Fujita et al. 2017). As previously mentioned, if artificial reefs are placed in habitats that did not contain kelp (e.g., sandy bottom, as is common), the approach is considered afforestation as opposed to true habitat restoration. Using reefs for afforestation is commonly used in Japan and Korea (Lee et al. 2017) but faces greater resistance elsewhere (l'vfeier 1989, Tickell et al. 2019).

The trade-offs between adding artificial materials to the ocean and leaving the naturally-occurring habitat unaltered (often replacing sand or unconsolidated substrate habitats), remains a societal decision that may be increasingly considered (Paxton et al. 2020). A key benefit of artificial reefs is that managers can place them where they are easily maintained, and kelp transplants can be more easily attached than on the natural sea floor. New materials for artificial reefs include those that structure the concrete to enhance rugosity and provide additional settlement area (Ishii et al. 2013, Bishop et al. 2017), as well as infusing the concrete with iron, nitrates, and other growth-enhancing materials that are slowly excreted over time (Oyamada et al. 2008). The materials required to build artificial reefs are however very expensive (~$717,000 USD, 2020/hectare, Fig. 6) and require substantial investment, which has typically been provided by governments.

Kelp restoration projects can use a combination of methodologies which may improve the chances of success. For instance, restorationists can install a reef with transplants, clear the benthos and then seed, or as is most common, seed or transplant kelp and work to control grazer populations. None of the methods are mutually exclusive and working with multiple methods may enhance growth of emerging kelp populations in different ways; for example, transplanted kelps could make the environment more amenable for the growth of seeded propagules. Removing competitors, controlling grazers, and/or adding substrate alone all rely on the availability of propagules; if no local populations or existing gametophytes are available to act as seed sources, kelp cannot naturally re-establish at the restoration site. Therefore, restorationists need to consider local conditions when applying any combination of these methods.

2.4.6 Restoration methodologies in the future

Despite a relatively static past, future restoration may be required to change substantially to match the accelerated rate of environmental change (Wood et al. 2019). For example, there may be important advantages to selecting certain kelp genotypes for restoration, either through selective breeding, direct genetic manipulation (Coleman et al. 2020), or by working with kelps that have survived extreme events (Coleman & Wernberg 2020). With careful consideration for unintended consequences, restorationists could select such individuals for their increased tolerance to warming sea temperatures or ability to ward off grazers, though selection for one trait could lower fitness in another (e.g., increased thermal tolerance may make individuals more susceptible to grazing (Coleman & Goold 2019). In addition, as populations are rapidly being lost, the creation of seed banks on land that can preserve genetic material that may otherwise disappear is being considered (Layton & Johnson 2021). Future restoration efforts should also consider the critical associations between a kelp "host" and its microbiome, which is essential for host health and functioning (Egan et al. 2013). Enhancing kelp microbiomes with beneficial microorganisms may also increase kelp resilience to stressors and enhance restoration success (Trevathan-Tackett et al. 2019, Wood et al. 2019, Dittami et al. 2021). More generally, enhancing positive interactions between kelps and other organisms may be critical for success (Eger et al. 2020a) .

The question of scale may be addressed by borrowing techniques from the aquaculture industry which cultures spores on rope, suspends them in the ocean, and grows kelps free from the pressure of sea urchin grazing (Eger et al. 2020a). These seeded lines could then be directly installed on the sea floor or suspended mid-water to act as a source population (Camus et al. 2019). Adding any foreign materials in the ocean requires careful consideration but given the scale at which we can grow kelp for food, it is plausible that we can use similar methods to help restore wild populations.

Changes in future management of fisheries for urchins and herbivorous fishes also offer potential practical long-term solutions for assisting in the recovery of overgrazed populations (Larby 2020). Such fisheries could be carefully integrated into protected areas and management zones, allowing for selective removal from the area (Bengtsson *et al.*, 2021). Further, while currently only a concept, the use of autonomous robots, such as those designed to kill crown of thorn sea stars on the Great Barrier Reef, could work to continually remove urchins over large spatial scales (https://balancedoceans.com/). However, consideration of any automated and remote methods must be carefully balanced against potential risks to other ecosystem components, including species at risk (e.g., abalone).

At the policy level, if we are to invest in restoring kelp forests, that means working to address their causes of decline. Specifically, future management policies must work to reduce overfishing of key species, reduce sedimentation and pollution rates, and ultimately work to slow or even reverse greenhouse gas emissions that are warming the oceans past some species' physiological tolerances (Gann et al. 2019, Wood et al. 2019). Each of these restoration strategies should be taken with consideration of the potential risks, benefits, and societal willingness to engage with different methods (Coleman et al. 2020).

Evaluating the causes of ecological success and failure will be a key step for advancing the field of kelp restoration. Although this review is a start, the field is rapidly advancing and continued efforts to compile this information in a central place as progress is made will be important to promote sharing and collective learning from individual project experiences. One potential avenue to achieve this is a collaborative project called the Kelp Forest Alliance, which includes a website (www.kelpforestalliance.com) that will freely host the database used for this work and can provide a framework for future restorationists to contribute the same data about their projects. The Kelp Forest Alliance intends to work as a nexus for information on kelp restoration projects that links together peoples from around the world, while also helping to advance research and resources for restoration projects.

2.6 Socioeconomic considerations for restoration

2.6.1 Financing restoration

Reported costs of kelp restoration vary substantially between and within methodologies and projects. Controlling sea urchins had the lowest costs, with quickliming costing an average ~$1,500/ha and manual removal averaging ~$67,800/ha. The other methods, transplanting, seeding, and building artificial reefs, ranged between $526,000/ha and $707,000/ha, with seeding averaging the lowest of the three (Fig. 6, all USD 2020). These values only considered a single method being used at a time, and multi-method projects may have similar or lower costs. For example, transplanting on artificial reefs can have lower costs than transplanting on natural ocean substrate. Interestingly, despite being easier to access, intertidal transplants were more costly than subtidal transplants, potentially due to a longer history of subtidal work and more refined methods; in addition, intertidal restoration project areas have been exceptionally small, and scaling costs per hectare based on a 1-m^2 plot can produce overestimates. Presumably, intertidal restoration costs would be reduced as the marginal cost for each additional m^2 plot should not be linear.

The sample size used to collect data for the costs of kelp restoration was very low as most projects did not report costs, however the magnitude of difference suggests that kelp restoration can cost substantially more than restoration in other marine ecosystems (coral ~$196,000, seagrass ~$126,000, mangroves ~$11,000, saltmarsh ~$80,000, per ha, USD, 2020; Bayraktarov *et al.*, 2016). Not considering projects in Japan where we had little cost data, relatively few kelp restoration projects have taken place compared to restoration of other marine systems (Saunders et al. 2020). More extensive experience and refinement of methods may be contributing to lower costs per area restored in other systems. If this is the case, the expected costs for kelp restoration should decline as the people gain further experience, methods are refined, and efficiency is improved. Economies of scale should also result in reduced cost per hectare with larger projects (Turner & Boyer 1997). Indeed, reports from two large-scale kelp restoration and afforestation projects in Japan and Korea have reported costs of $10-20,000 per hectare (Eger et al. 2020c).

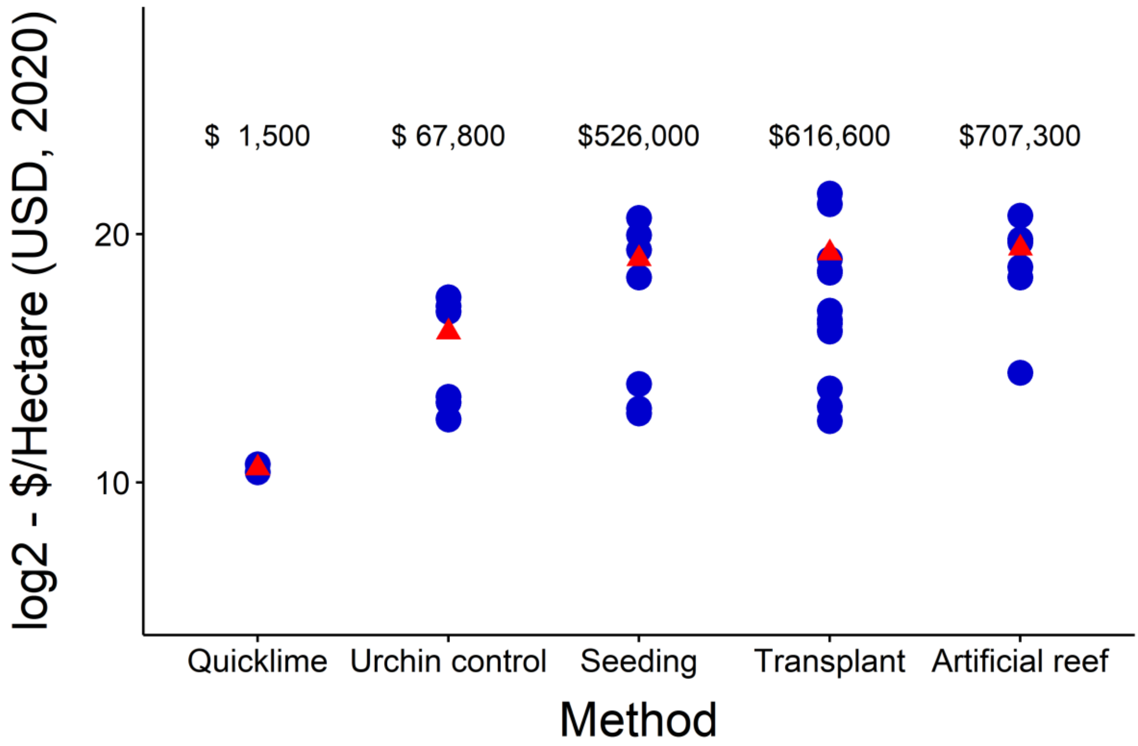

Figure 6 Reported costs per hectare of restoring kelp populations by method. Note the logged y-axis. Red triangles are log-transformed mean values.

Ecological restoration is currently very expensive, yet societal economic benefits from investing in kelp restoration can be substantial. Preliminary analysis of *Ecklonia, Nereocystis, Macrocystis,* and *Laminaria* forests and the services they provide through fisheries, carbon sequestration, and nutrient cycling suggest that restored kelp forest should result in $59-194,000 USD 2020/ha/year of economic benefit (Eger et al. 2021). These benefits would potentially offset the costs of restoration within 1-12 years, depending on the methods used. Although the costs are currently high, if prices decrease with improved techniques and larger scales, the business case for restoring kelp populations should become stronger.

Further, carbon, nitrogen, and phosphorus credits are already being traded on local and global markets and groups that restore kelp populations could be awarded the respective number of credits, which they could then sell to offset and potentially even profit from kelp restoration projects (Rutherford & Cox 2009, Herr et al. 2017). Because the fate of kelp biomass is often unclear, the values for carbon and nutrient sequestration are still poorly understood in most kelp genera and regions. Early estimates suggested that 5-20% of a species' yearly net primary production acts as a long-term sink (Krause-Jensen & Duarte 2016, Gouvêa et al. 2020), which though smaller than other marine macrophytes, suggests potential for the use of kelp restoration in such trading schemes. If verified trading schemes are developed for kelp restoration, then projects could contribute towards meeting a country's commitments to reduce greenhouse gas emissions under the Paris Agreement, which would provide a very strong incentive for national governments to invest in kelp restoration. Restoring kelp forests is also expected to increase fishery yields of not only the kelp itself but kelp-associated species (Bertocci et al. 2015). Because many fisheries have closed due to kelp collapse, investing in restoration would help revitalize these lost industries and should also help governments justify the costs of restoration. For example, the now closed abalone fishery in Northern California was valued at $24-44 million USD dollars in 2013 (Reid et al. 2016, Rogers-Bennett & Catton 2019) and the lobster fishery in Australia was assessed at $700 million AUD ($520 million USD) in 2018 (ABARES 2020).

Although large-scale restoration requires significant financial inputs, there can be potential economic and societal benefits. In the past, governments have attempted to revitalize their economies following a disaster or recession by increasing spending, often funding large infrastructure projects (Restore Act, 2012; Mannakkara & Wilkinson, 2013). Kelp restoration could be viewed as a similar investment, as financing kelp restoration would lead to substantial positive economic and social benefits. This approach was already taken in the USA in 2009, when the US administration included $178 million USD for oyster reef restoration as part of an economic stimulus package (Smaal et al. 2018). Similarly, the Australian government is investing tens of millions of dollars into coastal restoration and blue carbon as a part of its COVID-19 response spending (Prime Minister of Australia 2021), while the EU's "European Green Deal" invests in nature and other technologies to achieve carbon neutrality by 2050 (European Green Deal 2021). Other countries could look to stimulate growth by using similar approaches. The FMDP project in Japan (see regional history of Japan) is another model for how government groups can work together to set aside funding for restoration, provide access to experts, and facilitate collaboration across different sectors of society (Sekine 2015, Fujita 2019). Collaborative funding and support structures are promising ways to implement restoration at a national scale.

Finally, another potential source of funding may come from private enterprises. Business interests are increasingly looking to build social capital by "giving back" while remaining profitable (Sneirson 2008). For kelp restoration, companies such as Urchinomics (https://www.urchinomics.com/) and the not-for-profit Greenwave (https://www.greenwave.org/) are exploring pathways to not only restore kelp forests but also generate sustainable revenues and operate outside the not-for-profit space. These alternate pathways could be vital to address the high costs of restoration (Eger et al. 2020c). For example, government and fisheries groups in Korea are working with budgets of hundreds of millions of USD to restore kelp (Eger et al. 2020c) and a proposed kelp restoration project by the US Army Corp of Engineers in Los Angeles, California, USA, has a budget of ~$150 million USD (United States Army Corp of Engineers 2019). These high-cost budgets are unattainable for many conservation groups, and green businesses may present opportunities to reduce costs and possibly create profits from kelp restoration projects.

2.6.2 Legal frameworks for restoration

Marine management policy has often lagged behind the rapid environmental changes occurring in the oceans (Rilov et al. 2019). As a result, laws initially intended to protect marine resources could now be hindering restoration efforts. Current environmental laws focus on either prohibiting the removal of resources from the oceans (e.g., fishes) or the addition of unwanted materials into the ocean (e.g., waste dumping; Lumsdaine, 1975). Restoration of kelp forests can require either or both actions. To address hyperabundance of grazers, removal or reduction in the number of herbivorous species can be necessary. Conversely, to re-establish kelp populations addition of biogenic materials, such as transplants or propagules, is sometimes needed, or input of artificial substrates for kelp attachment or settlement.

Current discussions regarding reforming environmental laws have focused on identifying appropriate baselines and target species (McCormack 2019); additional discussions are also needed to revisit the rules regarding exploitation of “unwanted” or hyperabundant species and the addition of desirable materials. For example, marine reserves often prohibit the removal of sea urchins which can prevent kelp from returning, as happened in Hong Kong (Leung et al. 2014). While no-take marine reserves remain the gold standard in marine conservation (Sala & Giakoumi 2018), shifting these paradigms to allow for limited removal of endemic grazer species (such as for the project in Gwaii Haanas, BC, Canada Lee *et al.*, 2021) and invasive grazing species and potential addition of habitat into reserves may be needed to address specific issues. As an example of changing legislation, in September 2021, the state of California passed Bill AB-63 to facilitate restoration and monitoring activities within marine conservation areas. The challenges presented by modern restoration projects will therefore require adaptive legislative frameworks that allow for the trialling of environmental interventions, scaling them up when successful, and the reconsideration of previously-held tenants.

Other laws or directives will also be useful in motivating restoration efforts. Specifically, laws that require the offset of habitat destruction. For instance, offsetting regulations were responsible for a 172 hectare project in southern California which is working to ensure no net loss of kelp (Bull & Strange 2018) from that project (Schroeter et al. 2018). The United States, Canada, Australia, the EU, Korea, and New Zealand, have offsetting regulations and policies (Niner et al. 2017) which are useful examples for how to create such policies. Interestingly, we only recorded four offsetting projects in our database, potentially because these project reports are not easily accessible or because offsetting for kelp is uncommon. Regardless, future offsetting projects should be reported in public repositories to allow for open consideration of their success. Notably, Norway, Japan, and Chile, do not have offsetting directives. Although offsetting policies are important, they can only ensure no net loss of kelp and are not necessarily effective for increasing kelp area. Governments can look to increase kelp populations by setting directives such as Law N°20.925 in Chile which legally sets aside funds for restoration.

2.7 Conclusions

1) Kelp forest restoration has a long history, spanning 16 countries and over 300 years of practice. The field is diverse with representation in many sectors of society, including academia, governments, communities, indigenous groups, and businesses. The field is accelerating with more projects in the 10 years between 2009 and 2019 than ever before. While a global field, more restoration projects have occurred in Japan than the rest of the world combined, but access to the results of those projects remains limited.
2) To date, most restoration projects have been small in size, short in duration, and focused on a few genera (*Macrocystis*, *Ecklonia*, *Cystoseira*, and *Sargassum*).
3) Six recorded projects have achieved large-scale success (100s and 1000s of hectares) in restoring kelp forests. This success shows that large-scale restoration is currently possible and a reasonable goal to strive for.

4) The most successful restoration projects are those that are near existing kelp forests. Preventing kelp forest decline aids kelp recovery, therefore actions to ensure that kelp is not lost from a system are critical.
5) Urchin grazing is the most frequent singular reason that kelp restoration is needed and also the most common cause of project failure. Projects should work to mitigate this stress prior to restore and maintain low grazer densities to achieve success. Although not necessarily acceptable due to potential ecological risks, quicklime maybe a technically viable solution to remove large numbers of sea urchins at low financial cost. Urchin fisheries and/or urchin ranching are other options which may profitably remove urchins.
6) Transplanting kelps should work to establish significant population sizes for the best chance of success, particularly if they are adjacent to existing kelp beds.
7) Artificial reefs are a common but expensive and contentious tool for afforestation and restoration. Projects need to carefully consider the economic and environmental costs and benefits before deploying artificial reefs.
8) Further work is needed to investigate seeding methods for restoration. If successful, this method could help scale up kelp restoration projects to larger sizes at reasonable costs.
9) Projects have been very expensive to date, but costs are lowering and the social and economic benefits of kelp restoration are high.
10) Future methods for restoration (genetic manipulation, kelp aquaculture, autonomous technology) have the potential to address barriers to restoration (warming oceans, low abundance of existing kelp, high urchin populations), but risks and benefits must be weighted, and considered in context of holistic ocean management.

11) Legal frameworks are often maladapted for kelp restoration and may need to be reconsidered to allow for careful manipulation of ocean spaces for restoration where needed (e.g., transplanting, seeding, herbivore removal).
12) Kelp restoration initiatives present opportunities for rich collaborations among individuals, organizations, and countries, to reforest the ocean, achieve benefits for multiple user groups, and link into the UN Sustainable Development Goals. Global efforts to consolidate and share experiences and learning, such as the Kelp Forest Alliance (kelpforestalliance.com), take concrete steps towards collectively advancing future efforts.

2.8 Acknowledgements

We thank and acknowledge the indigenous peoples on whose traditional territories these projects were implemented for continuing to take care of the land and sea. We would like to thank Molly French and Emma Mellis for working to validate the database. This work was supported by a Scientia PhD scholarship to AE, and the Australian Research Council through projects LP160100836 to PDS, EMM and AV, DP180104041 to PSD and EMM and DP190102030 to AV.

2.9 References

Entries denoted with an asterisk (*) are found only in the supplementary material (Appendix 1.4).

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Chapter 3 - The need, opportunities, and challenges for creating a standardized framework for marine restoration monitoring and reporting

Link to thesis

Collecting the information for **Chapter 2** was a substantial effort, information was not well recorded, or stored in a central location, and the content and quality of the data related to restoration projects was highly variable. In discussing this issue with my colleagues working in other marine restoration fields, we realized that this problem also occurred in other marine restoration fields such as coral reefs, seagrasses, mangroves, oyster reefs, and tidal marshes. I therefore organized and hosted a workshop at the 6th International Marine Conservation Congress. This workshop brought together experts from all areas of marine restoration and initiated the work for **Chapter 3**, a roadmap of why need a monitoring and reporting framework, how we can achieve it, and what barriers we will face in doing so.

I have published this work: **Eger AM**, Earp HS, Kim F, Gatt Y, Hagger V, Hancock BT, Kaewsrikhaw R, McLeod E, Moore AM, Niner HJ, Razafinaivo F, Sousa AI, Stankovic M, Worthington TA, Bayraktarov E, Saunders MI, Verges A, Reeves S (2022) The need, opportunities, and challenges for creating a standardized framework for marine restoration monitoring and reporting. Biol Conserv 266:109429.

The project was initiated with a hosted workshop: **Eger, A.M.**, et al. (2020). Creating a standardized monitoring and reporting framework for marine restoration. 6th International Congress on Marine Conservation, Kiel, Germany, August 16th- 27th, 2020.

Abstract: Marine ecosystems have been used, impacted by, and managed by human populations for millennia. As ecosystem degradation has been a common outcome of these

activities, marine management increasingly considers ecosystem restoration. Currently, there is no coherent data recording format or framework for marine restoration projects. As a result, data are inconsistently recorded and it is difficult to universally track progress, assess restoration's global effectiveness, reduce reporting bias, collect a holistic suite of metrics, and share information. Barriers to developing a unified system for reporting marine restoration outcomes include: reaching agreement on a framework that meets the needs of all users, funding its development and maintenance, balancing the need for 'ease of use' and detail, and demonstrating the value of using the framework. However, there are opportunities to leverage arising from the United Nation Decades of Ecosystem Restoration and Science for Sustainable Development and with existing processes already developed by restoration groups (e.g. Global Mangrove Alliance, Society for Ecological Restoration). Here we provide guidelines and a roadmap for how such a framework could be developed and the potential benefits of such an endeavour. We call on practitioners to collaborate to develop such a framework and on governing bodies to commit to making detailed reporting a requirement for restoration project funding while also providing support for monitoring activities. Using a standardized marine restoration monitoring framework would enable the application of adaptive management when projects are not progressing as expected, advance our understanding of the state of worldwide marine restoration, and generate knowledge to advance restoration methodologies.

3.1 Global state of marine ecosystem restoration

Humans have undertaken restoration-like actions, including hydrologic modification, transplanting, and weeding in coastal and marine ecosystems to maintain and enhance culturally important natural resources for millennia (Saunders et al. 2020). However, modern ecosystem restoration, i.e. "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (SER 2004), was only conceptualized by Aldo Leopold in the 1930s. Ecosystem restoration has since evolved into a robust body of research and practice and has expanded from terrestrial into freshwater and marine systems. Restoration is now recognized as vital to support the recovery of the abundance, structure, and function of marine life due to catastrophic declines in marine species, habitats, and ecosystems (Appendix 2.1 - "Awareness" Duarte et al., 2020).

While there is evidence from the 18th century of ecosystem restoration of oyster reefs and the 20th century in coral reef, kelp forest, seagrass meadow, mangrove, and saltmarsh ecosystems, the field remains relatively small compared to terrestrial restoration and grew slowly over the 20^{th} century (Saunders et al. 2020). This lag is thought in part due to marine ecosystems being 'invisible' to much of the population (Crowder & Norse 2008), but also due to the large spatial scales of impacts, the decentralized ownership of marine ecosystems, and a perception that passive conservation approaches such as marine reserves could reverse habitat and biodiversity losses (Hawkins et al. 2002, Elliott et al. 2007). Despite these challenges, new approaches, a greater awareness of the degraded state of marine ecosystems (Lotze et al. 2006), and a growing appreciation of the services provided by marine ecosystems has meant that marine restoration has increased since 1990s (Saunders et al. 2020). Indeed, scientists, governments, industries, aboriginal governments, and non-profit groups worldwide are interested in marine ecosystem restoration (Bersoza Hernández et al. 2018, Zhang et al. 2018, Basconi et al. 2020, Saunders et al. 2020) to restore biodiversity, enhance ecosystem services, offset development, answer scientific questions, or improve society (Hagger et al. 2017). There are now more new marine restoration projects than ever before, and as we move into the United Nations Decade on Ecosystem Restoration (2021-2030) and the UN Decade of Ocean Science for Sustainable Development, there is an impetus to scale up marine and coastal restoration to restore critical ecosystem services such as food production, climate control, and coastal protection (Appendix 2.1 – "Partnerships).

