





CONTRIBUTED PAPER

Spatial cost–benefit analysis of blue restoration and factors driving net benefits globally

Phoebe J. Stewart-Sinclair¹  | Carissa J. Klein²  | Ian J. Bateman³  | Catherine E. Lovelock¹ 

¹ School of Biological Sciences, The University of Queensland, St Lucia, Queensland, Australia

² Centre for Biodiversity and Conservation Science, School of Earth and Environmental Sciences, The University of Queensland, St Lucia, Queensland, Australia

³ Land, Environment, Economics and Policy Institute, University of Exeter, Exeter, UK

Correspondence

Phoebe Stewart-Sinclair, School of Biological Sciences, The University of Queensland, St Lucia QLD 4072, Australia.

Email: p.stewart@uq.edu.au

Article impact statement: Blue restoration produces net benefits for all ecosystems assessed. Net benefits are driven by technique, duration, and ecosystem services.

Abstract

Marine coastal ecosystems, commonly referred to as blue ecosystems, provide valuable services to society but are under increasing threat worldwide due to a variety of drivers, including eutrophication, development, land-use change, land reclamation, and climate change. Ecological restoration is sometimes necessary to facilitate recovery in coastal ecosystems. Blue restoration (i.e., in marine coastal systems) is a developing field, and projects to date have been small scale and expensive, leading to the perception that restoration may not be economically viable. We conducted a global cost–benefit analysis to determine the net benefits of restoring coral reef, mangrove, saltmarsh, and seagrass ecosystems, where the benefit is defined as the monetary value of ecosystem services. We estimated costs from published restoration case studies and used an adjusted-value-transfer method to assign benefit values to these case studies. Benefit values were estimated as the monetary value provided by ecosystem services of the restored habitats. Benefits outweighed costs (i.e., there were positive net benefits) for restoration of all blue ecosystems. Mean benefit:cost ratios for ecosystem restoration were eight to 10 times higher than prior studies of coral reef and seagrass restoration, most likely due to the more recent lower cost estimates we used. Among ecosystems, saltmarsh had the greatest net benefits followed by mangrove; coral reef and seagrass ecosystems had lower net benefits. In general, restoration in nations with middle incomes had higher (eight times higher in coral reefs and 40 times higher in mangroves) net benefits than those with high incomes. Within an ecosystem type, net benefit varied with restoration technique (coral reef and saltmarsh), ecosystem service produced (mangrove and saltmarsh), and project duration (seagrass). These results challenge the perceptions of the low economic viability of blue restoration and should encourage further targeted investment in this field.

KEYWORDS

coral reef, ecosystem services, mangrove, marine coastal restoration, natural capital, restoration cost, saltmarsh, seagrass

Análisis de Rentabilidad Espacial de la Restauración Azul y de los Factores Determinantes del Beneficio Neto Mundial

Resumen: Los ecosistemas costeros marinos, llamados comúnmente ecosistemas azules, proporcionan servicios valiosos para la sociedad, pero se encuentran bajo una amenaza creciente a nivel mundial causada por una variedad de determinantes, incluyendo la eutrofización, el desarrollo, el cambio en el uso de suelo, la reclamación de tierra y el cambio climático. Algunas veces se necesita de la restauración ecológica para facilitar la

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recuperación en los ecosistemas costeros. La restauración azul (es decir, en los sistemas costeros marinos) es un campo en desarrollo, con proyectos que a la fecha han sido a pequeña escala y costosos, lo que resulta en la percepción de que la restauración puede no ser viable económicamente. Realizamos un análisis de rentabilidad mundial para determinar los beneficios netos de la restauración de ecosistemas de arrecife de coral, manglar, marisma y pastos marinos en donde el beneficio está definido como el valor monetario de los servicios ambientales. Estimamos los costos a partir de estudios de caso de restauración publicados y usamos un método de transferencia de valor ajustado para asignar los valores de beneficio a estos estudios de caso. Los valores de los beneficios fueron estimados como el valor monetario proporcionado por los servicios ambientales de los hábitats restaurados. Los beneficios superaron los costos (es decir, fueron beneficios netos positivos) de la restauración de todos los ecosistemas azules. El beneficio promedio consistió en que la proporción de costos para la restauración del ecosistema fue 8-10 veces mayor que en los estudios anteriores de la restauración de los arrecifes de coral y los pastos marinos, probablemente debido a que usamos estimaciones de costo más bajas. Entre los ecosistemas, las marismas tuvieron los mayores beneficios netos seguidos por los manglares; los arrecifes de coral y los pastos marinos tuvieron los beneficios netos más bajos. En general, la restauración en los países con niveles medios de ingreso tuvo más beneficios netos (ocho veces más en los arrecifes de coral y 40 veces más en los manglares) que aquellos países con niveles altos de ingreso. En cuanto al tipo de ecosistema, el beneficio neto varió de acuerdo con la técnica de restauración (arrecife de coral y marisma), servicio ambiental producido (manglar y marisma) y duración del proyecto (pastos marinos). Estos resultados desafían las percepciones de la baja viabilidad económica que tiene la restauración azul y deberían fomentar una mayor inversión focalizada en este campo.

PALABRAS CLAVE

arrecife de coral, capital natural, costo de restauración, manglar, marisma, pastos marinos, restauración de costas marinas, servicios ambientales

INTRODUCTION

Blue ecosystems, such as coral reefs, mangroves, saltmarsh, and seagrasses (i.e., marine coastal ecosystems), are highly productive, providing valuable goods and services to humanity (Pendleton, et al., 2016), such as provisioning (e.g., commercial and noncommercial fish), coastal protection (Koch et al. 2009), regulation (e.g., climate regulation), habitat (e.g., nursery service), and cultural services (e.g., recreation and tourism) (Costanza et al., 2014). Many of these services are understudied, including those important for human health (e.g., medicinal and genetic resources, air quality, regulation of water flow, biological control, and spiritual experience), and, as such, are likely undervalued (Himes-Cornell et al., 2018). These services provided by blue ecosystems are finite and valuable, and their loss and degradation have detrimental impacts on people, economies, and biodiversity (Costanza et al., 2014).

Global losses of blue ecosystems are 29% for seagrass, 35% for mangroves, 19% for coral reefs, and up to 50% for saltmarshes (e.g., Valiela et al., 2001; Waycott et al., 2009; Hughes et al., 2017; Mcowen et al., 2017). Drivers of these losses vary, but include eutrophication (excessive nutrients), coastal development, land-use change, land reclamation, and climate change-related warming (Hughes et al., 2017; Arias-Ortiz et al., 2018).

Increasing severity and frequency of anthropogenic disturbances will likely increase loss and degradation of ecosystems

and reduce their ability to recover naturally (Perrow & Davy, 2002). Thus, ecological restoration may be required to maintain ecosystem services. Ecosystem restoration is defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, 2004). Although terrestrial restoration has been practiced successfully for decades, blue restoration is still in development and is often short term, small scale, and expensive compared with terrestrial ecosystem restoration (Blignaut et al., 2013; Costanza et al., 2014; Bayraktarov et al., 2020). Blue restoration projects usually lack long-term monitoring and maintenance (median duration of 1 year [Bayraktarov et al., 2020]), which limits understanding of the social and economic benefits of restoration for local communities. Despite this, blue restoration is practiced widely around the globe and, as such, an assessment of the economic costs and benefits of restoration is timely (Stewart-Sinclair et al., 2020).

Previous research on the economic benefits of restoring ecosystems shows that the costs outweighed the benefits for coral reef restoration and coastal systems under most scenarios (De Groot et al., 2013). These findings led to the perception that blue restoration is not economically viable (Sumaila, 2004; De Groot et al., 2013). However, as blue restoration has developed, more recent and comprehensive datasets of costs and benefits are available and may offer more encouraging estimates (De Groot et al., 2012; Costanza et al., 2014;

Bayraktarov et al., 2020). A reanalysis of the costs and benefits of blue restoration and the variables driving variation in these parameters is imperative. This assessment is particularly important given the recent international focus on restoration (e.g., UN decade on ecosystem restoration 2021–2030 [<https://www.decadeonrestoration.org/>]) and on blue restoration specifically (Decade of Ocean Science for Sustainable Development 2021–2030 [<https://www.oceandecade.org/>]).

We examined whether blue restoration produces net economic benefits and, if so, what factors increase the net benefit of blue restoration projects. To do so, we constructed spatially explicit cost–benefit analyses of restoration for coral reef, mangrove, saltmarsh, and seagrass ecosystems under multiple scenarios. We then investigated the relationship between benefits and a variety of predictor variables (such as restoration technique, duration, and scale). Contextual factors, such as the type of ecosystem service provided and the economic and protection status of the location of restoration, could affect net benefits too. Our aim was to improve understanding of factors enhancing economic net benefits associated with blue restoration and to provide direction for future developments in this enterprise.