A major challenge that scientists, practitioners, and policy makers face is to fully determine the biophysical, political, and socio-economic drivers influencing restoration success and track progress towards global restoration and conservation targets. Further, whilst the scientific community has produced considerable research on marine and coastal restoration, there has been limited success in translating this science into information that can be used by policy makers and practitioners. While ecosystem restoration is a human Endeavor and project success is determined by more than the ecological attributes of a system, a recent review of marine restoration projects found that projects most often used only ecosystem attributes such as growth/productivity and survivorship to measure success, while failing to record ecosystem functions and associated socio-economic benefits (Bayraktarov et al. 2020). Monitoring and reporting of restoration outcomes against objectives should enable more reliable assessments of restoration success (Hagger et al. 2017, Seddon et al. 2020), and improve restoration strategies for the future (Suding 2011).

Here we propose an approach to address some of the challenges facing marine ecosystem restoration, namely outlining a roadmap for the development of a restoration monitoring and reporting framework (Appendix 2.1). Such a framework would provide a mechanism to measure the progress of a restoration project, stimulate adaptive management, capture its success level, and measure restoration impact. This information will then inform more effective decision making for future marine restoration projects and will assist further development in the field of ecosystem restoration, particularly given its growing societal importance and need.

3.2 Why is a standardized marine restoration framework needed?

We suggest that a restoration reporting framework (RRF) is needed so that we can learn from past and present restoration projects in an efficient way to inform better evidence-based decision making for future marine restoration (Fig. 1). The proposed RRF is achievable in the short-term and we argue that its creation should be prioritized before the number and magnitude of restoration projects accelerates further. A RFF will enable the standardization of reporting, so that restoration outcomes from projects applying different methodologies becomes comparable. We define a RRF as a cohesive set of tools (a structured set of activities, guidelines, and standards) for the planning and management of reporting success and failures for restoration projects or programs. Therefore, it is important that an RRF includes a standardized set of information, i.e., ‘metrics’, that are recorded for all restoration projects. This standardization would encompass the metrics that are recorded (e.g., duration, actors, extent, costs), their units (e.g., days, m^2, or specific categories), as well as a standardized protocol for storing and accessing the information. This framework could encompass all coastal, habitat forming ecosystems because they share several key characteristics (i.e. biotic marine environments in the photic zone) and monitoring requirements. We believe it is beneficial to encompass all marine ecosystems as lessons learned in one system may be applied to another and because many marine ecosystems are in fact mosaics and are not independent in the seascape (Gillis et al. 2014, Saunders et al. 2014, Nagelkerken et al., 2015).

The proposed RFF would provide a number of advantages over currently uncoordinated and disparate efforts, including to: 1) consolidate the metrics being recorded 2) facilitate progress tracking and project synthesis to advance our quantitative understanding of restoration success 3) ensure collation of wider set of metrics to ensure socio-economic and cultural aspects are taken into consideration 4) reduce reporting bias, and 5) facilitate greater information sharing between projects. Below we expand on each of these concepts.

3.2.1 Project tracking and synthesis

Understanding the drivers of restoration project success is a complex process that currently involves hundreds of disparately collected metrics. When standard data (i.e. the same metrics collected across many projects) are available, large scale meta-analyses allow us to identify the overall impact of restorative actions and the factors driving the impact (Benayas et al. 2009). However, Bayraktarov et al., (2020) found that in 275 publications on marine restoration, of the 465 different metrics recorded, only the survival of the restored organism was universally recorded. As a result, syntheses often have data gaps with only partial information recorded by all projects (Bayraktarov et al. 2016, Eger et al. 2020a) or incompatible formatting that results in their exclusion from a larger analysis altogether. The wide array of metrics used, and the lack of standardization and comparability hampers our ability to draw conclusions about restoration success across multiple projects using different methodologies. Having a RRF that standardizes the data collected will greatly increase the statistical rigor of analyses. Cumulatively, these improvements should allow for better predictions of what drives restoration success, better project planning, and ultimately, more successful restoration projects (Christie et al. 2020).

Multiple national or international organizations have restoration targets or goals. For instance, the Global Mangrove Alliance has a target of 20% of mangrove areas restored by 2030 (Waltham et al. 2020) and the European Union has a goal of restoring ‘significant areas’ by 2030 (European Commission 2020). Yet, it remains difficult to track restoration progress towards these goals. The RRF would help increase data reporting and comparability across projects, such that we are comparing like-to-like and produce a comprehensive understanding of the national, regional and global state of restoration (i.e., quantification of the area that has been restored or how much progress has been made toward restoration targets and the delivery of ecosystem services (Greiner et al. 2013, Zu Ermgassen et al. 2020). Consistent and accurate monitoring of these restoration targets will be essential for meeting governmental goals as well as for potential industries such as blue carbon credits (Wylie et al. 2016).

3.2.2 Capturing multiple dimensions of restoration

Ecosystem restoration is a human construct, accordingly societal preferences and motivations dictate the future of restored and unrestored ecosystems (Bayraktarov et al. 2020). While ecosystem restoration has traditionally focused on its namesake, ecology, resulting in the collection of biological metrics, there is increasing recognition of the need to incorporate social, cultural and economic indicators when making restoration decisions (Cohen-Shacham et al. 2016, Fischer et al. 2020). Recording and reporting these metrics can help determine whether marine ecosystem restoration is meeting its true potential as a 'triple bottom line' activity that supports the environment, society, and the economy (Halpern et al. 2013).

To date there has been less attention paid to the social than to the ecological outcomes of restoration projects. For instance, information to understand the socio-economic benefits (e.g., jobs, recreational opportunities, cultural value, wellbeing) generated by the project are often unrecorded. Without recording these metrics, we cannot determine how the restoration action is impacting people. This human dimension is outlined in the SDGs and UN decade guidelines (Claudet et al. 2020) and will become increasingly visible as ecosystems are managed to include and not exclude human activity (Mace 2014). There is a particular need to ensure that communities that rely on these ecosystems (e.g., Indigenous persons) are not marginalized or disenfranchised from restoration activity.

Through considered design, a RRF will help define what social, economic and governance metrics can be measured and reported. Additionally, the RRF can be supported by guidance on the best approaches and outline best-practice methods for measuring these metrics. Whilst not all project teams will be able to complete the entire RRF, it is envisaged that by outlining the full suite of factors that could be considered when reporting on a restoration project, future project design processes will be stimulated to include a greater breadth of the metrics in the planning process. As such, a RRF will help to evaluate whether projects are achieving social outcomes and indeed benefiting local and global communities.

The ecosystem services generated or enhanced through restoration are also underreported (Bayraktarov et al. 2016), yet recognition and enhancement of these benefits are vital to advancing the field. The quantification of the full set of benefits from restoration is a key component of the total economic value of restoration (Spurgeon 1999). Decision makers and restoration practitioners need to be able to identify the benefits of restoration so that they can understand the real return on the investment (ROI). The field currently tends to focus on the habitat restored and presumes that benefits will flow from there. However, without adequate documentation of the benefits of restoration there will be less incentive to allocate the high level of resources needed for large scale restoration. A RFF can help to overcome this problem by capturing the metrics needed to parameterize and validate models estimating the ecosystem service benefits (both monetary and non-monetary values) from restoration. These ecosystem service models can then be applied to any restoration projects as long as standard metrics are recorded. As data become more readily available, a greater understanding of the benefits and value of restoration will further motivate additional restoration projects, in particular by enabling ROI estimates and benefit-cost analyses (BCA) to support the case for the expansion of restoration in a growing range of ecosystems and situations (Knoche et al. 2020).

Project financing is a major element of marine restoration (Eger et al. 2020b) that currently receives little focus. Both the cost and cost efficacy of projects influence the likelihood that a project will be attempted or completed. At present there are major inconsistencies in reporting project costs or the breakdown of these costs (Bayraktarov et al. 2016). A lack of cost reporting makes it difficult for future projects to formulate accurate budgets or understand the cost-benefit trade-offs of certain actions when undertaking ecosystem restoration (Iacona et al. 2018). As actors are often motivated to make decisions based on the premise of a net economic gain (Brent 2006), the absence of accurate cost estimates may inhibit or even prevent investment in restoration projects. Further, as funding for restoration projects is limited (Evans et al. 2012) restoration practitioners need to make efficient use of the funds available to them. A RFF will standardize how costs are monitored and reported across projects and help generate an improved understanding of the costs of restoration and encourage the sharing of this kind of data. In turn, better restoration accounting will facilitate planning and cost-effectiveness analyses. Combining the costs with the benefits will also enable the development of BCA models and allow for more nuanced restoration planning decisions to be made (Duke et al. 2013).

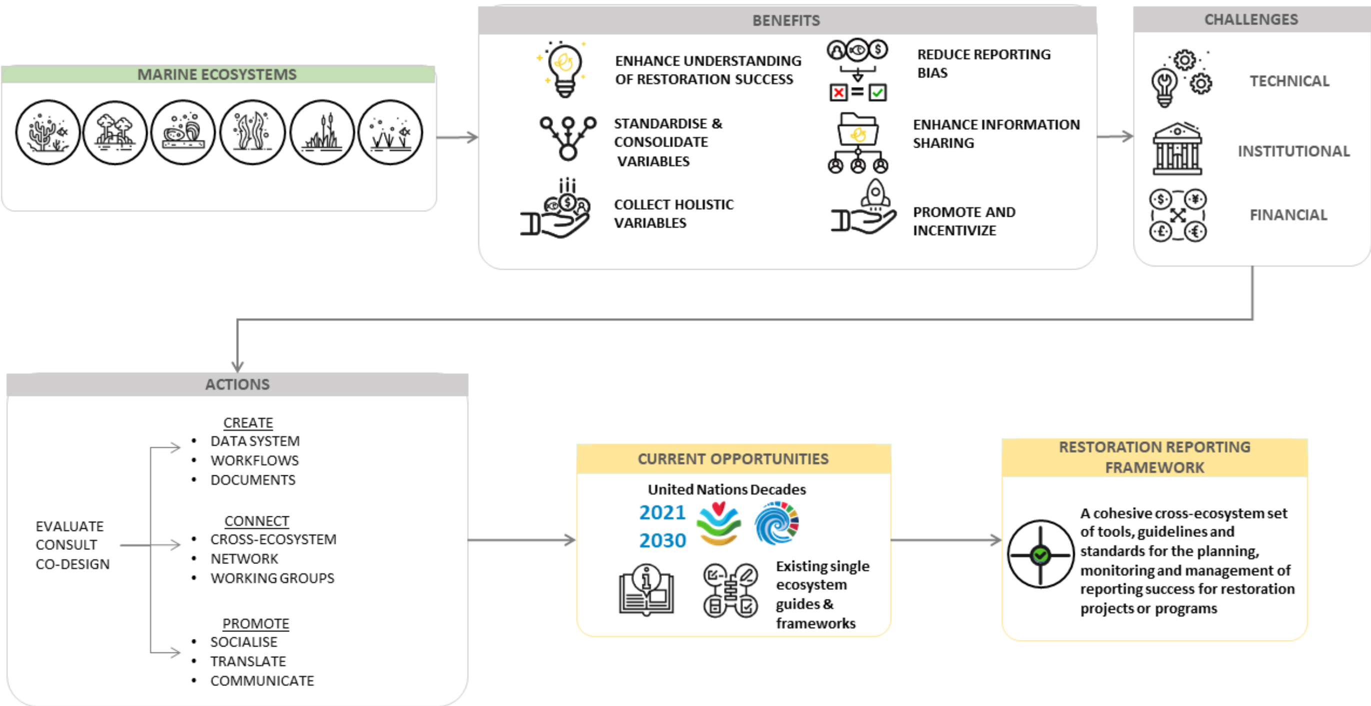

Figure 7 Overview of the opportunities, actions, benefits, and challenges for creating a standardized marine restoration reporting framework. Ecosystem icons represent all major marine ecosystems targeted for restoration icons (from left to right): corals, mangroves, shellfish reefs, kelp forests, tidal marsh, and seagrasses.

3.2.3 Reporting bias

Reporting bias is the selective presentation of successful results. It limits our understanding of the causes of project failures, which are often not recorded and/or not reported (Catalano et al. 2019). This bias can be driven by many factors, including a tendency to only publish the information perceived to be most attractive to scientific journals, the desire to avoid admitting project failure, the desire to meet statutory or organizational environmental management targets, or other unknown factors (Cooke et al. 2019). Regardless of the underlying reasons, it is likely that failures in ecosystem restoration are underreported. Although these “failed” projects may not have succeeded in restoring an ecosystem, they can still provide essential information on what prevented success, as understanding, and addressing the causes of failure is a key process in improving ecological restoration practices. Instituting a RFF from the beginning of a project will help guarantee that all the relevant information is recorded, not just the most positive or desired results. Projects could commit to using the RRF before starting and thus ensure that all available information will be used to determine the efficacy of the methodologies used.

Restoration projects are also often funded for limited durations (Bayraktarov et al. 2016, Eger et al. 2021), typically shorter than the ecological succession periods of marine ecosystems. A RFF could help establish recommended monitoring periods for observing the impact of a restoration activity and allow monitoring responsibilities to be easily shared between project partners, by clearly identifying what is being measured, when how and by whom. Committing to recommended monitoring periods prior to a project's onset, will ensure that projects are adequately budgeted and improve recording of relevant information over a meaningful timeframe.

3.2.4 Enhanced information sharing

Successful restoration projects are being conducted by many different actors across the world. Unfortunately, they are often undertaken in isolation and lessons are rarely shared between projects. Such an absence of knowledge transfer hinders new projects which might have benefited from the experience gained by previous projects. A RFF could adopt a FAIR (Findable, Accessible, Interoperable and Reusable) approach to data dissemination (Wilkinson et al. 2016). Such an approach would allow information to be easily communicated across regions, disciplines, and languages, enabling the RRF to enhance the dissemination of information, accelerate the uptake of valuable lessons learned, and work to build a stronger global restoration community. Making the RRF available in multiple languages and contextually applicable across cultures is a major challenge which could be turned into a significant opportunity to access and share knowledge with restoration practitioners around the globe. Translation or iterative coproduction of an RRF can help reduce some of the barriers associated with publishing biodiversity data (Amano & Sutherland 2013) while also creating a more inclusive global restoration community for non-English speaking countries which are currently underrepresented in restoration (Bayraktarov et al., 2020). Similarly, a well-designed RRF would help create a common language between actors in differing fields and disciplines (e.g., practitioners, researchers, and policy makers).

3.3 What are the challenges to the framework?

Despite the benefits arising from a standard framework for marine restoration monitoring and reporting, there are inevitable challenges to the development and the eventual uptake of a RFF. These challenges can be divided into technical, institutional, and financial barriers and will require consideration as the framework is developed to ensure its application meets user expectations and leads to the desired outcomes.

3.3.1 Metrics to be included

Creating a universal standardized framework, that is robust enough to present useful ecological and socioeconomic information across all marine environments, yet simple enough to be applied by non-technical users and local communities is a major challenge. There are many different metrics that can be, and have been, recorded in marine restoration projects, which reflects the complexity of marine systems as well the multiple needs of different marine user groups. Deciding which of these metrics are essential and which are auxiliary will require careful consideration and require buy-in and collaboration from groups working in specific ecosystems and across some or all ecosystem types. An RRF will require a fine balance of including enough information to ensure the records are comprehensive and not recording too much information so that it becomes burdensome and creates an aversion to using the framework.

3.3.2 RRF Platform and Repository

After the RRF is developed, the data recorded will need to be collected, stored, and readily accessible (Wilkinson et al. 2016). These elements require an online home for the documentation describing the framework, a data portal for uploading data, and a reliable server to store and display the information (Siddiqa et al. 2017, Ranjan et al. 2018). While these elements are not exceptionally complex, they require due consideration, funding, and long-term support.

3.3.3 User uptake

Institutional challenges to a RFF relate to user uptake and support. As there are many elements to restoration, there are also many different projects being led by a wide variety of actors in different countries (Ounanian et al. 2018). For instance, many governments already have reporting frameworks established for service providers and funding recipients under governmental restoration programs, and there may be a lack of administrative flexibility to adopt new frameworks. The first challenge to uptake will be connecting the RRF to project practitioners, whether they are scientists, government groups, Indigenous peoples, businesses, non-profits, or other actors.

Adoption of the framework will likely require a shift away from existing practices towards one that involves a greater degree of transparency. Existing ecological monitoring protocols have evolved to meet user needs and such a change could be perceived as a risk (Harries & Penning-Rowsell 2011) which could lead to resistance to its uptake. These risks could relate to the explicit recording of restoration failure, which may threaten the legal (e.g. development consent) or social license of an organization (Niner & Randalls 2021). Data ownership and sharing is also acknowledged as a contentious issue and a barrier to adoption. Issues of commercial interest may lead to further resistance to uptake or 'trust' in a new system. A short publication embargo period may help to address some of these concerns but, some projects or aspects of certain projects will never be publicly reported due to data privacy concerns (e.g., development projects).

3.3.4 Funding

The last barrier to a restoration reporting framework is funding. Creating a RFF will require significant resources to review existing frameworks, consult users on the development of a new framework, and promote and disseminate the finished product. Because this framework aims to span multiple ecosystems, it may be difficult to entice any one group to fund it in its entirety. For instance, if a country has no coral reefs, they may lack the incentive to fund a project that partially aims to monitor coral reef restoration. Funding will also need to be continuous as the framework will need to be adjusted for changing future conditions, improved based on user feedback, and hosted in a permanent location to ensure sustained access. If funding were to fail, the framework would fail to be useful for future projects and any data hosted alongside the framework might become inaccessible.

A lack of funding is a common reason that projects fail to monitor outcomes in any fashion, standardized or otherwise (Weber et al. 2018). Therefore, a key challenge will be convincing projects to allocate adequate budget to using the proposed RRF. The benefits outlined in section 3.2 may help motivate future projects to make this decision.

3.4 How do we make it happen?

The success of a marine RRF will be dependent on funding, collaborative and participatory development, and uptake by the global restoration community. These requirements are not trivial, but we believe they are surmountable given the existing and emerging marine restoration landscape, in particular the growth and diversification of a marine restoration constituency.

3.4.1 Identify existing initiatives and end users

Given the increasing interest in ecosystem restoration (Basconi et al. 2020), nature-based solutions (Cohen-Shacham et al. 2016), payment for ecosystem services (Meyers et al. 2020), restoration standards and methodologies (Gann et al. 2019), and the growth in active participation from groups with substantial resources (e.g. national and international governments, businesses, and philanthropists), there are feasible funding streams to finance the necessary steps (UNEP-WCMC et al. 2020). For instance, the European Union's second environmental target is to "maintain and restore ecosystems" and requires millions of euros in contributions from member states (European Commission 2020). Further recognition of nature based solutions for climate change and sustainability will provide additional funding avenues, either through party contributions (European Commission 2021) or from industries offsetting carbon emissions (Vanderklift et al. 2018) or meeting environmental sustainability targets (Barko et al. 2021).

Much of the required work will be logistical and first requires the identification of existing resources to avoid unnecessary duplication of effort (Appendix 2.1 – "Synthesize knowledge"). After the state of the field in each ecosystem is established, efforts will be needed to generate a list of potential end users across the different sectors for each ecosystem

(Appendix 2.1 – “Partnerships”). Ideally a key contact person(s) working in each ecosystem and/or region would make these connections. It will be important to ensure that representative end users are included in this step, local persons have a wealth of knowledge about their local ecosystems and can help identify the most important metrics to consider.

3.4.2 Pilot project(s)

A pilot project focusing on one or two ecosystems in select jurisdictions would help minimize the initial complexity and provide a proof of concept to help incentivize further partnership and uptake (Appendix 2.1 – “Pilot projects”). Mapping the state of marine restoration (Section 3.4.1) will identify which groups have made the most progress in creating a community of practice and developing reporting standards (e.g., the Global Mangrove Alliance), and which jurisdictions (e.g. countries or states) would be amendable to running a pilot project using those standards.

Once the confines of the pilot study are specified, and the users are identified they can then be engaged on how they monitor, evaluate, report on, and inform restoration projects in their respective ecosystems (Worthington et al. 2020). Minimizing complexity, regardless of the ecosystem, will be key to the success of any RRF – if the framework is too complex, users are unlikely to use it consistently and accurately. This consultation process could consist of multiple rounds, each going back to the end users for feedback (Appendix 2.1 – “Improved workflows”). Such work could be conducted virtually and in multiple language to encourage wide participation across geographies, although if funding and opportunity are available, the processes could be conducted, at least partially, through in-person workshops or field trials in the specified regions.

Following this pilot project, the process could be repeated across other geographies and ecosystems, each time using the lessons learned from the collective marine restoration community.

3.4.3 Hosting infrastructure

After the RRF structure is agreed upon, the supporting infrastructure will need to be developed (Appendix 2.1 – "Hosting"). Specifically, it will need to be hosted online, with a simple data entry portal for users to submit new information. A recent example of such a system designed for coral reefs is MERMAID (Marine Ecological Research Management AID), which is an open-source data platform that aims to accelerate the transformation of data into decisions to save coral reefs. The development of infrastructure to support the RRF will require the development of data templates, user guides linked to best practice, a web page to access these materials, a data portal for entering new information, and a queryable database or data warehouse with an interface to visualize the information (Appendix 2.1 - "Improved Workflows"). As data are collected, it will be important that they are subject to quality control, either from QA/QC steps built into the data entry, a centralized team or from a peer-review process. After the data are uploaded, they should be freely available and downloadable to maximize their use in restoration practice and research. These are not technologically complex steps but will require adequate funding and resources to ensure their development.

3.4.4 Release and publicization

Once the RRF has been developed, the next task will be to publicize and ensure uptake (Appendix 2.1 – "Publicity"). The afore-mentioned UN Decades can both be leveraged to advertise the framework and encourage its usage. In particular, the UN Decade on Ecosystem

Restoration or the Society for Ecosystem Restoration could be potential homes for the completed framework. Alternatively, the framework could be hosted across a range of ecosystem specific restoration groups and alliances, or a new group could be formed to host and promote the framework. Although subsequent discussions will be needed, it is important that these steps be considered and ideally a host confirmed, prior to the development of the actual framework. Therefore, once the framework is complete, there will be no delay in hosting and making it available.

Regardless of the project's home, a well-publicized project launch and promotional materials will help increase uptake of the platform (Appendix 2.1 – "Launch"). Within this launch, it would be helpful to develop training materials on how to use the framework and the platform (Appendix 2.1 – "Capacity Building"). It will also be helpful to select one or a few key events to use as launch points for the RRF and provide demos to potential users such as the World Conservation Congress (iucn.org). Uptake can also be motivated by demonstrating the usefulness of the RRF. If users see that using the RRF has benefits such as improved analysis, consolidated project tracking, and readily available data for improved adaptive management, they will be more willing to adopt the new framework.

3.4.5 Multiple languages

A key step to ensuring uptake and success of the RRF will be to ensure that it meets user needs, globally across all restoration contexts (Appendix 2.1 – "Partnerships"). This requires that it be available in multiple languages and that its development is ideally co-produced with members representative of the global restoration community. There are many logistical constraints to achieve this, and substantial investment will be required to support the development and maintenance of a multi-lingual platform. Recognizing the current funding constraints within the marine restoration field (Bos et al. 2014) it is unlikely to be achieved from the outset and a reliance on English language for the first iteration will likely be necessary with an aim to translate to multiple languages as funding is made available. To support an equitable approach to this the English iteration should be produced in close collaboration with users of many contexts and languages to ensure representation and inclusion. This engagement will not only ensure that the RRF is inclusive in its application across the restoration community but also that appropriate terminology is applied that can translate across varying global restoration contexts.

3.4.6 Incentives and requirements for use

If high level partnerships are established, the framework could become a mandatory requirement for restoration projects published in academic journal or those funded by and associated with certain bodies. For instance, as is increasingly common, scientific journals require that data be open access and uploaded alongside publications or environmental data-sharing could become a stipulated condition of biodiversity offsetting resulting from human development and the RRF could be the specified standard. Similarly, project grants and funding could be contingent on a mandated level of restoration reporting as well as the release of data. A common theme for uptake and success is the decentralization of the framework and the buy-in of numerous partners, small and large, from different sectors around the world. Ultimately the success of the framework will rely primarily not on technology, but on societal buy-in.

3.5 What current opportunities can be leveraged?

Given the global expansion of ecological restoration and its increasing recognition as a global priority we believe that there will be growing opportunities to develop a RFF. There are two ongoing United Nations led initiatives: the “UN Decade for Ecosystem Restoration –

UNDER" (Waltham et al. 2020) and the "UN Decade of Ocean Science for Sustainable Development – UNDOSSD" (Claudet et al. 2020). Further, national and international commitments to restoration are increasing (European Commission 2021, Prime Minister of Australia 2021) and countries have standing commitments to reducing CO_2 levels (Paris Agreement 2015), protect biodiversity through conventions such as Ramsar (Verhoeven 2014) and cultural connections to nature, e.g. through the UNESCO program (Lennon 2006, Gardner and Davidson 2011, Reed and Massie 2013), and are increasingly considering restoration as a tool to achieve these goals (Herr et al. 2017). Indeed, tracking the success of these initiatives requires that each adopt a monitoring and reporting framework. Any RRF should consider how to fit within these initiatives and report the required information. In addition, there is growing support for the field of environmental accounting (Vardon et al. 2018). This work is grounded in robust monitoring and reporting and the System of Environmental Economic Accounts has been developed to help standardize this process (United Nations et al. 2021) and maybe incorporated into restoration monitoring and reporting frameworks. A high level panel of 17 countries (oceanpanel.org) has already committed to exploring the development of environmental accounts for the ocean and the RRF can support that work. Creating a RFF and enhancing restoration efforts works to meet these goals and are thus valuable contributions to the decade objectives and ocean management.

There are several promising existing frameworks that can provide valuable lessons learned and/or potentially be incorporated into the development of a comprehensive marine RRF. Chief among these is the Society for Ecological Restoration (SER) framework "International Principles and Standards for the Practice of Ecological Restoration" (Gann et al. 2019). This comprehensive document details the principles for successful restoration projects, including the goals set, as well as the project planning and design stage. Within this framework is a 5-

point star system that details how managers can evaluate the success of their restoration project. This framework relies on broad categorical goals such as “soils and waters repaired”, “cultures conserved”, or “science drawn upon”. Any new RRF could be specifically designed to inform these categories and further improve best practices in restoration. Some of the categories within the SER framework are focused on terrestrial systems (e.g., “soils and water repaired”) and will need to be modified for the marine and coastal environment. Importantly, SER is an internationally recognized body in ecosystem restoration and could help develop and-or promote the uptake of the RRF ensuring integration between marine, freshwater, and terrestrial ecosystem restoration. Therefore, a partnership with the SER would be beneficial for creating and promoting the RRF.

There are several ecosystem-specific marine restoration guides which could be leveraged to develop a marine RRF. There are currently guides for restoration in coral reef ecosystems (Edwards & Gomez 2007, Goergen et al. 2020), shellfish reefs (Fitzsimons et al. 2020), seagrasses (Fonseca 1998), mangroves (Global Mangrove Alliance 2019), and a guide is in development for kelp forests (Eger et al. 2021). These guides provide some information on which metrics should be recorded (e.g., habitat cover, area extent, project dates) but none contain a comprehensive list across ecological, economic, and social metrics. Furthermore, the guides have not been developed with the intent of sharing information across ecosystems or even necessarily projects. Nevertheless, they can all support a strong knowledge base on which to develop a cohesive RRF.

3.6 Conclusion

Restoring marine ecosystems at a scale relevant to reversing ecological degradation and to meeting societal goals such as food security, water filtration, biodiversity conservation, and climate adaptation and mitigation, is necessary. This challenge will require iterative research, critical analysis of success and failures, informed decision making, and societal buy-in. A standardized restoration reporting framework will systematically advance the field and ultimately lead to increased efficiencies which can substantially increase the extent of restored marine habitats. The field is currently primed for such a framework with heightened interest, restoration activity, habitat specific restoration and monitoring standards to work from across marine systems, and increased recognition of the importance of ecosystem restoration. Nevertheless, there are logistical and societal hurdles that challenge the framework's development or hinder its adoption. These challenges can be overcome by developing relationships among end users, funding bodies, and regulatory groups. Funding could be a notable barrier, but ecosystem restoration is an increasingly fundable field that has demonstrated economic returns to society (De Groot et al. 2013, Edwards et al. 2013, Knoche et al. 2020). As we consider the need, opportunity, challenges, and steps for developing a framework, it appears that such an endeavour is feasible and will be a significant asset for the global marine restoration community and ocean users worldwide.

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Chapter 4 - Playing to the positives: Using synergies to enhance kelp forest restoration

Link to thesis

The implicit goal of any restoration project is to restore a fully functioning ecosystem and along with it, all the species interactions and synergies that have evolved over the years. In **Chapters 2** and **3**, I saw that while this was often stated as the goal, it was not executed, and projects most often only considered the habitat forming kelp species in their restoration projects. **Chapter 4** thus explores potential ecosystem and human interactions that can not only be included in kelp restoration projects but also increase the probability that the project restores a fully functioning ecosystem.

I have published this work: **Eger AM**, Marzinelli E, Gribben P, Johnson CR, Layton C, Steinberg PD, Wood G, Silliman BR, Vergés A (2020) Playing to the Positives: Using Synergies to Enhance Kelp Forest Restoration. Front Mar Sci 7:544.

Abstract

Kelp forests occupy much of the world's coastline and constitute some of the most productive ecosystems in the world. Given their large range and role as foundation species, kelp is crucial to the ecological, social, and economic well-being of coastal communities. Yet, due to a combination of acute and chronic stressors, kelp forests are under threat and have declined in many locations worldwide. Active restoration of kelp ecosystems is an emerging field that aims to combat and reverse these declines by using methods such as transplanting, seeding, herbivore control, and creating artificial structures. Most of these efforts have focused on eliminating or mitigating negative interactions or physical stressors, but the incorporation positive interactions into the restoration process has received less attention. New evidence from other marine ecosystems illustrates that the inclusion of

positive species interactions can enhance restoration results with little extra cost while also promoting entire ecosystem recovery. This approach to restoration is highly relevant in the context of climate change, because positive interactions can expand the range of physical conditions that species can persist under, improving the chances of survival in future, altered environments. Here we highlight inter- and intraspecific, direct, and indirect positive interactions within kelp ecosystems and provide recommendations for how restoration efforts can incorporate them. We catalogue useful interactions in the following categories: 1) facilitation between primary producers; 2) indirect trophic effects; 3) genotypic and microbial interactions; and 4) anthropogenic synergies. As kelp forests continue to decline and the field of kelp restoration continues to develop, it is important that we use the best available solutions. Incorporating positive species interactions into future restoration practice stands to promote a more holistic form of restoration that also increases the likelihood of success in a shifting seascape.

4.1 Introduction

4.1.1 Significance, threats, and declines of kelp forests

Kelp, defined here as large brown seaweeds from the orders Laminariales, Fucales, Desmarestiales (Wernberg & Filbee-Dexter 2019), are habitat-forming marine macroalgae that form the basis for some of the most productive ecosystems in the world's sub-tropical, temperate and polar seas (Dayton 1975, Coleman & Wernberg 2017, Smale et al. 2019, Wernberg et al. 2019). These habitat formers provide a complex three-dimensional habitat (Miller et al. 2018, Layton et al. 2019b) that support other macroalgal species (Melville & Connell 2001, Wernberg et al. 2005), fish, and invertebrates (Graham et al. 2007, Teagle et al. 2017, Olson et al. 2019). Kelp is also a valuable food source, both through the production of live tissue and of detritus that is often exported to other ecosystems (Dayton 1985, Bustamante et al. 1995). Exportation of carbon outside the ecosystem, combined with their high productivity means they can act as a valuable carbon sink (Chung et al. 2013, Filbee-Dexter et al. 2018, Queirós et al. 2019). Other ecosystem services include wave attenuation and reductions in coastal erosion, critical under a changing climate (Smale et al. 2013). Many kelp species are also part of a wild or farmed harvest economy (Vásquez et al. 2014), are efficient nutrient cyclers (Graham et al. 2007), and provide recreational and cultural value (Smale et al. 2013). Based on these services, kelp ecosystems are currently valued at ~1 million USD km^{-1} $year^{-1}$, though these values are considered underestimates (Wernberg et al. 2019).

Given the great ecological and economic importance of kelp forests, there is growing concern about their disappearance from the world's oceans. Krumhansl et al. (2016) found that laminarian populations in 38% of studied ecoregions showed declines over several decades. Compounding the global average decline, several regions have experienced range contractions and near total losses of their kelp populations in the last 5-10 years (Bennett et al. 2015, Ling & Keane 2018, Rogers-Bennett & Catton 2019). These dramatic losses of kelp have already led to severe socioeconomic consequences and resulted in the declines, closures and limitations of major fisheries, such as abalone fisheries in eastern Japan and California (Kiyomoto et al. 2013, Rogers-Bennett & Catton 2019) and rock lobster fisheries in Australia (Hinojosa et al. 2014). Detailed syntheses do not exist for fucoid species, but there have been notable local declines of *Phyllospora*, *Fucus, Sargassum,* and *Cystoseira* species throughout the world as well (Thibaut et al. 2005, Coleman & Wernberg 2017). Without directed intervention, the loss of kelp and their associated services will continue (Smale et al. 2019). Furthermore, natural recovery is not common and is not anticipated at a significant scale (Wernberg et al. 2019, Layton et al. 2020).

The causes of kelp forest decline and disappearance are complex and range from local, often mitigatable impacts, to global, irreversible changes over the course of decades. Water pollution and habitat destruction are the primary abiotic causes of kelp forest decline at the local scale. Nutrient and contaminant inputs from untreated sewage and agricultural runoff can distribute toxic materials (Burridge et al. 1996, Coleman et al. 2008), increase abundances of competitors (Connell et al. 2008), and cause high turbidity that can prevent kelp from photosynthesizing (Reed & Brzezinski 2009, Tait 2019). Local biotic stressors can also play an important role in reducing kelp forest distributions. Overgrazing by herbivores has resulted in the marked decline of kelp forests in many locations around the globe (Filbee-Dexter & Scheibling 2014, Ling et al. 2015). The main actor, sea urchins, are a natural part of the kelp ecosystem, but their populations can increase in numbers when their predators (e.g. otters, fishes, lobsters) disappear from an ecosystem (Shurin et al. 2010), or when warming temperatures result in their arrival in a new location (Ling et al. 2009). Furthermore, warm water herbivorous fishes have expanded their ranges in many parts of the world in response to ocean warming, causing declines in kelp populations (Vergés et al. 2014, 2019). Climate change poses a major threat to kelp forests, as most kelp are cool water species, and warming temperatures can push them beyond their physiological limit and either kill adult plants or prevent further recruitment by killing the spores (Smale et al. 2019).

Ocean warming and other climate-related stressors are unmitigable threats over short time scales and may cause a revaluation of which populations are manageable under changing conditions (Coleman & Goold 2019). For example, along the warm edge of the distribution of many species, management of kelp forests may entail facilitating the expansion of warm-adapted genotypes or even alien species, or expanding the niche of native species, either through assisted evolution (Coleman & Goold 2019, Wood et al. 2019) or through positive species interactions and facilitation.

4.1.2 Traditional management interventions in kelp forests

Kelp conservation has an extensive history and managers across the world have been working to conserve kelp forests since the 1800s (Fujita 2011), most focusing on eliminating the causes of kelp decline (also needed for restoration; see Eger et al., 2020b). For example, managers have focused on addressing kelp overharvesting (Buschmann et al. 2014) and water pollution (Coleman et al. 2008). Overharvesting can be a straightforward fix in systems that contain wild harvest industries (e.g. Chile, France, Japan), and appropriate management that regulates kelp extraction can allow for populations to return (Fujita 2011, Buschmann et al. 2014, Frangoudes & Garineaud 2015). Enhancing the water quality in an area can also slow kelp loss or sometimes allow it to return (Hawkins et al. 1999). While kelp restoration is not usually a focal motivation for implementing marine protected areas (MPA) (Woodcock et al. 2017), MPA restrictions may limit the harvest of certain marine predators that can help control herbivore population and thus their installation may promote the resilience of kelp ecosystems (Ferrari et al. 2018). These efforts have had some success around the world in maintaining or restoring kelp populations, particularly where food webs are less complicated and there is no nutrient limitation or other stressors present, whereby increases in the populations of urchin predators such as sea otters or lobsters have had a positive cascading impact on kelp (Estes & Duggins 1995, Shears & Babcock 2002, Watson & Estes 2011, Caselle et al. 2018). Still, we must consider other active interventions if kelp does not re-establish following such interventions (Barrett et al. 2009, Campbell et al. 2014a).

4.1.3 Restoration of kelp forests

As attempts at preventing further losses of kelp have failed, coastal societies have developed an accelerated interest in active and passive kelp forest restoration (Eger et al. 2020a). Successful accounts of kelp restoration are rare and costs have been high (Bayraktarov et al.

2016, Eger et al. 2020a, Layton et al. 2020). The majority of the work conducted thus far is at spatial scales of less than 1 hectare and over durations of less than 2 years, and the costs have often exceeded hundreds of thousands of dollars per hectare (2010 USD, Eger et al., 2020a). Despite these limitations, there is an emerging interest in large scale kelp restoration from universities to NGOs, governments, and industries. Active efforts to restore kelp forests include the addition of kelp transplants, seeds, or habitat (via artificial reefs) to the marine environment (Basconi et al. 2020), but can also involve the removal of kelp consumers such as urchins and fishes (Terawaki et al. 2001, Tracey et al. 2015, Layton et al. 2020). The main goal of these early kelp restoration efforts has been passive restoration via first eliminating threats, followed by more active and intensive efforts that focus on supplementary activities such as transplanting (Wilson & North 1983, Campbell et al. 2014a, Verdura et al. 2018). While these techniques will remain relevant, it is important to consider what further elements might enhance the chances of success and lower the costs of kelp forest restoration, which can be significant (Eger et al. 2020b).

4.1.4 Positive Species Interactions, Stress, and Kelp Forests

One promising method to complement previous ecosystem restoration methods is to incorporate positive species interactions and other synergies into the process. Positive species interactions occur between organisms where at least one individual benefits and the other individual is not harmed (e.g. mutualism, commensalism, facilitation, Bruno et al., 2003). There is now evidence from other coastal marine ecosystems (coral reefs, saltmarshes, mangroves, seagrasses) that positive interactions can work to enhance restoration success and reduce costs (Shaver & Silliman 2017, Renzi et al. 2019, Valdez et al. 2020). Examples of positive interactions from other systems can be intra- and inter-specific. For the former, examples include positive density dependence, whereby clumping of saltmarsh or mangrove saplings reduces oxygen stress (Howes et al. 1986, Gedan et al. 2009) and can allow plants to grow up to three times faster (Silliman et al. 2015). Inter-specific positive interactions include, for example, ascidians and sponges growing on mangrove roots, where their presence can protect mangroves from isopod grazing (Ellison & Farnsworth 1990).

According to the Stress Gradient Hypothesis, the frequency of positive interactions should increase with greater levels of stress (Bertness & Callaway 1994). Positive interactions may thus become more important in the future as conditions become more stressful due to multiple, interactive stressors including climate change (He et al. 2013, Wright & Gribben 2017, Uyà et al. 2019). In particular, positive interactions can influence the physical conditions under which species persist, and thus have the potential to mitigate the effects of warming, drought or acidification on the distribution of species (Silliman et al. 2011, Angelini et al. 2016, Bulleri et al. 2016, 2018). For example, positive species interactions can help foundation species such as saltmarsh survive acute abiotic stresses such as drought (He et al. 2017) and might increase the thermal tolerance of some species such as corals to otherwise lethal warming events (Shaver et al. 2018). In intertidal systems, canopies of the fucoid *Ascophyllum nodosum* can reduce maximum summer rock temperatures in New England by up to 8° C (Leonard 2000). The presence of such canopies also influences biotic processes and interactions of key grazers in the system (Marzinelli et al. 2012), which in turn can affect kelp recruitment (Hawkins & Hartnoll 1983). In subtidal kelp ecosystems, the photosynthetic activity of canopy seaweed species can also buffer ocean acidification by increasing the pH (Britton et al. 2016). This buffering capacity of kelp not only facilitates the presence of pH-sensitive calcifying associated species (Cornwall et al. 2015, Wahl et al. 2018), but can also improve conditions for seaweed reproduction and early germination processes (Roleda et al. 2012, Britton et al. 2016, Layton et al. 2019a). Recognizing and encouraging these interactions may aid in successful restoration of kelp forest ecosystems, especially as ecosystems become more stressed and variable. While these interactions are not yet catalogued and considered in a kelp restoration context, there are some well-known positive interactions from ecological literature on kelp forests that may aid restoration efforts.

Interest in kelp restoration is increasing and it is important that managers consider the best available options for developing successful and cost-effective restoration. Incorporating positive species interactions into kelp restoration could help kelp recovery, but also accelerate the re-establishment of associated biodiversity (Angelini et al. 2016) and ecological processes (Thomsen et al. 2018). Given that kelp restoration is an emergent and fast-growing field, the opportunity exists to incorporate positive interactions into the development of management interventions and improve the likelihood of success of future efforts and their cost-effectiveness. The aim of this paper is to catalogue known and potential positive interactions in kelp forests and provide context about how future kelp restoration efforts can use these interactions. Our work uses a combination of a structured literature review and expert knowledge to identify several different positive interactions under current and future conditions. These are: 1) facilitation between primary producers; 2) indirect trophic effects; 3) genotypic and microbial interactions; and 4) anthropogenic synergies. For each interaction, we review the existing knowledge for kelp forests and provide advice on how current and future restoration efforts can apply these.

4.2 Methods

We first conducted a literature search using SCOPUS on July 12th, 2019, with the following search terms:

kelp* OR seaweed* OR macroalga* OR Laminariales OR Fucales OR Desmarestiales

AND

species interact* OR biotic OR connect* OR link*

AND

positiv* OR benefic* OR facilitat* OR density dependen* OR mutalis* OR synerg* OR commensal* OR cascad*

The search returned 156 results. We then conducted a preliminary assessment for suitable papers that might 1) involve a species of seaweed from the order Fucales or Laminariales or Desmarestiales and 2) involve positive interactions (e.g., mutualism, synergism, commensalism). This process refined the initial search results down to 92 possible papers (Figure 8). We then read these papers to ensure they met the same two criteria, and if so, classified the positive interaction detailed in each paper to create a table of all identified positive interactions (Table 1). We then created a final list of 14 interactions by combining the returned topics with suggestions from the authors (Table 1). Each author then identified which 6 interactions they thought were most relevant to include. We created a final list of topics by selecting the interactions that had three or more votes; this process resulted in a final list of 9 interactions (Table 2). We removed the topics on facilitation cascades and settlement because insufficient material exists for kelp, and we incorporated the topic “hypothesized interactions from other ecosystems” into the main text.

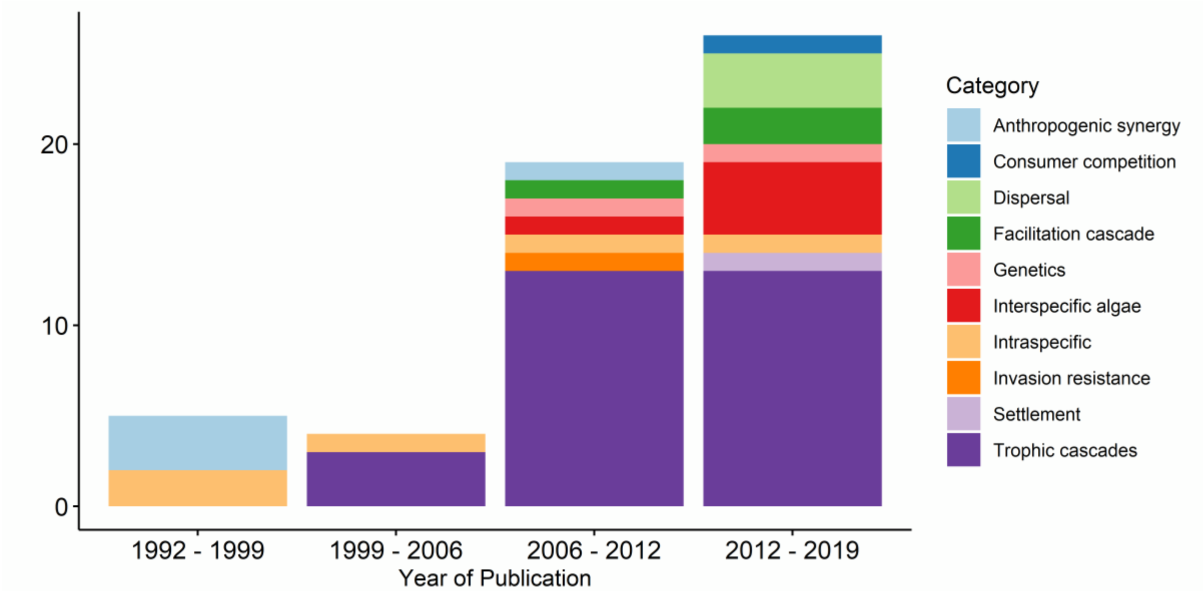

Figure 8 Number of publications identified in the literature search by year and by category.

4.3 Synergies in kelp forest restoration

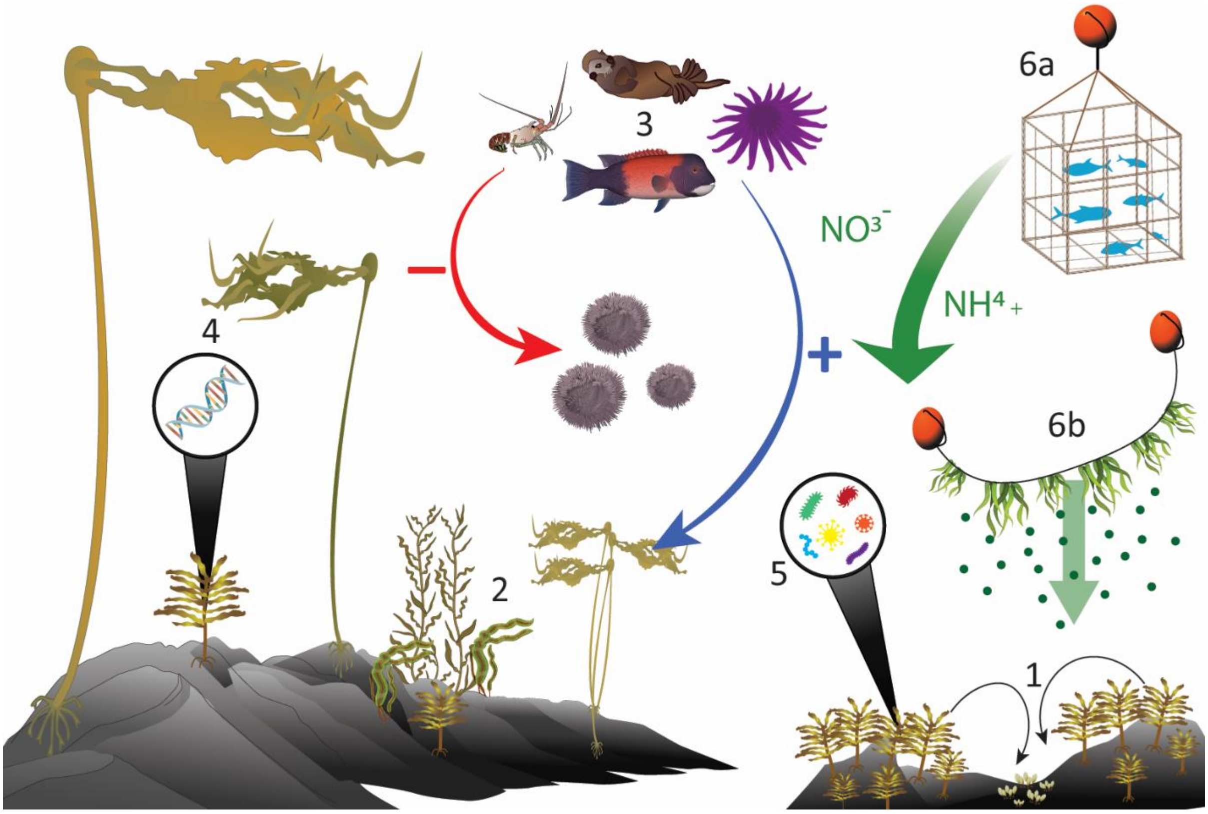

Figure 9 Ecosystem diagram of positive interactions that exist within and may benefit kelp forest restoration.