METHODS

We constructed spatially explicit cost–benefit analyses for coral reef, mangrove, saltmarsh, and seagrass restoration. To do this, we gathered published costs from global restoration projects over the last 40 years (Appendix S2) and benefits of ecosystem services as valued and compiled by The Economics of Ecosystems and Biodiversity (TEEB) Valuation Database (TEEB, 2010). We used the value transfer approach to pair benefit values with restoration cost values (Bateman et al., 2011). To choose a model with a specified discount rate and time scale, we performed a sensitivity analysis in which discount rates and time scales varied among nine models. Once a model was chosen, we then accounted for uncertainty by conducting cost–benefit analyses for each ecosystem under a baseline and a conservative scenario (Appendix S2).

Costs of blue restoration

To determine the costs of coral reef, mangrove, saltmarsh, and seagrass restoration, we used published databases from Bayraktarov et al. (2020). Restoration costs were extracted for 58 coral reef, 117 mangrove, 73 saltmarsh, and 67 seagrass restoration observations. The database also included oyster reefs, but there were insufficient benefits data to carry out the cost–benefit analyses for them. All restoration costs were converted to 2010 US\$ ha⁻¹ year⁻¹. Details of cost database construction and cost conversions are in Appendix S2 and in the database on cost of restoration (Bayraktarov et al., 2020).

Benefits of blue restoration

To determine the monetary benefits provided by coral reef, mangrove, saltmarsh, and seagrass ecosystems, we used the Ecosystem Service Value Database (ESVD), developed by the TEEB Foundation and published in de Groot et al. (2012). For more information on this database, see Appendix S2. Because data were collected in different years, all ecosystem service values were converted from 2007 US\$ ha⁻¹ year⁻¹ to 2010 US\$ ha⁻¹ year⁻¹, the same units as the cost data. Each benefit observation was associated with the geographic location of the case study from which it was calculated (Van der Ploeg & De Groot, 2010).

Value transfer

To conduct a cost–benefit analysis, we paired observations from the restoration cost database for coral reefs ($n = 58$), mangroves ($n = 117$), saltmarsh ($n = 73$), and seagrass ($n = 67$) with benefit observations from the ESVD. To do this, we used a value transfer approach (for more information on this method, see Appendix S2), whereby existing estimates from one site (i.e., TEEB estimates of ecosystem service values) were applied to a restoration site where the value had not been estimated (Bateman et al., 2011). We excluded all observations in the database that did not have a matched benefit value point from within the same country. This resulted in cost and benefit values for 29 coral reef, 53 mangrove, 70 saltmarsh, and 58 seagrass restoration projects.

Sensitivity analyses

We conducted a sensitivity analysis to choose a Cost-benefit analysis (CBA) model with a specified discount rate and time scale because prior cost–benefit analyses were highly influenced by different discount rates and time frames (De Groot et al., 2013). We compared model results under three different discount rates (low, 1%; moderate, declining 3.5–3%; high, 4.5%) and time frames (30, 60, and 90 years), which resulted in nine different models (Appendix S2). The time frame chosen must allow for full ecosystem services to be restored and benefits to be achieved, which has been estimated as 20–30 years for marine and brackish ecosystems (Duarte et al., 2020). We then calculated benefit:cost ratios (BCRs) and compared models with analysis of variance (ANOVA).

Uncertainty analyses

To reduce uncertainty in the results of the cost–benefit analyses, we constructed two scenarios that varied the value of costs and benefits over time: baseline and conservative (Figure 2 and Appendix S2). We then used Welch's t tests to determine