4.3.1 Intraspecific facilitation – Figure 9-1

There are various impacts of intraspecific processes in kelp forests but there is strong evidence for positive density dependencies. Studies show that kelp populations have density thresholds that alter the environment and support future generations (Dayton 1985, Harrold & Reed 1985, Schiel 1985, Pearson & Brawley 1996, Anderson et al. 1997). Indeed, the slow recovery of kelp after large-scale losses (Kirkman 1981, Toohey et al. 2007, Connell et al. 2008) is often attributed to the breakdown of these positive 'environment-engineer feedbacks' (Cuddington et al. 2009, Jones et al. 2010). Likewise, a failure to re-establish this intraspecific facilitation may explain the limited success of some previous kelp restoration efforts (Layton et al. 2019b, 2020).

One pathway by which this feedback manifests is via the supply and dispersal of reproductive propagules in the environment. In general kelp species are short dispersers and only have single generation dispersal ranges of 0.1 – 10 km (Chan et al. 2013, Schiel & Foster 2015, Luttikhuizen et al. 2018). Additionally, populations need very high densities of adults to supply propagules to future generations (Dayton 1985), which, in turn, can enhance fertilization (Pearson & Brawley 1996). As a result, the lack of a local adult populations limits the unassisted range expansion of a single population. Without adequate propagule supply to enhance recruitment success, the survival of those offspring is thus likely limited (Schiel & Foster 2006).

The modification of the local physical and chemical environment by the adult kelp canopy can also facilitate the survival and development of juvenile conspecifics within the sub-canopy (Schiel & Foster 2006, Layton et al. 2019b). Degraded kelp canopies (e.g. reduced patch sizes or densities) lower the ability of the canopy to engineer the sub-canopy environment and can cause a reduction or break down of the positive feedback processes (Layton et al. 2019b). In turn, this loss can lead to disruption and even collapse of the demographic processes of micro- and macroscopic juvenile kelp and can result in a total loss of habitat stability and resilience.

The importance of intraspecific facilitation, especially for juvenile kelp, might strengthen in more stressful environments (Bertness & Callaway 1994). At local scales, for instance, the importance of facilitation may relate to depth gradients in light, ice scour, or wave exposure (Kitching 1941, Wood 1987, Chapman & Johnson 1990). At larger scales, gradients of abiotic stress across latitudinal gradients, due to changes in water temperature and irradiance, may be more important (Wernberg et al. 2011). At both scales, the presence of adult kelp in stressful conditions can expand the realized niche of juvenile conspecifics beyond their fundamental niche, thus allowing juveniles to thrive in areas where they would otherwise perish in isolation (Bruno et al. 2003, Layton et al. 2019b). This is likely to become more important in the future given projections suggest that the marine environment will become more stressful (Frölicher et al. 2018, Smale et al. 2019).

As we continue to improve and refine active restoration interventions, there are several ways to better harness and re-establish the internal processes that promote the stability of kelp forests. Given the importance of intra-specific facilitation for kelp patch expansion and dispersal (Schiel & Foster 2006), future restoration attempts might be most successful when they occur nearby intact kelp forests, thus ensuring there is an adequate supply and exchange of propagules between neighbouring populations. If new patches are being installed, it would be prudent to orientate them such that there is connectivity with nearby forests as to enhance the contributions of local propagule supply. Effective dispersal distances vary amongst species, with distances less than 1-2 km in genera such as *Saccharina, Alaria, Ecklonia, Sargassum, and Undaria* (Norton 1992, Forrest et al. 2000, Serisawa et al. 2005, Chan et al. 2013, Akino et al. 2015, Luttikhuizen et al. 2018), and up to 10 km in *Macrocystis*. Smaller distances between populations may further enhance the likelihood of propagule exchange and restoration success.

The facilitative role of kelp canopies is usable in restoration projects using multiple approaches. For instance, managers can transplant kelp individuals or propagules to enhance existing but declining kelp populations and help re-establish positive density-dependent processes before they disappear. If successful, this approach avoids a phase shift to a barren or turf-dominated state, after which it may be more difficult to restore (Gorman & Connell

2009, Johnson et al. 2017, Filbee-Dexter & Wernberg 2018), and aids dispersal. In restoration attempts using propagules or juveniles, it may also be helpful to transplant (or outplant cultured) adult individuals to help prime the environment for the new recruits. Indeed, it seems for some species and locations that juvenile kelp do not recruit nor survive (if transplanted) in the absence of adult conspecifics (Layton et al. 2019b).

4.3.2 Interspecific facilitation – Figure 9-2

Facilitation cascades, whereby a habitat-forming species promotes a secondary habitat-former with positive effects on associated biodiversity, occur in almost all marine ecosystems (Thomsen et al. 2018, Gribben et al. 2019). Most studies on facilitation cascades have focused on synergistic effects of positive interactions among habitat-forming species on the overall biodiversity they support. In contrast, few studies have explored how interactions between the habitat-forming species influence their own performance (Bulleri 2009, Gribben et al. 2019), despite such positive interactions being potentially critical for restoring or increasing the resilience of kelp forests.

For instance, in the absence of established kelp beds to facilitate recruitment, other habitat-forming species may be critical recruitment habitats that reduce biotic (e.g. herbivory) or abiotic (e.g. wave action) stress (Bulleri et al. 2011). As an example, recruitment of the habitat-forming fucoid *Scytothalia dorycarpa* is facilitated by the canopy of the kelp *Ecklonia radiata* (Bennett & Wernberg 2014). Interestingly, a similar positive effect is found on recruits of the fucoid *Sargassum* spp., but only under partial *Ecklonia* canopies, whereas dense canopies had a negative effect on recruitment of *Sargassum* (Bennett & Wernberg 2014). This result suggests that we need to better understand the context and species specificities of positive interactions between habitat-forming kelp before they can be incorporated in management interventions to avoid undesired outcomes.

Experimental tests with artificial kelp blades show that the motion or "whiplash" from frond movement can help deter urchin grazing and facilitate the growth of juveniles (Vasquez & McPeak 1998). Though this example used artificial blades, the presence of other kelp species nearby could play a similar role, but further testing is required to determine the efficacy. Some kelp species may be better at deterring grazing through such mechanisms and thus outplanting adults of these species alongside focal restoration species or transplanting the focal species near to extant canopies of the grazing-deterrent species, could enhance effective restoration.

There is also some evidence that habitat-forming species can facilitate other disconnected habitat-formers, that is, facilitation often occurs at larger, seascape scales. For example, in soft-sediment environments, beds of mussels can promote the high abundances of other bivalves by altering hydrodynamic regimes at distances of 100s of metres away from the mussel beds (Gribben et al. 2019). Kelp restoration may only succeed where another habitat-forming species (e.g., another kelp species) that occurs somewhere else in the seascape creates conditions in a way that promotes the focal kelp species' recruitment and growth. It is predicted that these types of interactions will have larger positive seascape-scale effects on habitat-forming species and may thus provide the biggest benefits in ecosystem services and function, but for kelp forests such effects remain unknown. Pragmatically, reinstalling these types of interactions may be more difficult than utilising other habitat-formers to facilitate restoration of a focal kelp species at smaller scales.

Harnessing positive interspecies interactions has the potential to aid kelp restoration efforts. But before managers can achieve this goal, we require a better understanding of how other species enhance kelp populations, under what conditions do positive interactions perform best, and what the consequences for all interacting species are.

4.3.3 Trophic Cascades – Figure 9-3

Trophic cascades where predators impact the health of foundation species are well documented across many marine ecosystems and often positively affect foundation species (Eger & Baum 2020). Tri-trophic cascades in which predators promote foundation species by suppressing populations of their grazers are powerful examples and include blue crabs and fish protecting salt marsh plants (Silliman & Bertness 2002, Altieri et al. 2012) and sharks promoting seagrass growth (Burkholder et al. 2013). Trophic cascades are particularly relevant in the context of kelp restoration as the loss of predators such as sea otters (Estes & Duggins 1995), sea stars (Burt et al. 2018), lobsters (Ling et al. 2009), and predatory fish (Caselle et al. 2018), and later expansion of consumers such as sea urchins, is often linked to the initial loss of the kelp habitat. Therefore, controlling herbivore populations and re-establishing predator populations, along with the kelp, may not only be an additive step to increase the success of kelp restoration but a requisite step, without which long term restoration success may never be possible.

Two interventions that have been successful in elevating predator populations are the establishment of strict harvest limits on predators and the creation of marine protected areas (MPAs). For example, installing limits on predator harvest has resulted in large scale returns of kelp habitat in Alaska, California, British Columbia, and New Zealand (Estes & Duggins 1995, Shears & Babcock 2002, Watson & Estes 2011, Caselle et al. 2018). Marine protected areas are a common marine management tool to help restore animal populations (Boonzaier & Pauly 2016). Since both fisheries limits and MPAs are gaining momentum, used in governmental policy (Watson et al. 2014), and are often politically viable (Jones et al. 2013), these two methods have great promise as key mechanisms to help kelp recovery. To date, however, management of kelp through the management of predators has tended to stop at the predator level (Woodcock et al. 2017). That is, there has been less focus on how the active re-establishment of predators can further increase kelp recovery and resilience. As a result, future MPA designs should consider how their placement can also suit the restoration of primary producers, instead of solely focusing on high trophic levels. For example, restoration efforts can occur within MPAs or managers can space new MPAs to ensure population connectivity among kelp populations (Coleman et al. 2017). Through these planning adjustments, restoration efforts could also benefit from the increased predator populations.

Often, the restriction or elimination of a harvest pressure is not enough to allow for the return of predators, and in turn, kelp. For example, after the end of the fur trade, and following legal protection as an endangered species, sea otters (*Enhydra lutris*) failed to return to parts of their previous range. To resolve this problem, managers translocated otters and reintroduced into parts of the USA and Canada (Bodkin 2015). Though these efforts were costly, difficult, and resulted in significant otter mortality (VanBlaricom et al. 2015), they have been successful at restoring kelp beds at large scales and maintaining those restored populations (Filbee-Dexter & Scheibling 2014). To date, no captive breeding program exists for restoration purposes (VanBlaricom et al. 2015) and if otters require introduction, scientists instead advocate for additional otter translocations to help connect the populations and restore kelp ecosystems (Davis et al. 2019). Despite their success, translocating otters, as with other predators (Hayward & Somers 2009), can be contentious because they are very likely to interact with humans, eat recreationally and commercially harvested species, and opportunities for development can disappear because of their endangered status and legal protection (Booth 1988). Additionally, otters can sometimes avoid using urchin barrens as feeding grounds because urchin barrens contain nutritionally poor urchins, and instead hunt in nearby kelp forests, which defeats the purpose of their reintroduction (Hohman et al.

2019). Thus, introduced otters may be most effective at maintaining kelp forests rather than promoting their recovery. As a result, managers are currently hesitant to introduce more otter populations in the Eastern Pacific (Hohman et al. 2019). Potentially, the restoration of a diversity of predators may be needed to control herbivore populations (Katano et al. 2015) and other species could be introduced alongside or in place of otters.

Artificial stock enhancements of marine fishes and invertebrates, often for harvest, have been successful in augmenting the wild populations of many species worldwide (Bell et al. 2008, Lorenzen et al. 2010). As a result, programs focused on other species that consume urchins may prove to be a more cost-effective and politically tenable alternative or supplement to sea otter introduction. In areas such as Tasmania, Australia, where overharvest of the Southern Rock Lobster (*Jasus edwardsii)* has contributed to increases in urchin populations and declines in canopy-forming algae (Ling et al. 2009), managers could release cultured *J. edwardsii* into the environment. Although, in some situations lobsters alone are unlikely to restore kelp forests (Layton C, Johnson C, personal communication), they can complement other restorative actions and aid in conserving extant kelp forests. While *J. edwardsii* is not currently used to restore kelp populations, researchers are successful culturing the species (Hooker et al. 1997, Ritar 2001, Kittaka et al. 2005) and managers could redirect this practice to a restoration focus. Similar species such as the Eastern rock lobster (*Sagmariasus verreauxi*), a key predator of *Centrostephanus rodgersii*, are also cultivable (Jensen et al. 2013) and are candidates for wild enhancement programs.

Other species which are not as developed from an aquaculture standpoint, but that also positively affect kelp ecosystems are the predatory crabs (red king crab, *Paralithodes camtchaticus* and brown crab *Cancer pagurus*) in Norway (Christie et al. 2019), the California sheephead (*Semicossyphus pulcher*) in the Eastern Pacific (Caselle et al. 2018), and sea stars, such as the carnivorous *Pycnopodia spp.* along the Pacific Coast of North America (Burt et al. 2018). Little work has assessed the feasibility of culturing these species, but preliminary results on other analogous species suggest that it could be feasible (Stevens 2006, Brooker et al. 2018). For example, large scale cultures of *P. camtchaticus* supplement wild fishery populations (Epelbaum et al. 2006, Daly et al. 2009) and maybe adjusted for restoration purposes. The California sheephead is a popular target of sports fishers in California and preliminary work shows they can spawn in captivity (Jirsa et al. 2007), though their social structure, feeding requirements, and hermaphroditism make them difficult to culture and further efforts by the "Hubbs-Seaworld Research Institute and the Ocean Resources Enhancement and Hatchery Program" in California, USA are no longer under investigation (Stuart, Pers. Comm, 2019). Following the sea star wasting syndrome die off in the Eastern Pacific (Eisenlord et al. 2016), scientists at the University of Washington and The Nature Conservancy California are beginning to experiment with culturing wild sea stars *Pyncnopodia spp,* spawning them, and raising the juveniles to maturity, and determining their impact in the ecosystem. If the trials are successful, they plan to scale up the results, incorporate genetic diversity into the breeding program, and work to develop a recovery plan for the species (Eddy, Pers. Comm. 2020).

The restoration of an ecosystem through restored trophic interactions has been and will continue to be the subject of much debate (Seddon et al. 2007, Lorimer et al. 2015, Svenning et al. 2016). As this conversation continues, any attempt at restoring kelp forests in parallel with one of the prior mentioned species must consider: the ecosystem effects of that species, the genetic diversity of the introduced population, potential disease transmission, actual and opportunity costs, and public perception, and will for reintroduction along with other societal issues. Other authors (McCoy & Berry 2008, Lorenzen et al. 2010) consider these barriers elsewhere, but this is beyond the scope of our review.

As oceans continue to warm, species ranges and territories will change, and new trophic interactions will form. For example, the Tropical Rock Lobster (*Panulirus ornatus*) is currently mass cultured for commercial sale (Petersen & Phuong 2010) but the species is currently restricted from most of South Australia by temperature. As oceans get warmer, there may be the opportunity to introduce *P. ornatus* into these now habitable areas to help control urchin populations. Such considerations and novel interactions may become important in any attempt to assist in future kelp restoration efforts (Wood et al. 2019).

4.3.4 Genetics in Kelp Restoration – Figure 9-4

Over the past few decades, it has become clear that genetics is an influential component of an individual's, population's, or wider ecosystem's health. For example, genetic diversity and provenance can affect establishment rates and population fitness in many plants and animals (Hughes & Stachowicz 2004, Forsman & Wennersten 2016). Restoration efforts can thus benefit by incorporating the mechanisms responsible for these positive health effects (McDonald et al. 2016, Gann et al. 2019). The positive population and ecosystem effects from enhanced genetic diversity may be achieved through the restoration of diverse genotypes or individuals (Gann et al. 2019). The case is particularly strong for foundation species, where enhanced genetic diversity has benefitted not only the target species but also other components of the ecosystem, such as primary productivity and rates of decay and flux of nutrients (Whitham et al. 2006, Hughes et al. 2008, Reynolds et al. 2012, Kettenring et al. 2014).

Although genetic approaches are only now considered in the context of kelp restoration (Coleman & Goold 2019), the kelp aquaculture industry uses analogous techniques. For example, phycologists in the industry have used chimeras in *Laminaria sp*. populations to insert traits for increased tolerance to irradiance, seawater temperatures, and tissue rot (Li et al. 2007, 2008, Robinson et al. 2013). Strain selection and manipulation is also common in aquaculture of the alga *Saccharina*, *Undaria*, and *Porphyra*, with manipulations aiming to increase yield and flavour (Wu & Guangheng 1987, Dai et al. 1993, Liu et al. 2006, Bast 2014). Further work to increase the genetic heterogeneity of seaweeds may potentially allow for increased resistance to abiotic stressors (Medina et al. 2015) and may also confer adaptive capacity to climate stress (Wernberg et al. 2018).

The selection of donor biological material (reproductive tissue, individuals, populations) that contain desirable traits such as tolerance to thermal stress may also be necessary to future-proof populations (Wood et al. 2019). This process might involve sourcing biological material for restoration from warm-adapted populations, breeding under specific conditions designed to achieve "super strains" or even implementing synthetic biology techniques, e.g. using CRISPR-Cas9 genome editing tool to edit the genomes of kelp species to bring out desirable traits (Coleman & Goold 2019, Wood et al. 2019). Such future-proofing concepts are in development for terrestrial (Aitken & Whitlock 2013) and coral reef systems (van Oppen et al. 2015), and are being explored in the context of seaweed restoration as well (Wood et al. 2019).

While the explicit incorporation of genetics in marine restoration is rare (Mijangos et al. 2015), the techniques exist in industry (Robinson et al. 2013) which when coupled with the advancement of other genetic and genomic tools, e.g. rapid DNA sequencing technologies, can enable scientists to understand how to further advance restoration (Mijangos et al. 2015, Wood et al. 2019). For example, (Wood et al. 2020) recently demonstrated that genetic diversity and structure of restored *Phyllospora comosa* (order Fucales) populations mimicked that of a mixture of local extant populations and this provides a platform to effectively "design" populations of this species as desired. While the application of seaweed genetic diversity in a restoration/management context requires further research, there is encouraging evidence for its future application to seaweed restoration programs.

Manipulating the genetic composition of a kelp species or releasing genetically modified kelp into wild populations bears considerable ethical considerations (Corlett 2016). Managers must consider how the local gene pool may be affected, how the new species or species type will interact with the environment, and the societal acceptance of these actions (Wood et al. 2019). It is important the managers consult local communities when making these decisions, run phased introductions to evaluate the impacts, and generally take the precautionary approach with any of these manipulations.

4.3.5 Microbial interactions and kelp restoration – Figure 9-5

Another aspect that may enhance effective restoration and management is the incorporation of kelp-microbiome interactions. Evidence from multiple systems suggests that microorganisms play fundamental roles in the life and performance of their eukaryotic hosts (McFall-Ngai et al. 2013). This knowledge has led to the proposal of the "holobiont" concept (Margulis & Fester 1991), which argues that 'macrobial' hosts and their associated microbiota form a coherent biological entity and we need to considered them together to understand the biology and ecology of hosts (McFall-Ngai et al. 2013). In marine systems, this concept was first applied to reef-forming corals (Rohwer et al. 2002), but recent work highlights its applicability to other marine macroorganisms, including seaweeds (Egan et al. 2013). For instance, surface-associated microorganisms can influence the development, growth, photosynthesis, and reproduction of seaweeds (see review by Egan et al., 2013), and recent work suggests that microbes may even influence interactions between seaweeds and other macroorganisms such as grazers and epiphytes (Campbell et al. 2014b, Marzinelli et al. 2018).

Most studies of kelp-associated microorganisms are, however, descriptive, showing relationships between environmental conditions and/or kelp performance and condition, and the structure of the associated microbiota (Lachnit et al. 2011). Often, the focus is on the negative effects of microbes on kelp (Marzinelli et al. 2015), e.g. via disease or dysbiosis (Egan et al. 2013). For example, changes in abundances of several bacterial taxa (Marzinelli et al. 2015) can cause a bleaching disease of the Australian kelp *Ecklonia radiata*, and experiments manipulating warming and acidification show that future environmental conditions are likely to exacerbate this (Qiu et al. 2019). Some studies have gone beyond establishing relationships to show causation in seaweed systems via isolation and subsequent experimental inoculation of target microorganisms (Case et al. 2011, Kumar et al. 2016). Despite the focus on negative/harmful interactions, experimental inoculations and similar experimental approaches (e.g. via selective removal of microbial taxa, Singh and Reddy, 2014) are potential techniques to determine positive interactions and isolate microbial taxa that may enhance kelp performance and/or confer resistance or resilience to future environmental conditions (see Rosado et al., 2019 for corals). Microbial communities associated with macroorganisms in marine systems are a “soup” of microbes and this presents manipulation challenges. However, recent work in corals has demonstrated that coral-associated microbiomes are influenceable and can develop in distinct directions following inoculations at early larval stages in experimental conditions (Damjanovic et al. 2017). Thus, focusing microbially guided restoration efforts on early life stages may enhance the feasibility of using such solutions in seaweed systems, either to enhance recruitment or growth, or resilience to abiotic (e.g., temperature) or biotic (e.g. grazing, fouling) stressors. For example, managers could grow kelp zygotes or recruits in the lab and inoculate them with specific taxa until they achieve a desired microbial community and then outplant them as normal.

Finally, host genetics can influence associated microbial communities (Org et al. 2016). Understanding the relative importance of host characteristics versus the environment in shaping the kelp microbiota is critical, as this may have implications on how we design restoration and/or future-proofing programs (Wood et al. 2019). If the environment influences microbial communities or important taxa, attempts to harness microbial interactions to improve restoration or future-proofing outcomes may fail as local microbial taxa swamp the microbial communities (but see Campbell et al., 2015). Alternately, if host specific traits influence microbial communities, harnessing positive microbial interactions may be as simple as including genotypes (or phenotypes) with beneficial microbiota. Another approach could be to tailor microbial manipulations to specific host types, as is in human medicine (Benson et al. 2010, Bonder et al. 2016).

4.3.6 Anthropogenic Synergies – Figure 9-6

It is likely that kelp forest restoration can receive ecological and environmental benefits from kelp aquaculture and marine harvest efforts. The impact of cultivated populations of kelp as concentrated sources of spores seems particularly promising, especially given that extensive localized losses of kelp in some areas combined with short dispersal distances and Allee effects can slow natural recovery of kelp populations. But these applications require suitable local substratum and may not be feasible everywhere. The aquaculture of kelp also has direct economic outputs, and this may help incentivize and contribute to the funding of local ‘restoration economies’ (BenDor et al. 2015). Kelp aquaculture would also help to ease pressure on kelp forests (restored or otherwise) that may be the target for wild harvest operations. In addition, kelp cultivation may also be a cost-effective method of trialling whether an area is suitable for kelp growth and re-establishment, especially where local conditions have improved/degraded relative to the established trend.

Another innovative solution is the removal of sea urchins by divers who then sell them as a food product, known as *uni* in Japanese restaurants (Hohman et al. 2019, Sea Urchin Harvest 2020). In many instances, however, the edible part of the urchin (the roe) is of poor quality due to limited food availability in the urchin barren (Claisse et al. 2013). Companies are working to solve this problem by establishing land-based aquaculture facilities that take urchins collected from barrens, feed them an adequate diet, improve the quality of the gonads, and then sell the urchins on the market (Urchinomics 2020). As conservation considers market-based solutions (Huwyler et al. 2016), this approach to kelp restoration holds significant promise and may be especially useful in areas where predators are unable to revert urchin barrens from an alternate stable state while also creating jobs and contributing to local economies.

Kelp forests are especially efficient nutrient cyclers and are thus recognized as sustainable and positive solutions to nutrient loading in aquaculture farms (Chopin et al. 2001, Stévant et al. 2017). While kelp forests do not directly benefit from this relationship (unless nutrient-limited), their services could motivate aquaculture facilities to restore kelp forests next to their operations, thus helping reduce the financial load on other organizations. While these solutions will not be applicable in all circumstances, these practices contribute to the broader idea behind ‘restorative aquaculture’ (Theuerkauf et al. 2019) and might provide a beneficial accompaniment to restoration activities.

4.3.7 Incorporation of positive interactions in kelp forest restoration

As managers continue to work to restore kelp forests, they will need to consider novel and adaptive approaches in a bid to achieve success while also crafting cost-efficient solutions. We posit that incorporating facilitative interactions and other synergies into traditional forms of restoration can help achieve these two purposes. Many of the solutions described above, need little to no further research to inform new restoration projects. To take advantage of intraspecific processes, managers can pair juvenile and adult outplants or combine adult transplants with seeding efforts. We also suggest that future restoration locations be closely spaced to each other or in close vicinity to extant kelp beds. Or, if kelp beds are declining but have not yet disappeared, restoration efforts can instead focus on augmenting existing beds and eliminating the need for future restoration. Depending on the species involved, managers could look for algal species, or genotypes, that promote each other and look to outplant polycultures instead of monocultures. Managers can further consider the benefits of restoring additional elements of the ecosystem in addition to the kelp itself. For example, where urchins are a problem, restoring species like otters, lobsters, crabs, or sea stars incurs a high upfront cost but can likely offset the cost of continual, manual urchin removal in the long term. Additionally, by adopting this approach to restoration, we are advancing the establishment of ecosystem functions beyond those provided by foundation species, an implicit goal in most all ecosystem restoration projects. Kelp and aquaculture farms also provide exploitable synergies to not only restore ecosystems but provide profits for their operators. Working to situate kelp farms near restoration sites can help seed barren grounds and once populations have become established, the kelp itself can work to offset nutrient pollution from aquaculture farms. It is also possible that kelp restoration could be profitable with new companies looking to remove, culture, and sell the urchins from barrens, thus letting the kelp regrow. Future permitting could be contingent on the company adopting best ecosystem practices and restorative aquaculture certifications can incentivize companies to restore kelp forests as part of their business.

Other approaches, namely incorporating genetic adaptation, interactions between specific genotypes and beneficial microbes are not as established, but steady progress is being made on understanding how future efforts can use these approaches. Because these approaches will initially be more costly than traditional restoration, it will be important to consider the added benefits of incorporating them into restoration practices. While this analysis is not completed, it is possible that with rapidly shifting environmental conditions, microbial and genetic approaches will be requisites to future restoration operations.

Managers can start integrating these interactions into restoration during the planning process, first by describing the known or plausible interactions in their system, determining which ones are feasibly included, experimentally testing them at small scales and then putting them into practice. As with any new conservation or restoration intervention, it is vital that we pair these approaches with adequate monitoring programs to evaluate them against goal-dependent performance criteria (Basconi et al. 2020, Eger et al. 2020b), and work to determine the marginal gains in success and the associated costs.

More generally speaking, kelp restoration efforts would benefit from positive remediation of the environment and other preventative conservation measures. For example, a decrease in land-based nutrient inputs that benefits turf algae or a decrease in sediment deposited in coastal ecosystems which interferes with the recruitment of kelp populations. As alluded to the positive species interactions section, it may indeed be most effective to restore kelp populations on the periphery of existing natural populations. Therefore, any efforts to conserve extant kelp populations may indeed be facilitating future restoration efforts. These efforts are also tied to improvements in water quality but also related to the destruction of rocky reef habitat, overfishing, overharvesting, or introduced species (Wernberg et al. 2019).

While we document the reported positive interactions that are feasibly useable to enhance kelp restoration, there are several other interactions from marine ecosystems that are not yet described. For instance, facilitation cascades (a set of positive species interactions) are well described and hypothesized to apply to saltmarsh and coral restoration, but we are unaware of applicable analogs in kelp restoration. Further, as kelp species are typically limited dispersers, any interaction that worked to enhance the dispersal range of kelp forests would be a great aid to restoration efforts as established, restored populations could act as a source population for other areas. Even among the topics included in our review there is very little empirical evidence for most subjects. Of the 54 papers found in our literature search, over half were about trophic cascades and no other topic had more than 5 papers on that subject. Both the topics included and excluded from this literature review require additional research.

The importance of these positive interactions should increase with additional anthropogenic stressors related to coastal development in climate change. Unfortunately, there is little empirical evidence, and these remain theoretical improvements to restoration. Therefore, we encourage scientists and managers not only to attempt to incorporate these approaches into their projects but work to test their efficacy and allow for restoration to act as both an experiment and a conservation outcome. By doing so, we can quickly and efficiently work to determine how to best restore our underwater forests in the face of mounting pressures.

4.4 Acknowledgments

The vector graphics were adapted from The Integration and Application Network, University of Maryland Centre for Environmental Science (http://ian.umces.edu/imagelibrary/).

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4.6 Appendix

Table 1 Overview of the topics selected by the literature review and expert opinion process.

Reference	Interaction
Andrew, N. L., & Viejo, R. M. (1998). Effects of wave exposure and intraspecific density on the growth and survivorship of Sargassum muticum (Sargassaceae: Phaeophyta). European Journal of Phycology, 33(3), 251-258. doi:10.1017/S0967026298001735	Intraspecific
Barner, A. K., Hacker, S. D., Menge, B. A., & Nielsen, K. J. (2016). The complex net effect of reciprocal interactions and recruitment facilitation maintains an intertidal kelp community. Journal of Ecology, 104(1), 33-43. doi:10.1111/1365-2745.12495	Interspecific foundation
Bell, J. E., Bishop, M. J., Taylor, R. B., & Williamson, J. E. (2014). Facilitation cascade maintains a kelp community. Marine Ecology Progress Series, 501, 1-10. doi:10.3354/meps10727	Facilitation cascade
Bracken, M. E. S. (2018). When one foundation species supports another: Tubeworms facilitate an extensive kelp bed in a soft-sediment habitat. Ecosphere, 9(9). doi:10.1002/ecs2.2429	Increased settlement
Bulleri, F. (2013). Grazing by sea urchins at the margins of barren patches on Mediterranean rocky reefs. Marine Biology, 160(9), 2493-2501. doi:10.1007/s00227-013-2244-2	Consumer competition
Burt, J. M., Tim Tinker, M., Okamoto, D. K., Demes, K. W., Holmes, K., & Salomon, A. K. (2018). Sudden collapse of a mesopredator reveals its complementary role in mediating rocky reef regime shifts. Proceedings of the Royal Society B: Biological Sciences, 285(1883). doi:10.1098/rspb.2018.0553	Indirect trophic effects (e.g. trophic cascades)
Carney, L. T., & Edwards, M. S. (2010). Role of nutrient fluctuations and delayed development in gametophyte reproduction by Macrocystis pyrifera (phaeophyceae) in Southern California. Journal of Phycology, 46(5), 987-996. doi:10.1111/j.1529-8817.2010.00882.x	Anthropogenic synergy
Dunstan, P. K., & Johnson, C. R. (2007). Mechanisms of invasions: Can the recipient community influence invasion rates? Botanica Marina, 50(5-6), 361-372. doi:10.1515/BOT.2007.041	Invasion resistance
López, B. A., Macaya, E. C., Jeldres, R., Valdivia, N., Bonta, C. C., Tala, F., & Thiel, M. (2019). Spatio-temporal variability of strandings of the southern bull kelp Durvillaea antarctica (Fucales, Phaeophyceae) on beaches along the coast of Chile—linked to local storms. Journal of Applied Phycology, 31(3), 2159-2173. doi:10.1007/s10811-018-1705-x	Dispersal
Segovia, N. I., Vásquez, J. A., Faugeron, S., & Haye, P. A. (2015). On the advantage of sharing a holdfast: Effects of density and occurrence of kin aggregation in the kelp Lessonia berteroana. Marine Ecology, 36(4), 1107-1117. doi:10.1111/maec.12206	Genetic component
Suggested	Microbial
	Competitor reduction
	Hypothesized interactions based on other systems
	Cross ecosystem

Table 2 Results of the topic selection process, each author was given 9 votes and we considered topics with 3 or more votes (highlighted in blue).

9 votes per author	Authors						Votes	Examples
Categories								
Intraspecific	1	1	1	1	1	1	6	Positive density dependence
Interspecific foundation	1	1	1	1	1	1	6	Positive species richness effect
Facilitation cascade	1	1	1	1	1	1	6	Ecklonia, urchin, and gastropod, all + links
Indirect trophic (cascades)	1	1	1	1	1	1	6	Otter-urchin-kelp
Hypothesized interactions based on other systems	1	1	1	1	1	1	6	Hypothesized interactions based on other systems
Anthropogenic synergy	1		1	1	1	1	5	Growing kelp near high nutrient input
Microbial	1	1	1	1		1	5	Microbe community facilitates growth/resistance/survival, etc
Genetic component	1		1	1	1		4	Genetic diversity promotes growth/resistance/survival etc
Settlement		1		1		1	3	Tubeworms create substrate for settling
Consumer competition		1			1		2	Non kelp grazing urchin competes for space with a kelp grazing urchin
Competitor reduction					1	1	2	Species X grazes preferentially on a kelp competitor (e.g. turf)
Dispersal/connectivity		1					1	Species X spreads kelp spores
Cross ecosystem							0	Sargassum, mussels, and mangroves
Invasion resistance							0	High diversity kelp communities resist invasion better than low diversity species

Chapter 5 - The value of fisheries, blue carbon, and nutrient cycling ecosystem services in global marine kelp forests

Link to thesis

Ecosystem restoration is a value laden decision, society only performs restoration because there is the perception that it will be beneficial to society or the natural world. None of the restoration works outlined in **Chapters 2**, **3**, or **4** are possible if society does not choose to do the restoration. While there is a strong ethical argument for protecting and enhancing the natural world based on its intrinsic value and right to exist outside of human society, decisions about restoration are often based on the perceived benefits for humans. I wrote **Chapter 5** to inform this perspective and in it, I seek to quantify the ecological and economic benefits that kelp forests provide to society. The work does not intend to wholly commodify the unique interconnected existence that is a kelp forest but rather highlight the benefits and encourage greater recognition of those benefits.

This work is now in the 3rd round of review with Nat Comms: **Eger AM**, Marzinelli E, Baes R, Blain C, Blamey L, Carnell P, Choi CG, Hessing-Lewis M, Kim KY, Lorda J, Moore PJ, Nakamura Y, Perez-Matus A, Pontier O, Smale DA, Steinberg PD, Verges A. The value of fisheries, blue carbon, and nutrient cycling ecosystem services in global marine kelp forests.

Abstract

While marine kelp forests have provided valuable ecosystem services for millennia, the global ecological and economic value of those services is largely unresolved. Kelp forests are diminishing in many regions worldwide, and efforts to manage these ecosystems are hindered without accurate estimates of the value of the services that kelp forests provide to human societies. We present the first global estimate of the ecological and economic potential of

three key ecosystem services - fisheries production, nutrient cycling, and carbon removal provided by six major forest forming kelp genera (*Ecklonia*, *Laminaria*, *Lessonia*, *Macrocystis*, *Nereocystis*, and *Saccharina*). Each of these genera creates a potential value of between $79,400 and $150,800/hectare each year. Collectively, they generate between $479 and $602 billion/year worldwide, with an average of $523 billion. These values are primarily driven by fisheries production (mean $35,222 & 904 kg/ha/year) and nitrogen removal ($73,831 & 621 kg N/ha/year), though kelp forests are also estimated to sequester 4.91 million tons of carbon from the atmosphere/year highlighting their potential as blue carbon systems for climate change mitigation. These findings highlight the ecological and economic value of kelp forests to society and will facilitate better informed marine management and conservation decisions.

5.1 Introduction

"*The number of living creatures of all Orders, whose existence intimately depends on the kelp is wonderful.*" – Charles Darwin 1845

Vast underwater forests of kelp (defined here as brown macroalgae in the order Laminariales) along polar to subtropical coastlines have enormous value to peoples across multiple continents and eras. Archaeological excavations show how kelp forests facilitated southward travel for early peoples in the Americas some 20,000 years ago. During this migration, people relied on the food provided by kelp forests to survive (Erlandson et al. 2007). Subsequently, ecological management of kelp forests has occurred since approximately 3,000 BCE in the NE Pacific, with peoples regulating harvest and transplanting kelp to enhance growth and trap fish roe (Thornton 2015). In the NW Pacific, kelp harvesting has played an important role in Japanese, Korean, and Chinese economies since the 8th century, where it is eaten as food and supports a myriad of associated plants and animals, many of which are also harvested. In Europe, kelp has been used for many centuries to fertilize soil and increase crop yields, treat illnesses caused by iodine deficiency and, for many centuries, as the base in the production of soda ash (Kain & Dawes 1987). In the 20th and 21st centuries kelp forests have become the main source of alginate (also known as algin from alginate-yielding seaweeds), a common food, medical and bioengineering additive (Peteiro 2018). Globally, kelp forests provide habitat for important fisheries of abalone, lobsters, reef fishes, and kelp itself (Steneck et al. 2002). Additionally, through their high productivity, kelp forests draw carbon from the atmosphere (Filbee-Dexter & Wernberg 2020), release oxygen (Hatcher et al. 1977), and help reduce marine nutrient pollution (Kim et al. 2015). Long before Charles Darwin wrote his essay on the Patagonian kelp forests, these habitats provided essential services for human society that continue to this day.

The fact that kelp forests have cultural and socioeconomic importance is not disputed, but the magnitude and economic values of these ecosystems are poorly understood (Smale et al. 2013, Vasquez et al. 2014, Thurstan et al. 2018). Relevant research on kelp forests to date has generally grouped kelp with other marine habitats as “coastal systems” (Costanza et al. 2014), treated values from limited genera as representative of not just kelps but all macroalgae (Krause-Jensen & Duarte 2016), or has not assigned a monetary value to the services provided (Bertocci et al. 2015). This knowledge gap leads to an underappreciation of their contribution to nature and people. Since both the economic value of ecosystems and the recognition of their ecological and cultural importance are increasingly major considerations for conservation and natural resource management, the lack of value estimates for kelp ecosystems is a barrier to effective management and policy (Carpenter et al. 2009).

For example, societies are increasingly considering active kelp forest restoration and management strategies to combat regional declines in kelp forests (Morris et al. 2020, Eger et al. 2022). However, restoration may not be pursued if the costs outweigh the perceived benefits (Grabowski et al. 2012). Furthermore, while kelp forests are valued to some degree by ocean users (Grover et al. 2021, Hynes et al. 2021), they are not perceived to be high-value ecosystems to the public (Bennett et al. 2016, Coleman & Wernberg 2017), which can limit public support for kelp conservation and restoration (Kareiva & Marvier 2007, Pearson 2016). Moreover, quantifying and valuing services provided by marine ecosystems is an important goal in the context of the UN Decade of Ocean Sciences, achieving the UN Sustainable Development Goals, growing the field of ocean accounting, and cost-benefit analyses (United Nations 2014, Global Ocean Accounts Partnership 2019, The World Bank 2019).

Regional economic valuations of kelp forests which have incorporated various ecosystem services (e.g., harvest, fisheries, and tourism) have estimated regional kelp forests to be worth between $290 million (e.g. *Ecklonia* and *Laminaria* forests in South Africa) (Blamey & Bolton 2018) and $540 million USD per year (e.g. *Lessonia* and *Macrocystis* forests in Central-Northern Chile) (Vasquez et al. 2014). In Australia, Bennett et al. (2016), valued the ~71, 000 km^2 of 'The Great Southern Reef', including the lobster and abalone fisheries largely supported by *Ecklonia* habitat, at ~ $7.3 billion USD per year; though this value included all marine habitats, not only kelp. However, the above estimates were not standardized per area and did not directly link fisheries production within kelp forests to their final value. Consequently, there are currently no quantitative estimates of the area-adjusted economic value of major kelp genera worldwide.

Here we analyse three ecologically and economically important ecosystem services provided by six dominant kelp genera across the world: *Ecklonia, Lessonia, Laminaria* (now *Saccharina* in some regions), *Macrocystis,* and *Nereocystis*. While the order Laminariales comprises 33 genera (Bolton 2010), many of which provide similar ecosystem functions, we focused on kelp genera with the most widespread abundance and distributions and those with the highest regional socio-ecological importance (e.g., dominant habitat formers with important associated fisheries) (Wernberg et al. 2019b). These genera are distributed across the Northern and Southern Pacific, Northern and Southern Atlantic, and parts of the Arctic and Southern Oceans, and encompass most of the global kelp distribution (Wernberg et al. 2019b). Within these genera we analysed three services that had market values reported: fisheries (i.e., secondary) production, carbon sequestration, and nutrient cycling, which past studies suggest are the most valuable market services provided by kelp forests (Vasquez et al. 2014, Bennett et al. 2016, Blamey & Bolton 2018).

We first detailed the extent of the biophysical services generated and then assigned open market values (the price an asset would fetch in a marketplace, converted to international dollars 2020) to each service (see methods & Figure 14). We then generated a range of biophysical and potential economic values provided by each genus across regions, per unit of area, per year (see methods, Figure 14). As a result, our work describes the capacity of global kelp forests' to supply ecosystem services (Hein et al. 2016). This capacity is the potential economic value (herein value) as opposed to the realized value. Like previous authors who have adopted this approach for valuing natural systems (de Groot et al. 2012, Kubiszewski et al. 2013, Buonocore et al. 2020), we focus on potential value because, though it generates a higher estimate of economic value than realised value (Costanza et al. 2017), it creates an inventory of resources (Vo et al. 2012), highlights potential future value (Knox-Hayes 2015), can identify areas for protection and management (Spake et al. 2019), and generates awareness about the socio-economic importance of an ecosystem (Guerry et al. 2015). Our analysis provides the first global quantification of the core ecological services provided by kelp forests as well as the first global economic assessment of those services.

5.2 Results

We included 1354 fish and-or invertebrate surveys at distinct times and locations across the six different kelp genera in eight different ocean regions (North-East Pacific, North-West Pacific, South-West Pacific, South-East Pacific, North-West Atlantic, North-East Atlantic, South Atlantic and Southern Ocean).

We also collected 74 measures of net primary production (NPP), 23 measures of carbon composition, 29 measures of nitrogen composition, and eight measures of phosphorus composition. These values were collected from the eight ocean regions, though sample size varied among regions (Appendix 3.1).

5.2.1 Fisheries production economic value

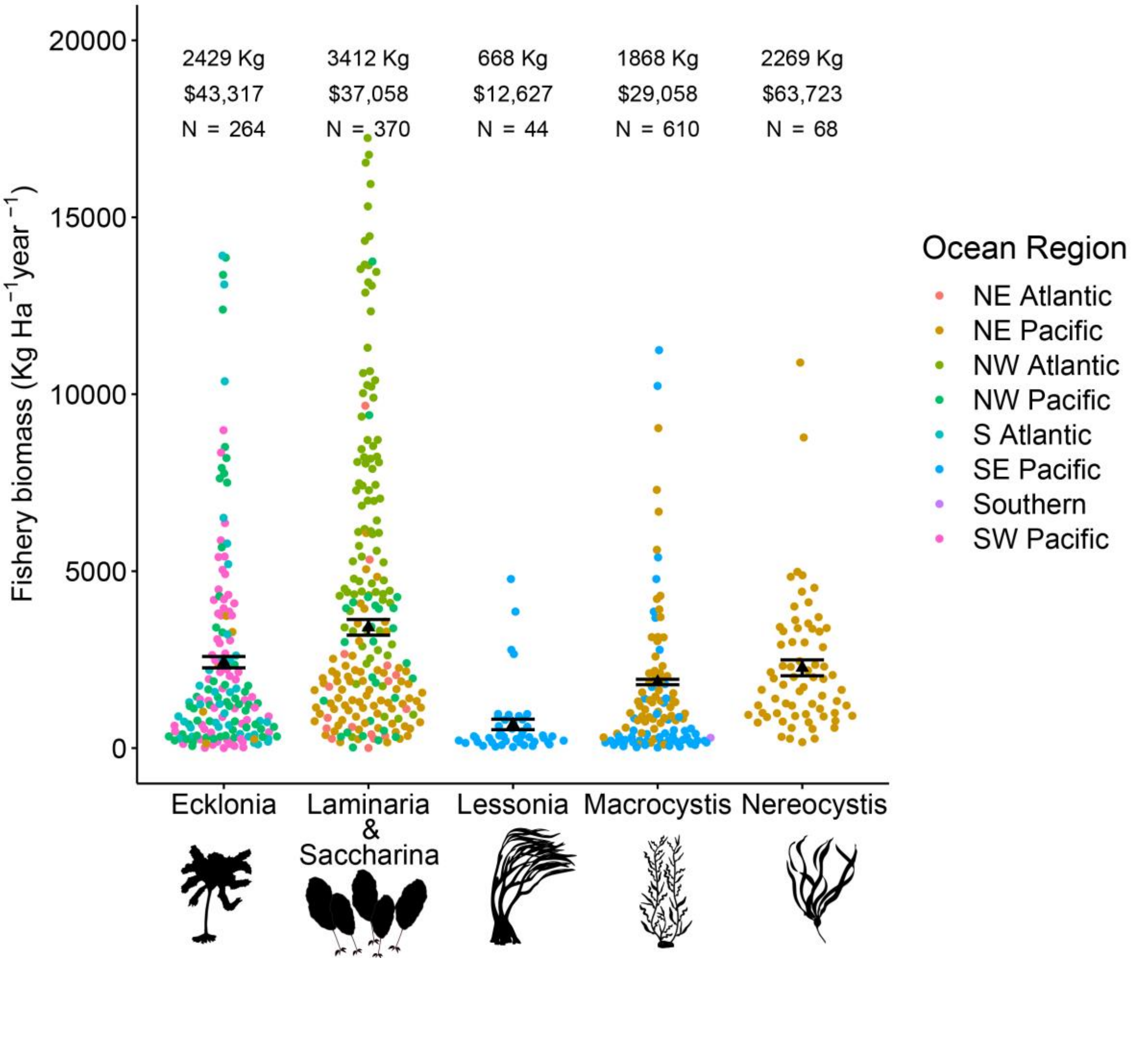

Figure 10 Site (unique time and location) yearly total biomass and the economic value of the harvestable fisheries production per ha per year. The values are presented for each kelp genus, colours represent the ocean region, the black triangle and number are the mean values.

We found substantial variation in the fisheries values between the different genera and within genera by region (Figure 10). Further, the economic value of the fisheries depended on the harvest rate. To obtain a range of values, we varied extractions rates between 20 and 70% (Sparholt et al. 2019, Fisheries Research and Development Corporation 2021), while using an average value of 38% (Sparholt et al. 2019). The lowest mean annual fisheries production rate was 111 kg/ha/year ($2,341/ha/year), for *Macrocystis* in the Southern Ocean, the highest mean biomass value was 3,187 kg/ha/year ($38,244/ha/year) for *Laminaria*/*Saccharina* in the Northwest Atlantic, while the highest economic value was for *Ecklonia* forests in the Northwest Pacific ($74,590/ha/year). Using our selected harvest ranges, 20 and 70%, the range of economic values, expressed as per ha per year, were *Ecklonia* ($22,800 – $79,800), *Laminaria/Saccharina* ($19,500 – $68,300), *Lessonia* ($6,650 – $23,300), *Macrocystis* ($15,300 – $53,500), and *Nereocystis* ($33,500) (Appendix 3.2). Using a 38% harvesting rate, the economic values across ocean regions were: *Ecklonia* – 923 kg ($43,317), *Laminaria/Saccharina* – 1,296 kg ($37,058), *Lessonia* – 254 kg ($12,627), *Macrocystis* – 710 kg ($29,058), and *Nereocystis* – 862 kg ($63,723) (Figure 10, Appendix 3.3).

A relatively small number of genera comprised the bulk of the fisheries value at our sites. Indeed, only 57 genera from a total of 193 contributed more than an average of 10% of a site's economic fisheries production and 83 genera contributed more than 5%. On average, the most valuable genera were invertebrate species. These included lobsters (*Panulirus, Jasus, Hommarus*), abalone (*Haliotis*), false abalone "loco" (*Concholepas),* urchins (*Centrostephanus, Heliocidaris, Diadema, Strongylocentrotus, Loxechinus*), and crabs (*Necora, Cancer)* (Figure 11). The most valuable reef and finfishes were pollack

(*Pollachinus*), giant seabass (*Stereolepis*), South American morwongs (*Chirodactylus)*, and lingcod (*Ophiodon*).

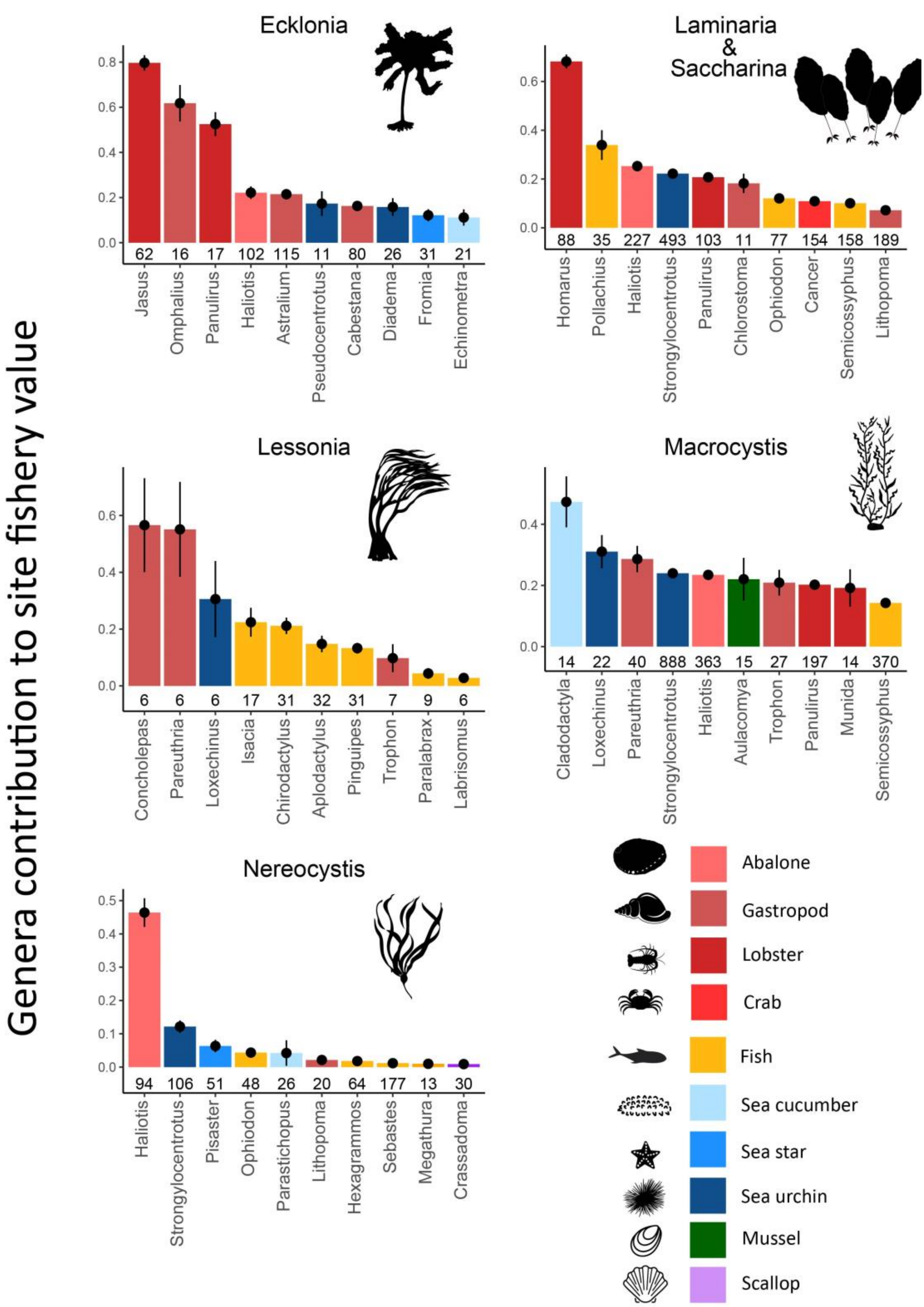

Figure 11 The mean proportion each genus contributed to a site's overall fisheries value per year, the lines represent plus and minus one standard error. Values below the bars represent the number of surveys a genus appeared in, only genera that appeared in more than 10 surveys are represented (more than 5 for Lessonia due to fewer surveys).

5.2.2 Nutrient cycling and carbon sequestration values

Bioremediation and carbon sequestration by kelp forests also provided substantial ecological benefits and economic value. The mean dollar value per ha per year for the sequestration and cycling of carbon, nitrogen, and phosphorus is $36,109 for *Ecklonia*, $113,681 for *Laminaria/Saccharina*, $83,799 for *Lessonia*, $72,020 for *Macrocystis*, and $79,956 for *Nereocystis* (Figure 12 split by ocean region). Of the three elements, nitrogen cycling provided the highest economic value per ha per year (mean = $73,831 & 620 kg), followed by phosphorus cycling (mean = $4,075 & 59 kg), and lastly carbon sequestration, valued using the Social Cost of Carbon (mean = $163 & 720 kg).

Carbon sequestration rates (see Methods) across genera and region varied by nearly an order of magnitude. Assuming 10% of annual NPP is sequestered in the deep sea, the minimum regional average of carbon sequestration per m^2 per year was 31 g (*Ecklonia* in the South Atlantic) while the maximum was 214 g (*Macrocystis* in the Southern Ocean). Across genera, the average value (g/m^2/year) per genus was 75 (*Ecklonia*), 109 (*Laminaria/Saccharina*), 151 (*Lessonia)*, 101 (*Macrocystis*), 82 (*Nereocystis*). These values are dependent on the amount of NPP sequestered. If we assume a range of 1 and 20% of NPP sequestered (Krause-Jensen & Duarte 2016), these values (g/m^2/year) range from 7 – 150 (*Ecklonia*), 11 – 219 (*Laminaria/Saccharina*), 15 – 302 (*Lessonia)*, 10 – 302 (*Macrocystis*), and 8 – 164 (*Nereocystis*). Considered globally over 30 years (to 2050), kelp forests would thus sequester between 14 and 292 million tons of carbon (Appendix 3.4).

The cycling rates for nitrogen and phosphorus varied by a factor of two to five. The average grams of nitrogen removed per m^2 per year were 41 (*Ecklonia*), 124 (*Laminaria/Saccharina*), 88 (*Lessonia*), 81 (*Macrocystis*), and 86 (*Nereocystis*), while the average grams of phosphorus removed per m^2 per year were 2 (*Ecklonia*), 13 (*Laminaria/Saccharina*), 16 (*Lessonia)*, 5 (*Macrocystis*), and 12 (*Nereocystis*).

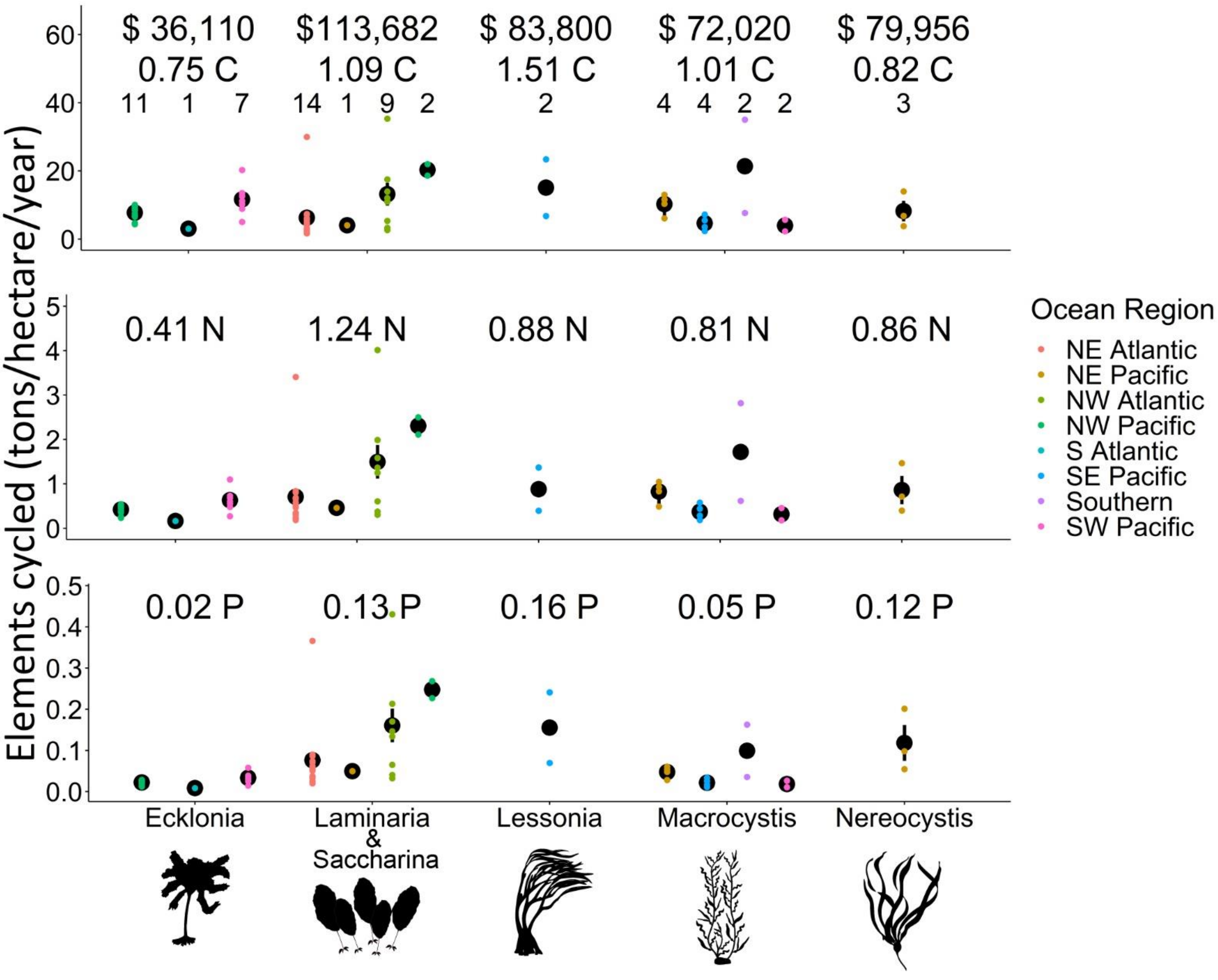

Figure 12 The mean yearly sequestration or cycling of carbon (C), nitrogen (N), and phosphorus (P) in tons per ha per year. The black dots represent the mean value for the genus in that region, the error bars are the standard error. The currency is in thousands of international dollars for the year 2020 and is given as an average value for each genus. The top text dollar values are the combined economic value for the cycling of all three elements. Sample sizes (unique location-time measurement) are presented above each point.

5.2.3 Combined values

The average combined value per ha per year of carbon storage, nutrient cycling, and fisheries services ranged from $43,044 (*Macrocystis,* South-East Pacific) to $175,100 (*Laminaria*, North-western Atlantic), with an outlier value of $281,393 (*Laminaria/Saccharina*, North-western Pacific). Based on the kelp distributions in these areas (Appendix 3.5), the regional value of kelp forests thus ranged from $0.65 billion – $166 billion per year (Fig. 4). Globally, these kelp forests produce an estimated average $523 billion per year with a Net Present Value of 7.79 trillion international dollars over the next 20 years (using a discount rate of 3%).

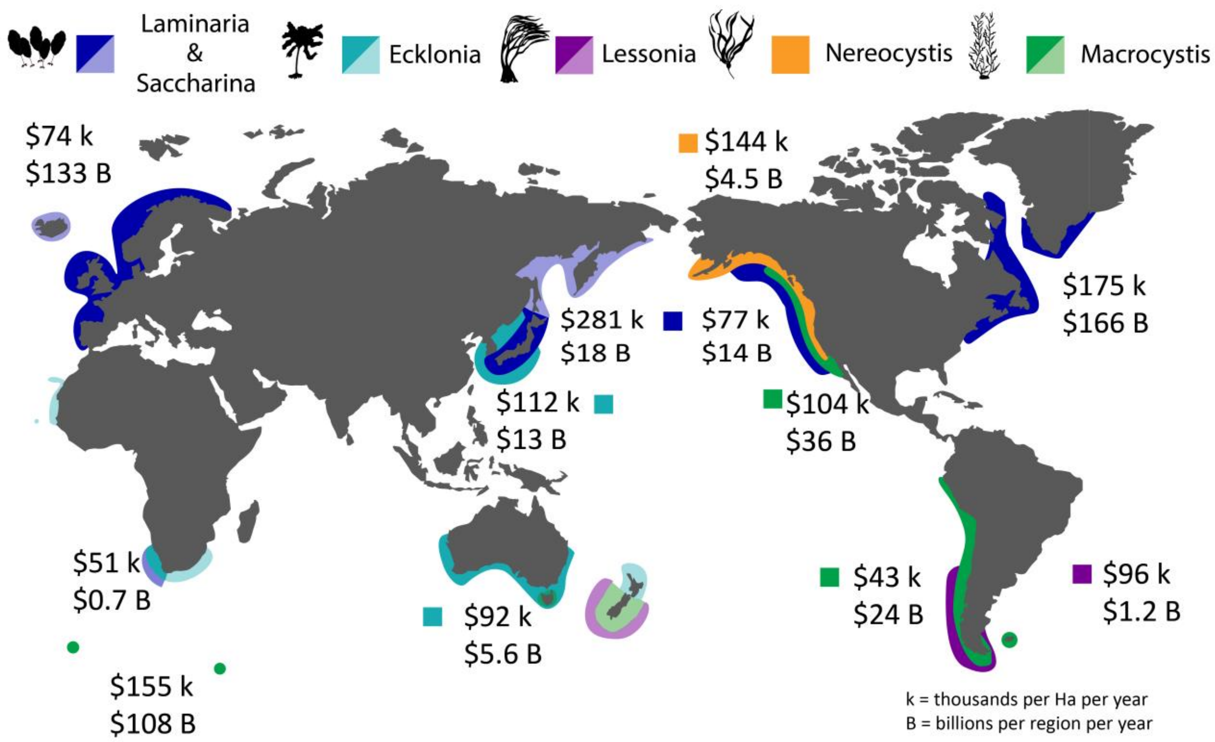

Figure 13 Map of kelp distribution, total economic value per m2 per year (k), regional value (B). Lighter shade colours are for regions where distribution estimates were not available and therefore these values were not included in the regional value calculation.

5.3 Discussion

Global kelp forests generate considerable ecological and economic benefits across the world's oceans. These benefits vary according to the service being considered, the kelp genus, and the ocean region. In areas with available data, we found that the six genera annually generate between $1 and $178 billion per year regionally and totalled $553 billion globally. On a per-area basis, the value for each genus ranged from $79,400 and $150,800/hectare each year, and the average value across genera was $117,051. Previous work by Costanza et al. (2014), which considered nine ecosystem services and grouped algae with seagrass, valued those services at ~$36,000/ha/year. As such, our estimate, which only considers kelp, and only three ecosystem services, is a 3.25-fold increase from the previous, best reported economic value of global kelp forests. These estimates are likely to increase when more services are considered.

We combined data on the spatial coverage of kelp forests (see methods) to provide the first global economic estimate of the value of the selected kelp forests. While most regional estimates varied between $~1 and 132 billion per year, *Laminaria/Saccharina* in the North-Western Atlantic was an exception to these values and was estimated to contribute $166 billion per year. The high value of *Laminaria* and *Saccharina* forests in the North Atlantic is attributable to its extensive distribution, covering 9,500 km^2 in Eastern North America (Appendix 3.5) and the large amounts of nitrogen that it removes, a service driven by its high primary productivity. Not all these services are converted to dollars (i.e., not all the fisheries production is removed and sold in a year and not all carbon sequestration or nutrient cycling is traded on markets), but these services have significant potential value to coastal economies. Past work suggests that non-market services like tourism and recreation can be the most economically important ecosystem service (Deloitte Access Economics 2017). Adding these values to our estimate could thus substantially increase our estimates. Further, the regional estimates will increase as additional kelp genera are considered (e.g., *Alaria*, *Undaria*).

5.3.1 Fisheries value

The potential fisheries value generated by kelp forests is substantial, with one hectare of underwater forest producing an average 2,380 kg/ha/year, of which 904 kg is harvested when applying a 38% extraction rate. The average economic value of that 38% harvest is $35,222 per year, while a 20% harvest yields $18,537 a year and a 70% harvest yields $64,882 a year. Under these same scenarios, the global value of kelp forests shifts from $523 billion to $469 billion in the low harvest scenario and to $602 billion in the high harvest scenario.

These fisheries values only consider economically exploited species and do not consider the numerous kelp-associated organisms that support other economically exploited components of the food web (Steneck et al. 2002) or the species caught only in recreational fisheries. Of the economically important species, invertebrates such as lobster and abalone contributed the most fisheries value to kelp forests, often accounting for over 25% of the value of a site's fisheries. In fact, the abalone *Haliotis rufescens* contributed an average of 43% of a site's value for the genus *Nereocystis* (N = 56) and the mean economic fisheries value was highest for *Nereocystis*.

Kelp forests support biodiversity, with some species transiting through forests, others spending part of their life stage there, and others entirely obligate on the kelp forest (Teagle et al. 2017). Consequently, it is important to understand how much of the calculated fisheries value is directly attributable to kelp forests. Some of the most valuable genera in our study, e.g., *Panulirus* (Withy-Allen & Hovel 2013), *Jasus* (Hinojosa et al. 2015), *Haliotis* (Shepherd 1973), *Pollachius* (Norderhaug et al. 2005), rely on kelp forests for habitat and food and declines in kelp populations have been linked to declines in these genera (Lorentsen et al. 2010, Eger et al. 2020, Castorani et al. 2021). However, for some genera (e.g., *Homarus* and some sea urchins), loss of kelp forests has not always resulted in notable population declines, (Mattison et al. 1977, Kenner 1992).

The exact contribution of kelp forest habitat to these fisheries services remains an important next step in understanding how kelp forests support food webs (Elliott Smith & Fox 2021) and their related economies. Our analysis of the relationship between kelp forest density and fisheries biomass revealed that there was a positive relationship between kelp density and fisheries biomass (Appendix 3.6). A more detailed review paper (Bertocci et al. 2015) revealed that kelp forests had a positive effect on fish abundance in 19 of the 24 studies reviewed, a positive effect on crustacean abundance in 4/4 studies, and a positive effect on gastropod abundance in 2/3 studies.

For our economic evaluation, we aimed to value the sustainable harvestable fisheries biomass that is produced each year (Döring & Egelkraut 2008, Martin et al. 2016). We chose this value over the total biomass produced to not promote the complete extraction of fisheries biomass and to enable the economic evaluation for consecutive years as opposed to a single year value (i.e., if all the biomass is removed in one year, there is no value left for the second year). Another alternative would be to report the realized value, i.e., the amount that is extracted, sold, and recorded by fisheries agencies.

While we chose to use the potential, sustainable value, records on fisheries landings provide an opportunity to examine how much of the service (secondary productivity) in kelp forests is being actively converted into a benefit (dollars). Such fisheries production estimates are available for some of the larger fisheries in areas with accurate records. For instance, the total value of wild fisheries in Australia are estimated to be worth $1,032 million/year (2020)

(Mobsby et al. 2021), whereas we estimated the fisheries production value of *Ecklonia* forests in Australia at $1,777 million/year (2020). Similarly, wild fisheries in California total ~$302 million/year (Sea Grant 2022) but we calculated that fisheries services for *Macrocystis* forests in the state are worth $1,285 million/year. These potential values are 1.5-4 times the realized value and while valuable species like lobster and abalone are likely already fully exploited (Fisheries Research and Development Corporation 2021), there could therefore be new markets for other, currently less desirable species such as sea urchins (Stefánsson et al. 2017). The harvest rate will influence the realized economic value and what is sustainable will vary by species, region, and even year. Therefore, the harvest rates we used are only for illustrative purposes and should not be used to set fishing policy. While the realized economic fisheries value should always be less than the potential values, it is important to acknowledge that the unexploited biomass supports additional, currently unknown tourism values and continue to play an important part in the ecosystem (Vianna et al. 2012, Essington & Munch 2014).

Our work only quantifies those species that are directly consumed or sold by humans. It does not place a value on the species which play an important role in supporting the food web (e.g., forage fish), on juvenile species that are not found within kelp forests as adults, or on the material value of the kelp itself. Obtaining accurate values for the associated fisheries services will be difficult but would increase the fisheries value of biodiversity in kelp forests once calculated. There are also a few remaining wild kelp harvest economies around the world, most notably in Chile (Buschmann et al. 2014), but also in Norway (Lorentsen et al. 2010), Ireland (Werner & Kraan 2004), Mexico (Vázquez-Delfín et al. 2019), and France (Frangoudes & Garineaud 2015) and these will add more value to kelp ecosystems. Indeed, a previous analysis of kelp forests in Chile found that wild harvest was 75% of the economic value in that region, while associated fisheries were only 15% (Vásquez et al. 2014). We did not include the wild harvest value in this analysis because the industry is not consistently found for all genera in all regions but doing so would increase the regional value of kelp in the locations where those markets occur, namely in South America.

5.3.2 Carbon sequestration

Assuming 10% of the yearly NPP is sequestered in the deep oceans (Krause-Jensen & Duarte 2016), we found that the six kelp genera sequester between 31 and 214 g of carbon per m^2 per year. This rate of carbon sequestration (31-214 g C/m^2/year) is similar to other ecosystems. Terrestrial forest ecosystems report sequestration values of 54 – 120 g C/m^2/year (Toochi 2018), seagrasses report ~83 g C/m^2/year (Laffoley & Grimsditch 2009), mangroves ~174 g C/m^2/year, and saltmarsh ~150 g C/m^2/year (Alongi 2012). While the exact values are subject to variation dependent on the year, location, and environmental conditions, these general comparisons suggest that on a per area basis, kelp forests, which generally do not provide below ground carbon burial in the habitats where they grow, could be comparable contributors to carbon sequestration in natural systems.

These values are, however, contingent on multiple mechanisms that influence carbon sequestration rate of kelp, such as consumption or decomposition after detachment (Pedersen et al. 2021), biotic interactions (Wernberg & Filbee-Dexter 2018), prevailing winds, ocean currents and local topographies such as the presence of adjacent coastal marine canyons (Harrold et al. 1998). If the sequestration rate were reduced to 1%, the potential for carbon sequestration in kelp forests would be significantly reduced to averages between 7 and 15 g/m^2/year depending on the kelp genus. Alternatively, if the sequestration rate were increased to 20%, kelp forests would be some of the best habitat for naturally capturing carbon, ranging, on average between 150 and 302 g/m^2/year. Further research addressing the fate and transport of kelp carbon to other habitats is needed to decrease the uncertainty associated with this range of potential sequestration values.

Putting these numbers into context shows that regional kelp forests sequester between 4,000 and 1.48 million tons of carbon per year. Because the area estimates we used are likely underestimates and did not account for deep water kelp, these values are conservative. Together, these six genera of kelp are estimated to sequester at least 4.91 million tons of carbon from the atmosphere per year. Taken over 30 years (e.g., 2050, a common climate goal), these kelp forests will sequester between 14 and 292 million tons of carbon (1 – 20% sequestration, Appendix 3.7). These values are a fraction of the ~10 billion tons of anthropogenic carbon emissions produced each year as well as a 1/100th to 1/10th of the approximately 2 billion tons of carbon that terrestrial forests absorb each year (Harris et al. 2021).

Filbee-Dexter & Wernberg (2020) recorded a much higher potential (e.g., 1.3 megatons C/year for Australia compared to 4.91 megatons C/year globally in our study) for carbon sequestration. This mismatch is likely due in part to the differences in estimated areal distributions, as they assumed all rocky habitat as kelp forest. The other major study (Krause-Jensen & Duarte 2016) estimated 173 megatons but accounted for yet unmapped deep sea kelp forests and considered all macroalgae in their estimates, resulting in values that are therefore not directly comparable to ours. Further, as the science of blue carbon in kelp forests continues to develop, new approaches and approximations will refine these results (Gallagher 2020, Bach et al. 2021).

Interestingly, despite the high per m^2 carbon sequestration potential of kelp forests, the economic value of this ecosystem service in our study was low relative to other values. The mean economic value of carbon sequestration was only $163 per ha per year even though we used the social cost of carbon (~$45/ton C (Nordhaus 2017)), a relatively high estimate that incorporates the social and environmental externalities of increased atmospheric CO_2 concentrations in our evaluation. Previous work suggests that even the social cost of carbon underestimates the true value of carbon sequestration (Pearce 2003). Nevertheless, even if the price of carbon were to increase ten-fold to $450/ton, the resulting economic value of carbon sequestration in kelp forests would remain relatively low at $1,630/ ha/year. As a result, the economic costs of restoring a kelp forest (10s-100s of thousands, **Chapter 2**) are significantly higher than the potential carbon sequestration credits that would be generated. This discrepancy highlights the risk of using a purely economic incentive for restoring or protecting kelp forests or indeed other marine ecosystems.

5.3.3 Nutrient cycling

At an average value of $73,831/ha/year, nitrogen cycling from the water column was a more economically valuable service compared to drawdown of carbon or phosphorus. The high value is attributed to the proportionally high uptake of nitrogen compared to phosphorus, the high dollar value allocated to nitrogen cycling, and the fact that nitrogen and phosphorus do not need to be transported to the deep sea to be effectively removed.

Placing an economic value on the nitrogen removed from the ocean requires some simplification. First, we obtained estimates of nutrient trading schemes from the Eastern United States, Southern Australia, and Europe. These schemes are based on the replacement cost of the service, that is, how much it would cost to build a water treatment plant to remove the same amount of nitrogen as the kelp. Our approach equates the ocean-based cycling of these nutrients with these economic values. While there are inherent mechanistic differences between upstream and ocean-based cycling, these equivalencies are necessary in the absence of market-based values for these processes (Hopkins et al. 2018). Further, we present the amount of nitrogen that kelp takes up in a year and do not quantify the instantaneous cycling rate. Therefore, our economic evaluation is based on the yearly amount of nitrogen removed by a kelp forest combined with the economic value of removing that amount of nitrogen before it enters the ocean. Altering either of these assumptions will alter the evaluation.

Nitrogen and phosphorus cycling only results in direct benefits in areas with excessive nutrients, typically near rivers, agricultural regions, and urban areas (Kitsiou & Karydis 2011) which also contain a kelp forest. Therefore, the realized value of nitrogen cycling will be lower than the potential value described here. Conversely, this value may also increase as kelp forests in these zones would provide additional services and value by reoxygenating hypoxic zones that are often caused by nutrient pollution (Howarth et al. 2011) and we have not included the oxygen production service. Further incorporating these complexities would increase the accuracy of our evaluations. Until that is possible, we suggest that the nutrient cycling services only be considered in areas with elevated nutrients that still have kelp present. We include these services in our approximation of the value of kelp forests as they represent the potential value of kelp to a region, should those services be needed. Indeed, Froehlich et al. (2019) found that 77 countries suitable for macroalgae growth have hypoxic, eutrophic, or acidic waters, signalling a high potential for the use of these services.

5.3.4 Realized versus potential value

There are numerous ways to place an economic value on ecosystem services (Farber et al. 2002) and while estimating the potential value of ecosystems services is a common approach (Costanza et al. 2014, Schultz et al. 2015, Hooper et al. 2019), other methods will result in different evaluations (Faccioli et al. 2016, Hufnagel 2018, McGrath & Hynes 2020). This fact is well demonstrated by the previous discussions on potential versus extracted fisheries values, and nutrient cycling and carbon sequestration when no one is paying for them (i.e., no credits are purchased or traded). While we made several adjustments to assess the direct economic contribution, few nutrient markets exist, carbon trading is not widely applied or validated for kelp forests, and not all fish biomass is extracted for market sale. Therefore, our values are higher than the direct current contribution of kelp forests to global markets (i.e., GDP). Rather the values presented in this study represent the biophysical services generated each year (tons of fish, and kg of carbon, nitrogen, and phosphorus removed). We then obtain an economic value by attributing the current market price to those values. We believe this approach highlights the global value of kelp forests, whether extracted or not, but acknowledge the results should not be used in decision making that is motivated by exchanges of physical currency or direct economic benefits. Further work should continue to refine these values to account for realized value (Knox-Hayes 2015), marginal costs (Farley 2012), and supply and demand (Wei et al. 2017).

5.3.5 Drivers of variation

We found substantial variation in the ecosystem service values described in this study. This variation was found within and across genera and ocean region and was related to the services themselves, market pricing, and the spatial and temporal distribution of kelp forests. Market prices for the fish species will depend on the year, season, level of processing, distance to market, risk of spoilage, and other factors such as changes in regulation and governance (Peridy et al. 2000, Anderson et al. 2010, Sogn-Grundvåg et al. 2013). Similarly, the price of carbon, nitrogen, and phosphorus will also change through time. As the market prices change, there will be corresponding changes to the estimated values presented here and these values are thus a snapshot.

Spatially, the North-East Pacific region had the most data points and therefore, the averages for *Macrocystis* and *Laminaria* are biased towards that region. To try and understand whether these imbalances might bias our estimates, we removed random portions of the data points in that region until the number of samples were comparable to the other genera. As a result, average fisheries value for *Macrocystis* dropped from ~$29,000/ha/year to ~$22,000/ha/year, reflecting the higher value of fisheries in the NE Pacific compared to other *Macrocystis* related fisheries in South America. Conversely, the fisheries value for *Laminaria* was little changed by this resampling.

Explaining the rest of the variation will be a key next step in predicting the value of a kelp forest. The services considered in our study are based on production, first of the kelp and second of its associated biodiversity. At the regional scale, we expect this production to be driven by nutrients, temperature, and photoperiod (Chavez et al. 2010, Smale et al. 2020), while smaller scale differences maybe driven by depth, salinity, wave exposure, biotic pressures, and human stressors (Schiel & Foster 2015, Coleman & Wernberg 2017, Wernberg et al. 2019a). In an era of dynamic change due to impacts such as warming oceans and coastal development, it is crucial to evaluate the expected alterations to ecosystem services based on system-level drivers and pressures, addressing their consequences from both ecological and economic perspectives.

5.3.6 Kelp distribution

The differences in kelp cover between regions were much higher than the differences between per area average production or economic value. Therefore, the regional and global value of kelp forests is largely dependent on the estimates of kelp distribution. Estimates of the distribution of kelp forests for this research are dependent on two factors. First, true changes in kelp forest cover, due to natural environmental factors (e.g., El Niño (Reed et al. 2015)) and anthropogenic factors (e.g., overharvesting (Fujita 2011), nutrient pollution (Coleman et al. 2008), and human caused climate change (Wernberg et al. 2011)) may increase or (more likely) decrease the total contribution of kelp forests to human society. Kelp decline has already led to closures of important abalone fisheries (Reid et al. 2016, Eger et al. 2020) and our findings further quantify the losses that will be associated with further kelp forest decline. Secondly, our findings are also subject to measurement errors on kelp distribution. We used existing datasets to approximate the area covered by different kelp genera across global ocean regions (Appendix 3.5). While some of these estimates are precise, such as the estimates for *Macrocystis* which relies on satellite remote sensing data (Mora-Soto et al. 2020), other estimates were based on multiple assumptions. For instance, *Ecklonia* coverage in Australia was approximated using the area covered by rocky reef and the average kelp percent cover from the Reef Life Survey data set (Edgar & Stuart-Smith 2014). Notably, we could not find estimates of *Laminaria* coverage in Russia or Iceland, *Lessonia, Ecklonia*, or *Macrocystis* in New Zealand, and *Ecklonia* in the mid-Atlantic or parts of the Southern Atlantic (Western Southern Africa). As the areal distributions of forests are improved upon, our estimates of kelp's value to society will be refined.

We can also consider how addressing these distribution gaps will impact the overall evaluation. Because of the small physical size of the land, the missing data around New Zealand and the data in the mid and south Atlantic are unlikely to increase the global value significantly. Rather, the addition of yet unmapped or currently poorly mapped deep-water kelp could change the values significantly. Indeed, an upcoming study including these estimates (Pesseradona Pers. Comms) suggests that global kelp forest distribution could be ~10 million hectares. This value is roughly double the one presented here. Thus the global value would also roughly double to ~$1 trillion. This value will clearly need refinement as there is a strong relationship between depth and primary productivity which drives much of the economic value presented here. As the new data will be from deeper water forests, the value will likely be less than a simple doubling applied here.

5.3.7 Conclusion

As kelp forests become increasingly threatened by multiple drivers (Wernberg et al. 2019b) it is imperative that we understand their considerable economic contribution to human society. Our results represent the first global ecological and economic assessment of marketable kelp forest services. This evaluation is not intended to commodify kelp forests, which support immense arrays of life and many other ecosystem services, but rather we hope to draw attention to their importance and inform policy and management decisions where benefits of kelps might be an important factor. We found that kelp forests are on average 3.25 times more valuable than previously acknowledged and expect these evaluations to increase as more market and non-market services are assessed. For instance, canopy forming kelps can provide coastal protection (Jackson 1984, Løvås & Tørum 2001), decrease pH and facilitate other organisms (Krause-Jensen et al. 2016), as well as provide cultural connections and support tourism and other recreational opportunities (Hynes et al. 2021). Though unassessed in our study, kelp farms may offer similar ecosystems services and could be compared to natural populations and potentially considered in future regional and global accounts. While climate mitigating services will continue to be an important field of investigation, we found that the greatest economic value of kelp forests was from fisheries production and uptake of nitrogen. As a result, we present these services as the best economic motivators for kelp conservation and restoration. These values situate the value of kelp forests among other marine ecosystems while providing a template for conducting similar analyses in unassessed ecosystems. As the field advances, it will be important to expand on these approximations and work to explain the variation documented in our baseline study.

5.4 Methods

5.4.1 Literature search and data collection

We conducted genera-specific literature searches to compile densities for fisheries species found in kelp forests, as well as net primary production (NPP, i.e., the amount of biomass accumulated in one year) and elemental composition (percent composition of carbon, nitrogen, and phosphorus) values for the six kelp genera (Appendix 3.8). The first searches were conducted on Scopus Web of Science. We read selected papers in their entirety to ensure that they met our inclusion criteria, namely that they recorded the density of a commercially relevant species in kelp habitat, measured the average annual production or net primary production for the kelp species or reported a year averaged elemental composition of the same genera. If a paper met our criteria, we first assigned it to an oceanographic region, either North Eastern or Western Pacific, South Eastern or Western Pacific, the North Eastern or Western Atlantic, the Southern Atlantic, or the Southern Ocean. From each paper we recorded the mean density of fish or invertebrate associated with each genus, the mean net primary production, and the mean carbon, nitrogen, or phosphorus composition. Fisheries species were collected at any time during the year while NPP and percent elemental composition were collected as annual averages (Appendix 3.1 and 3.9). Fish surveys were collected between the years of 1988 – 2020, came from 11 countries, ranging from 56° S to 71° N.

We collected additional biodiversity and NPP data from online repositories such as Reef Life Survey, Reef Check California, and the Hakai Institute. Because there were limited publicly available data in some regions, we sought out additional unpublished datasets directly from researchers in Australia, Chile, Korea, the North Atlantic, South Africa, and Japan. Data sets from Japan and the Eastern United States contain surveys for species once classified in the genus *Laminaria* but now in *Saccharina*, these data are included in our analysis as *Laminaria*, and they are referenced together throughout this paper.

5.4.2 Fisheries calculations

We estimated the secondary production of fish and invertebrates by using published values on species' length and weights (Appendix 3.10) and a biomass to production relationship. Because most studies did not report a species' length or size, we first estimated a species' length at 60% of its recorded maximum length (Froese & Pauly 2010). We opted to use the 60% estimate because not all species observed in each survey would have been the maximum size. We then calculated a species weight (grams) using established length-weight relationships (Froese & Pauly 2010). If a species had no length or length-weight relationship values, we used values from species in the same genera or family. If there was no value available in the same genus or family, we searched for biomass estimates. After we obtained a species' biomass, we converted this value into production (grams per year) using a validated productivity-biomass relationship (Jenkins 2015) (Figure 14). To ensure a future harvest, not all fish production is harvested in one year. As a result, there is considerable variation in reported sustainable harvest rates for fisheries (Sparholt et al. 2019, Fisheries Research and Development Corporation 2021). Therefore, in our economic evaluation, we considered that a range from 20 – 70% of production is harvested each year while using an observed average value of 38% (Sparholt et al. 2019) as a base rate. The sustainable harvest level will vary by species, region, and time but these numbers cover the span of observed values.

We conducted repeated literature and internet searches to find species specific market or wholesale values for the fish and invertebrates. We first checked FishBase to see if a species was used by humans (Froese & Pauly 2010) and considered all potential fisheries including commercial, recreational, and artisanal (Appendix 3.11). If no fishery market value was reported on Fishbase, we conducted additional web searches to confirm this find. If after 50

Google and Google Scholar search results, we could not find a market value or indication of an active fishery, we considered that species to have no fisheries market value. If we found evidence of a fishery but could not find a value, we applied the same taxonomic averaging approach as described for obtaining biomass. Species market values were recorded at differing levels of processing (e.g., dried versus alive) and some were sold for consumption while others were sold on the ornamental market. All values are recorded in the supplement (Appendix 3.11). The fisheries values were then adjusted for purchasing power and converted into international dollars/ kg (Costanza et al. 2014) and adjusted for inflation to the year 2020 (Figure 14). If we found multiple values for a species, we took the average value.

Ultimately, we found market values for 502 species of fish and invertebrates with 395 from retail pricing, 76 from reports, 63 from peer reviewed literature, 18 from industry sources, 10 from news articles, 9 used genus averages, 9 from books, and 7 from webpages. The per kilo prices ranged from \$0.29 to \$324 and were collected from 32 countries. Because the amount of money invested before turning a profit varies by countries, we accounted for this “cost of capital” based on the country the fish was extracted from. These values ranged from 3 – 15% (Appendix 3.12) (Vásquez et al. 2014, Damodaran 2016, 2022). Further, as the prices were obtained for products with different levels of processing (e.g., live versus filleted versus dried), we adjusted for the resources required for each processing type as well as the risk of that product spoiling and being worth nothing. The discount rate for a highly processed product or a likely to spoil product was 2.5%, therefore a maximum discount rate of 5% per price was applied (Appendix 3.13). These values were approximated to help account for these differences but do not fully address this issue and may be improved upon in future analysis. We then obtained the annual fisheries value of kelp habitat by multiplying the species-specific productivity by the species-specific market value. Finally, we assessed the range of site values per ocean region.

5.4.3 Kelp density and fish biomass relationship

Kelp forest density was not associated with all our fishery survey data, so we ran a limited analysis of the relationship between kelp density and fisheries biomass. Together, we had 91 observations from 47 independent sites. We used a mixed effect model with “site” as a random factor to account for multiple observations at the same location but at different dates (Bates et al. 2015).

5.4.4 Carbon sequestration and nutrient cycling

We used the average elemental composition of each genus as reported in the literature to convert region specific NPP into the average amount of carbon, nitrogen, and phosphorus absorbed from the water each year (Appendix 3.1). Because not all fixed carbon is permanently removed from the water column, we used a tentative estimate that 10% of kelp NPP is exported to the deep sea and effectively removed from the system (Wilmers et al. 2012, Krause-Jensen & Duarte 2016). While this estimated percentage is the best available, it remains to be validated. This value represents the amount of carbon that is removed from the atmosphere over a prolonged period (> 100 years). It is the value that is most relevant to carbon trading schemes and for evaluating mitigation of carbon dioxide emissions associated with anthropogenic climate change. Because the exact sequestration value is undetermined, we also ran a sensitivity analysis to account for alternative sequestration values (1 – 20% sequestration, Appendix 3.7).

We collected market prices for the social cost of carbon and averaged nutrient trading schemes from around the world (Appendix 3.14). The social cost of carbon reflects the environmental and social costs (e.g., crop failure, damage from sea level rise) that are caused by emitting an additional ton of carbon into the atmosphere. It is typically higher than market schemes (e.g., cap and trade or taxes) but is increasingly being pressed for as a price that reflects the consequences of climate change (Pearce 2003, Nordhaus 2017). The value of nitrogen and phosphorus cycling were calculated as the mean of the available prices for cycling of a kilogram of that element (Appendix 3.14). The prices themselves are calculated by determining how much a society would have to invest in infrastructure to prevent a kilogram of nitrogen or phosphorus from entering the ocean and are reflective of nutrient trading schemes in the USA, Australia, and Europe (Newell et al. 2005, Molinos-Senante et al. 2010, Pollack et al. 2013).

We then multiplied the yearly amount of carbon, nitrogen, and phosphorus removed by the averaged dollar costs to obtain the value of these ecosystem services (Figure 14). As with the fisheries values, we assessed site values by ocean region.

All dollar values in our analysis are presented in international dollars for the year 2020 and have been adjusted using the purchasing power exchange rate (Feenstra et al. 2015), unless stated otherwise.

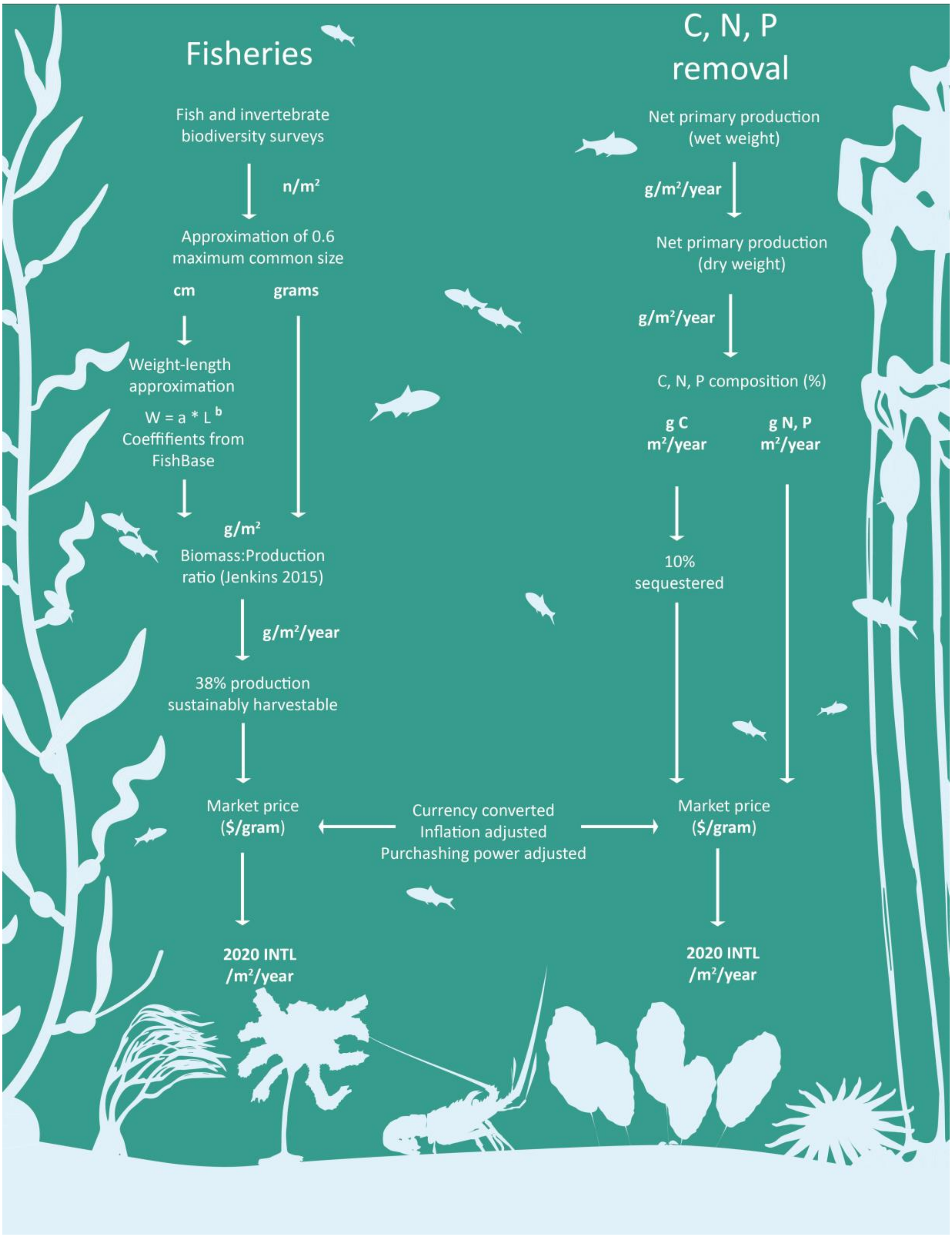

Figure 14 Flow chart of methodological steps for calculating the market value of different services.

5.4.5 Spatial distribution of kelp

We compiled existing estimates of the spatial coverage of kelp forests in each region as well as calculated new approximations for regions where specific survey data was available (Appendix 3.5). The data collection methods included in this compilation ranged from remote sensing (Mora-Soto et al. 2020), government reports from aerial images (Berry et al. 2001), to combinations of percent cover (Edgar et al. 2020) and suitable kelp habitat (e.g., rocky reef and depth) (Lucieer et al. 2019).

5.4.5 Net present value

The net present value was calculated using a 3% discount rate (Gouhari et al. 2021, Piaggio & Siikamäki 2021) and represents the current present value of 20 years of services provided by 1 hectare of kelp forest (i.e., potential economic value from 2021 – 2041) (Žižlavský 2014).

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Chapter 6 - Discussion and conclusion

I began this thesis by discussing previous and emerging paradigms about how society manages ecosystems. The traditional approach in Western conservation has been to take a protectionist approach where humans are excluded from the environment (Kimmerer 2013) and any ecological deficits are repaired by ecological processes and without further human intervention (Holl & Aide 2011). This paradigm is shifting and societies which have historically been protectionist in their environmental management are now recognizing the need to give nature a helping hand in repairing the damage caused by human activity (De Groot et al. 2013, Breed et al. 2021).

The ecological restoration of terrestrial ecosystems has progressed much faster than marine ecosystems (Saunders et al. 2020). This gap is likely caused by the difficulty of working in the marine environment, fuzziness about land tenure, as well as an element of “out of sight, out of mind” that is common for marine ecosystems. Within marine ecosystems, there is yet another gap, caused by the same problems described above. The restoration of intertidal marine ecosystems has progressed the furthest while the better-known subtidal ecosystems such as coral reefs have progressed relatively further than lesser known systems such as kelp forests, which are also in need of restoration (Basconi et al. 2020, Saunders et al. 2020, Feehan et al. 2021). Further understanding the development, lessons learned, and future directions of kelp forest restoration and conservation was thus the main aim of this thesis.

In **Chapter 2**, I explore how the management and restoration of kelp forests developed in 16 countries across the world. Kelp forest restoration started 300 years ago in Northern Japan and has since spread to almost every geography where kelp forests occur. **Chapter 2** details these 300 years of history, collates information on why the projects occurred, who conducted them, where they were located, how they were done, and what the lessons learned from each project were. We find that most projects were indeed small in scale, used transplants, and were conducted by academic institutions to answer ecological questions. There are, however, notable exceptions and we detailed some of the most successful restoration projects to date and found that they were most successful if they occurred close to an existing kelp forest and if they were well financed for long periods of time. This information provides a new foundation for the field of kelp restoration and brought together several new pieces of information. **Chapter 2** also explores the future of restoration. How we can fund restoration based on the ecosystem services and benefits it provides. How we can work at larger, more ecologically meaningful scales. How we will need to develop low-cost technologies that move away from transplanting. How, as the oceans change in temperature, restoration will need to change with them, either growing new species or modified versions of the species that used to live there. It concludes by calling for a global movement of kelp restorationists that collaborates, shares information, and promotes the restoration and conservation of these underwater forests, (see kelpforestalliance.com & Appendix 4).

In **Chapter 3** I describe how inconsistent monitoring and reporting of restoration outcomes is preventing a consistent understanding of the drivers of different restoration outcomes, prevents balanced quantitative syntheses (as was the case in **Chapter 2**), and fails to report on the benefits associated with restoration. I detail how existing organizations and efforts can host accessible working groups and consultations to create a user friendly but comprehensive framework for marine restoration reporting and monitoring. Such an initiative faces barriers such as funding and language separation but international efforts such as the UN Decade for Ecosystem Restoration and Decade for Ocean Science and Sustainable Development provide opportunities to generate funding and how new technologies can reduce language and technical barriers.

The implicit goal in ecosystem restoration projects is the restoration of entire ecosystems (SER 2004). This focus is often lost, and most projects have focused on only restoring and monitoring the target species, most often a habitat forming organism such as a kelp. This exclusion can not only prevent full ecosystem restoration but can also reduce the likelihood that a restoration project is successful in restoring the target species (Gedan & Silliman 2009).

As ecosystems have evolved, a number of positive, win-win interactions have evolved with them (Halpern et al. 2007, Gribben et al. 2019). In kelp forests, these interactions include interactions between kelps of the same species, different algal species, herbivores, predators, microbes, and human activities such as fishing and aquaculture. Therefore, in **Chapter 4** I review our knowledge of these interactions in kelp forests and describe how to use these interactions in restoration projects. I close by encouraging a more holistic consideration of kelp forest restoration for the future.

Many conservation and restoration decisions are made based on the perceived or realized benefit they have for society (Pearce 1998). Despite being the largest biogenic marine habitat, kelp forests have been historically underappreciated and the benefits they provide to society have not been well quantified (Costanza et al. 2014, Bennett et al. 2016). I use **Chapter 5** as an opportunity to quantify the ecological and economic benefits generated by six key kelp genera from around the world. Kelp forests provide numerous ecosystem services, many of which do not have market values. Therefore, as a first step, I focus on three services which are relatively well recorded and have market prices attributed to them: secondary production, i.e., fisheries, carbon sequestration, and nutrient pollution cycling (nitrogen and phosphorus).

In this chapter, I create a new kelp forest ecosystem service database for 6 dominant kelp genera, *Ecklonia, Lessonia, Laminaria, Macrocystis, and Nereocystis.* These genera span the whole range of kelp distribution. I found that kelp forests provide 2-4 times more economic value to society than previously thought while also highlighting the limitation we faced in creating this estimate. This work provides the first global evaluation of kelp forest ecosystems and highlights ways to improve upon these estimates.

6.1 The need for evidence-based decision making

After we have decided on a desired environmental outcome, such as, X population size of species Y, or X area of habitat Z, we must determine which actions will best achieve that outcome. Oftentimes this action is ad hoc, or is based on an idea that is logical but untested (Hemming et al. 2022), or a case study which has not been well replicated (Grubbs et al. 2016). Making decisions based on these incomplete understandings can mean the action fails to achieve its goal or even that it is harmful. As a remedy, conservation biology and environmental management have increasingly turned to the idea of "evidence based decision making" (Sutherland et al. 2004). Evidence based decision synthesizes information to make recommendations for interventions or actions that can lead to the desired outcome. While the concept originated in the field of medicine, it has significant potential for use in ecology and conservation. The need to make smart, efficient decisions is further stressed by the limited funding available for conservation projects (Cooke et al. 2017).

Evidence based decision making requires large amounts of evidence or data on which to make the decisions. Therefore, each chapter is predicated on the idea of pulling together existing information and using that to make recommendations or provide information to make recommendations. I must recognize the importance of these individual works. Because managing environmental systems is notoriously complex and it is difficult to make decisions and recommendations based on any one single study (Cook et al. 2017), I chose to conduct syntheses. However, my work is entirely dependent on the individual works that is summarized, and I see space for both approaches working together in the future. More studies can be designed to inform large syntheses while more recognition can be given to individual studies in those syntheses.

This fact may be particularly important as kelp forest restoration will occur in an increasingly changing world with elevated sea temperatures, increased herbivory, acidifying oceans, and ongoing coastal development. These barriers will require the development of new tools or innovative approaches such as heat tolerant kelp, large scale urchin removals, or artificial structures to aid growth (**Chapter 2**). It is particularly important that evidence be used in making decisions about how to protect and restore kelp forests in these conditions. In the past, the evidence base was informed by looking at existing studies and grouping them together. There is now the opportunity to coordinate the development and testing of these new approaches before they are released and ensure they are fit for the purpose of guiding decision making in changing seas (**Chapter 6.4** and **Appendix 4**).

6.2 Hypothesis testing to make decisions

Due to data limitations, this thesis focused on synthesizing mostly qualitative information, and I was unable to test many hypotheses. This level of synthesis still allowed me to make recommendations and generate information that may be used to make recommendations. But it is important to recognize that most of this thesis is not supported by statistics and none of it is based off controlled and replicated experiments. Going forward, it will be important to further test the recommendations presented here experimentally where possible and consider how those small-scale results match the results of our larger synthesis. This limitation was mainly driven by incomplete study design, incomplete monitoring and reporting, and reporting biases. Remedying these shortfalls will be an important step to progress the field further. In **Chapter 2** and **3** I discuss how future restoration projects can be designed better, for instance using the Before-After-Control-Impact approach (Underwood 1992) in the monitoring of the project or by collecting a consistent set of information about each project.

These data gaps and shortfalls meant that I was unable to do the fine scale analysis that I intended for **Chapter 2**. Originally, I wanted to explore questions such as "how many kelp transplants per m^2 are best for increasing survival rates", "what season is urchin culling most effective", or "do wild collected transplants survive better than aqua cultured ones". Unfortunately, there were very few projects which used treatment-control setups, the sample size across data categories was limited, and many variables were missing from each project. Getting sufficient data to answer these questions and others will be essential as we seek to make further recommendations about kelp forest management and restoration.

6.3 Economics and conservation

Much like conservation, the field of economics blends together methodologies and approaches from the arts and sciences (Niehans 1981). It is therefore possible to get multiple answers to the same question. These divergent answers may arise depending on how the analysis was done (Dow 2012) or the question was defined (Ryan 2006). **Chapter 5** sought to place a global economic value on kelp forests from the genera *Ecklonia*, *Lessonia*, *Macrocystis*, *Nereocystis*, *Laminaria*, and *Saccharina* but in doing so contained many limitations stemming from the economic tools used. The market prices for fisheries, carbon storage, and nutrient removal are all variable across time and space. Market prices of fish species vary from one country to the next and may even vary week to week within the same country (Kirman & Vignes 1991). Though perhaps less elastic, the markets for carbon, nitrogen, and phosphorus trading are in their infancy and have similar problems (Fisher-Vanden & Olmstead 2013, Kikstra et al. 2021). As a result, the economic estimates presented in **Chapter 5** are a snapshot and we would get a different answer were we to repeat the study again today. Further, I presented the potential value of the ecosystem as opposed to the realized value. Choosing to present the realized value or any other approach (e.g., marginal cost) would produce yet another result. The work presented in **Chapter 5** is best used to inform decisions about the ecological values of kelp forests as those numbers are less subject to change. It still highlights or draws attention to the economic contributions whilst acknowledging that the values are not an absolute truth.

6.3.1 Counter productivity of economic evaluations

The goal of **Chapter 5** was to demonstrate the value of kelp forest ecosystems and motivate their conservation and restoration. This rationale relies on the notion that people are motivated mostly or purely by economic incentives. While this thought may seem intuitive, there is some work that suggests that putting an economic price on “free goods” like nature or care giving may be counterproductive and cause people to value these items less (Raworth 2017). It is difficult to assess how publications such as this thesis can move the policy needle and spur or scorn meaningful personal actions. But in the absence of definitive evidence that says such evaluations make a net negative difference to the conservation objectives, I think it is worth including this information in the debate. I do not claim that economic evaluations are the only foundation on which decisions should be made but when the information is applied in the correct circumstances, I believe it is still useful.

6.3.2 Potential value of an ecosystem

My work presented the potential value of kelp forest ecosystems. In other words, what is the value of the services of the kelp forest should we seek to use it. If fish are not extracted or nutrient credits are not traded, the realized value of those services is zero. Therefore, presenting the potential value likely overinflates the final number while presenting the realized only deems something valuable if it is being extracted and undervalues ecosystems.

This conflict presents an important philosophical question, “do ecosystems only have value if we use them?”. Part of the problem lays within the definition of the word value. When we ask, what is the value of an ecosystem, we may implicitly mean the market value that is traded and sold, the potential value that exists if we should use it, or more intrinsically, does this entity have importance, usefulness, or worth? Does it hold importance to us? Since my work seeks to attribute an economic value, I was at least partially eschewing the intrinsic value of the ecosystem to provide a measure of its benefit to humans. As a global synthesis, I was also eschewing the purpose of creating a place-based estimate of value that might be used in decision making, such as benefit-cost analyses or monetary credits for restoration. I was therefore left with the potential value of the ecosystem. To me, this represents a hybrid of the intrinsic and realized value. On one side it is suggesting that the ecosystem has value regardless of if we are using it or not, but on the other, it uses market prices to quantify that value, a purely use based metric. While I recognize there will be criticisms to this blended approach, I think it allows us to try, albeit incompletely, to understand the intrinsic value of something in units that we are familiar with (dollars).

Once we have decided that we are going to place an instrumental value on nature, in this case dollars, we must consider the best uses of that information. The evaluation presented in this thesis is best used as a communication tool for society, to advocate for the protection and restoration of kelp forests, and to compare data from differing regions and economic conditions. This approach requires significant extrapolation and averaging but can produce a value with less input data than other approaches. As such, the potential value is most appropriate when applied at the global scale (Schägner et al. 2013). Alternative approaches such as the realized economic value are more appropriate if the goal of is to assess the costs and benefits of an action, create an ecosystem account of ecosystem services, or track site level ecosystem services over time (United Nations 2014). This technique is therefore more appropriate at the local or regional scale but may also be used to compile a national or even international account if the same approach is used in multiple locations.

As the number of economic evaluations of ecosystems continues to increase, we must be careful in making comparisons and presenting the findings. First, it is imperative that the methods used to create the evaluations are discussed up front alongside the numbers. As discussed, the approach has a substantial influence on the outcome (**Chapter 5**). There will also be an increasing need to ensure that evaluations are done to ensure the sustainability of the services and the equity of their distribution (Bateman and Mace 2020). These issues may be addressed with a standard system for creating evaluations or accounts of these ecosystems. The leading approach is the System for Environmental Economic Accounting (SEEA) which tracks the stocks and flows of ecosystems services while only attributing an economic value if that benefit is realized. This approach is now being piloted in marine systems with the Global Ocean Accounts Partnership (oceanaccounts.org). These newly formed projects present the opportunity to adopt standardized and transparent methods while ensuring data produced is accessible and comparable. The philosophy of this approach is very similar to the work presented in **Chapter 3**.

6.3.3 Streamlining ecosystem evaluations

The process of quantifying ecosystem services and assigning an economic value to them is complex and as discussed, is subject to substantial interpretation (Small et al. 2017, Barbier 2020). Many restoration or conservation projects lack the technical capacity for completing this work but could benefit from quantifying and evaluating these services. Thus, an important future management tool is the creation of a monitoring framework to quantify the services discussed. This framework is then coupled with an evaluation workflow to allocate an economic value to those services. Such tools would accelerate the analysis and understanding of the value of ecosystem services in kelp forests.

6.4 Keeping it updated with the Kelp Forest Alliance

Much of this work describes fluid processes and socio-economic-ecological actions and decisions and the outputs of such analysis can never be considered conclusive or final. The amount of information needed to reach a minimum threshold of assurance to answer socio-economic-ecological questions is substantial (Pawson 2002). It is unreasonable to assume that any one group or institution will collect all of this information itself. Therefore, coordinated data collection and analysis, as done in this thesis, is necessary to answer these big questions. Further, continued data collection and analysis is necessary to provide updates to those answers. It is therefore essential that future work builds off this analysis, as is common in science, but perhaps less commonly, it can be and should be done so in a more coordinated fashion. The ethos presented in **Chapter 3** provides a strong foundation with which to build this coordinated future.

For this future to be possible, we need digital infrastructure to host the information and coordinated research networks (Adams 2012) or communities of practice (Wenger 2011) to collect and use the information. The Kelp Forest Alliance (KFA – kelpforestalliance.com) platform provides an opportunity to solve this problem. Building from the data collected in this thesis and the persons met during the PhD journey, the KFA platform hosts information from over 260 restoration attempts and 306 persons involved in kelp forest restoration. In the future, I did not want someone else to have to repeat the data collection that was necessary to complete **Chapter 2**. Instead, we have built the KFA platform to allow people to upload information from newly completed or in-progress projects. A centralized data reporting platform also allows us to incentivize or require the monitoring and reporting that is described in **Chapter 3.** While Chapter 3 details the process for developing a marine monitoring and reporting framework, the next step is to create one for kelp forests. This work is now underway under the umbrella of the Kelp Forest Alliance (Appendix 4). Carrying on from the themes presented in **Chapter 3, 4, 5**, there is also a strong incentive to report the ecosystem services and benefits provided by restoration, in addition to the restoration outcome (e.g., kelp survival, kelp density). Going forward, this directive will ensure that projects are reporting similar information and using consistent units. As more, high quality information, becomes available, we will be able to conduct the fine scale analysis that was originally the intent for **Chapter 2**. This analysis will then allow for more directive recommendations in restoration, for instance, how many sea urchins need to be removed or what is the effect of temperature on restoration success.

The platform also provides a natural home for tracking the progress of kelp forest restoration. In other words, how many hectares of kelp forests have been restored at the global scale. Forest and mangrove ecosystems have their own restoration targets (Verdone & Seidl 2017, Global Mangrove Alliance 2019). For instance, the Bonn Challenge intends to bring 350 million hectares of forest ecosystem under restoration by 2030. These high-level challenges can help inspire new restoration action, promote the importance of restoration, increase collaboration between countries and organizations (Ehrenfeld 2000, Tear et al. 2005), but there are no such targets or challenges for kelp forests. Thus, I believe creating such a challenge is a key future step for restoration.

The KFA platform could also be expanded to document the ecosystem services and benefits associated with naturally occurring kelp forests. This expansion would help centralize information on what those services are and allow for a more predictive synthesis than was presented in **Chapter 5**. I described the mean and range of three key ecosystem services for kelp forests, fisheries, carbon sequestration, and nutrient cycling. These mean values masked a lot of variation and there is a lot to be learned from understanding the factors that drive that variance. As with the restoration data, answering those questions will require a large, robust, data set and a data collection and reporting platform, like the KFA may help with that process.

Kelp forest restoration is a global problem with local solutions. Future work should therefore seek to expand on the network of people and organisations discussed in **Chapter 2** and ensure that information and lessons learned flow more easily and are more accessible than they have been in the past. The kelp forest conservation and research community has been instrumental in completing this thesis and based on my experience, I believe that there will many more fruitful, mutually beneficial collaborations in the future.

6.5 Reaching outside of academia

Recommendations about environmental management are only useful if they reach the people making the decisions. Therefore, the thesis was designed to be accessible to those outside of academia and present information that can lead to actionable decisions and to elevate the global profile of kelp forests. As a result of this design, the works in this thesis have been featured in United Nations technical reports[1], a practitioner's guidebook[2], a global database and repository for restoration projects[3], the United Nations Ocean Conference[4], international government forums, meetings hosted by local not-for-profits, and in several news and media articles[5]. There have been many more one on one conversations with businesspeople, government representatives, artists, scientists from different fields, and citizens from many countries about this work and about how we can help the kelp.

Over these last four years the field of kelp restoration has grown rapidly and is receiving more national and international attention. I hope that the works presented here have helped

[1] www.grida.no/publications
[2] bit.ly/kelprestore
[3] kelpforestalliance.com/restoration-projects
[4] www.un.org/en/conferences/ocean2022/
[5] news.unsw.edu.au/en/help-for-our-kelp--the-global-movement-to-restore-our-underwater

with that acceleration and contributed in their small part to the growing demand for kelp restoration work and the information needed to conduct it. I am unrelentingly appreciative when someone has told me they have read this work and used it to inform their restoration project.

6.6 Conclusions

The field of kelp forest restoration has grown rapidly over the last four years, nearly as fast as a kelp forest. There are new restoration projects being announced regularly, a United Nations report on kelp forests, a kelp restoration guidebook, a global community of practice, and an emerging movement to restore kelp forests worldwide.

The key to accelerating kelp forest restoration is increased knowledge, understanding, and motivation to restore these kelp forests. The work in this thesis has tried to increase knowledge by synthesizing past restoration efforts, detailing the state of the field, describing how the field can advance, and by creating frameworks to ensure that reporting from new projects is done to a higher standard. The work also sought to increase the understanding of the importance of holistic ecosystem restoration that provides positive outcomes for the kelp, the ecological community, and the social community of people that interact with and rely on that kelp forest. Though only three ecosystem services were analysed, it also sought to highlight the depth of those services, communicate that importance to people, and motivate restoration and conservation. Taken together, the thesis describes the origins of restoration, suggests approaches to restoration, describes the benefits of restoration, and encourages a new movement of collaboration and high-quality data collection and sharing to guide the field yet further.

If the field can truly restore ecosystems, provide benefits for local communities, use evidence-based decision making, and openly collaborate, I think there is a bright future for kelp forest restoration.

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Appendix 4 - The Kelp Forest Alliance: A global community of practice to understand, advise, and motivate kelp forest conservation and restoration

This work has been submitted to the Journal of Limnology and Oceanography Bulletin for consideration as a "community perspective".

Authors: Aaron M. Eger, Norah Eddy, Mary Gleason, Cayne Layton, Tristin McHugh, Peter Steinberg, Adriana Vergés, and Kelp Forest Alliance members.

The Kelp Forest Alliance was born from a desire to accelerate kelp forest ecosystem restoration across the world by building a global community of practice to enhance information sharing. This mission started with a kelp restoration database to integrate information on past and existing restoration projects, analyse trends, and determine the "best practices" for restoration. As with many conservation and restoration projects, much of the relevant data was outside of the scientific and published literature and presented a language barrier. Therefore, collecting this information required reaching out, emailing, calling, and visiting people doing kelp restoration all around the world. From the beginning, we established meaningful relationships and tried to understand the field's basic needs. The kelp restoration data continues to expand and now paints a rich and diverse picture of the history and current practice of kelp restoration. We recorded over 260 instances of restoration and detailed a practice dating back over 300 years. The type of data we originally collected was extremely varied and we found that little information was consistently recorded across projects. While this prevented the full quantitative analysis that we had originally envisioned, it did help initiate the next phase of the project, a user-friendly data platform. This data collection also helped to form a worldwide network of individuals and organisations that are working to conserve and restore kelp forests (Figure A4.1).

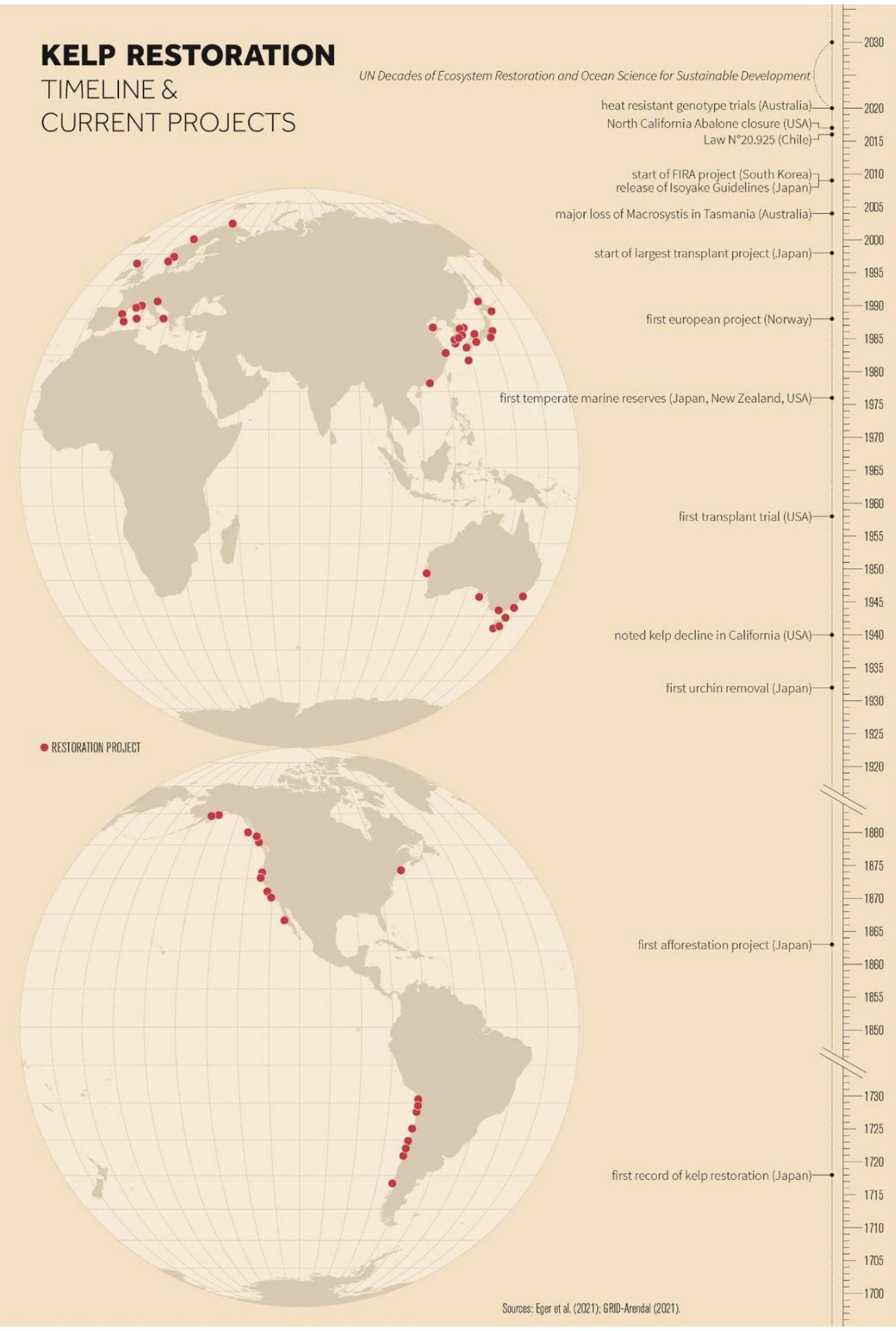

Figure A4.1 Timeline of important events in kelp ecosystem management and the documented past or current kelp restoration projects.

The data standardisation and quality issues encountered earlier in the project, led us to also develop a user friendly, centralized database that could 1) host project details 2) allow users to view and upload new data 3) track restoration projects and progress worldwide, and 4) support a new standard for restoring reporting. This platform is now live at Kelpforestalliance.com. Here people can view a map of restoration efforts and projects, learn from specific lessons and evolving issues, and even track how many hectares of kelp forest have been restored globally (Figure A4.2). Persons and organisations can also create their own account and profiles and join a restoration network of over 240 practitioners and workers from over 20 countries. The Kelp Forest Alliance data entry platform is tailored to encourage users to report the best available information in a consistent format. It also encourages users to highlight the benefits of restoration and report the ecosystem services and benefits that have been generated from their restoration activities. As more information is shared the platform will also track the number and extent of ecosystem services provided by restored kelp forests worldwide.

Figure A4.2 Kelp forest restoration tracker.

We still needed information on how to do restoration effectively and ethically. Therefore, we collaborated with The Nature Conservancy in California and with 50 authors from 45 institutions around the world and published the world's first Kelp Restoration Guidebook. The guidebook was initiated with four workshops with restoration experts from Australasia, South America, North America, and Europe and resulted in a seven-chapter document detailing the best available information on kelp restoration knowledge and practice. The guidebook walks users through 1) What is a kelp forest and why they are important 2) How do you know you need to do kelp restoration 3) How do you engage with local communities to plan restoration 4) What steps are needed before you attempt restoration 5) What methods are available for kelp restoration 6) How do you monitor and report on the outcomes of restoration activities, and 7) How to consider climate change and warming oceans in restoration efforts. The guidebook is intended to be a starting point for any interested in restoration and provide users with the options available, along with the best available advice for those options. As the field grows and we gather more information, future iterations may be more prescriptive. We also highlighted 11 exemplar restoration projects from around the world that excelled in various aspects (e.g., large scale, achieving funding, communicating science, engaging citizens, or testing novel methods) and that demonstrate the practice and potential for kelp restoration. As we discover more information, we will publish new versions of the guidebook or related appendices. The first version of the guidebook and its future iterations are hosted o the KFA webpage.

Ultimately, the Kelp Forest Alliance will facilitate collaboration and data sharing across projects, countries, languages, sectors, and cultures. In February 2023, we are planning to launch an international restoration target for kelp forests. This will be an ambitious but scientifically-supported goal for the area of kelp forest to be restored globally over the next two decades. Following the Bonn Challenge for terrestrial forests, we will encourage members and organizations to make pledges or commitments for kelp restoration activities and ongoing monitoring of the outcomes. The target and the inaugural pledges will be announced at our first ever international kelp restoration summit at the International Seaweed Symposium in Hobart, Australia, February 18-24th, 2023. The progress will then be monitored on the Kelp Forest Alliance website. We invite any individuals or organisations interested in conserving and restoring the world's critically important kelp forests to contact us and join the alliance.