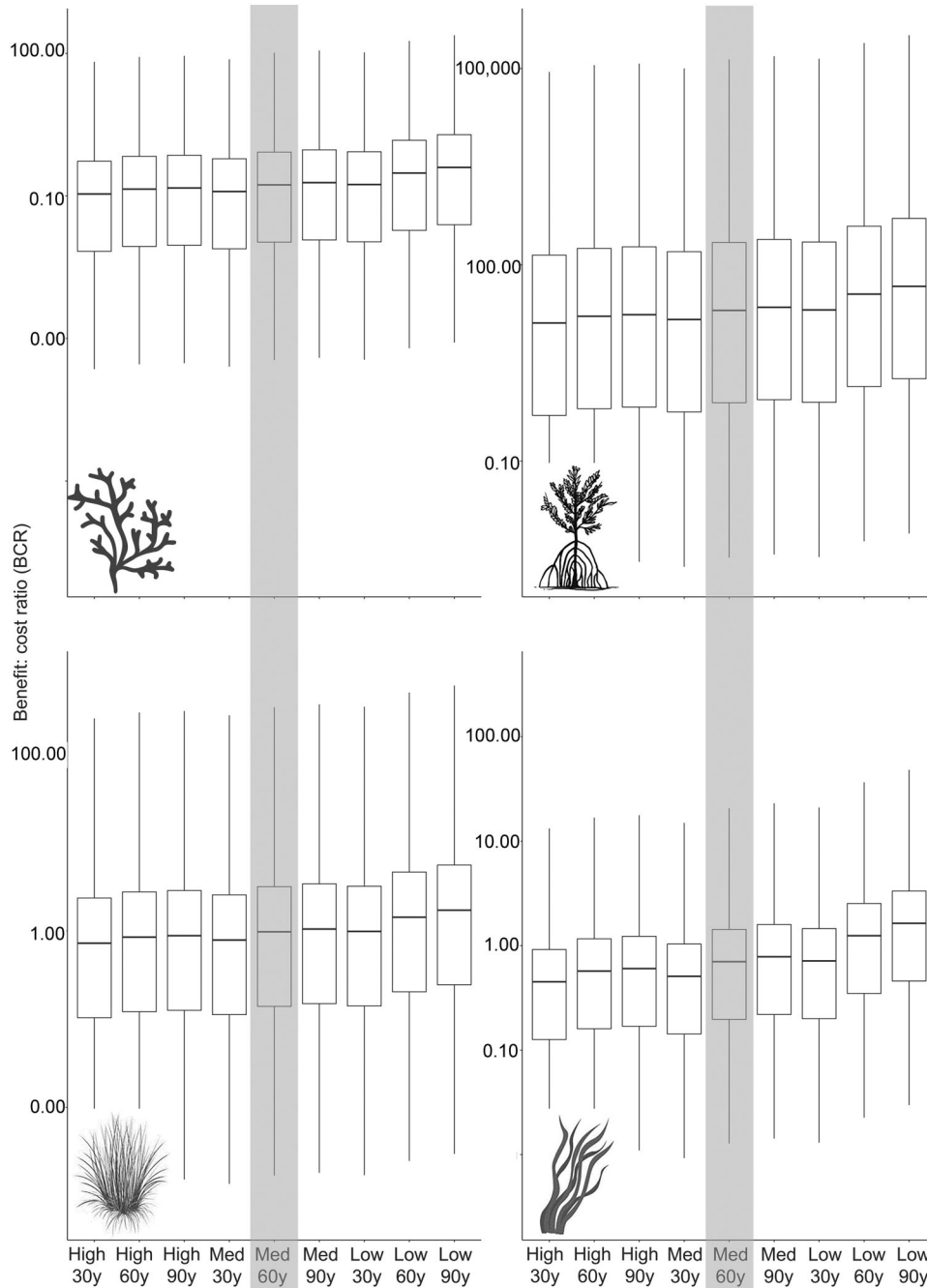


FIGURE 1 Sensitivity analysis of model assumptions (discount rate and time frame) for cost–benefit analysis of restoration of coral reef, mangrove, saltmarsh, and seagrass ecosystems under the baseline scenario (horizontal lines, median; bars, interquartile range; whiskers, minimum and maximum). Highlighted is model E (medium discount rate over 60 years), which was used for further analyses

whether there was a significant difference in the BCRs produced between these scenarios.

Spatial cost–benefit analyses

We performed cost–benefit analyses under the two scenarios by applying a discount rate to the costs and benefits for each observation over the given time frame. The BCR was then cal-

culated for all restoration projects in each ecosystem (details in Appendix S2). To determine the time at which each restoration project became profitable (i.e., time when benefits > costs), we extended our time frame out to 100 years under the baseline scenario. We then calculated the mean time to return on investment for each ecosystem.

To assess spatial patterns in net benefits (i.e., where benefits outweigh costs and $BCR > 1$) related to the economic status of the country where restoration was carried out, all points for each

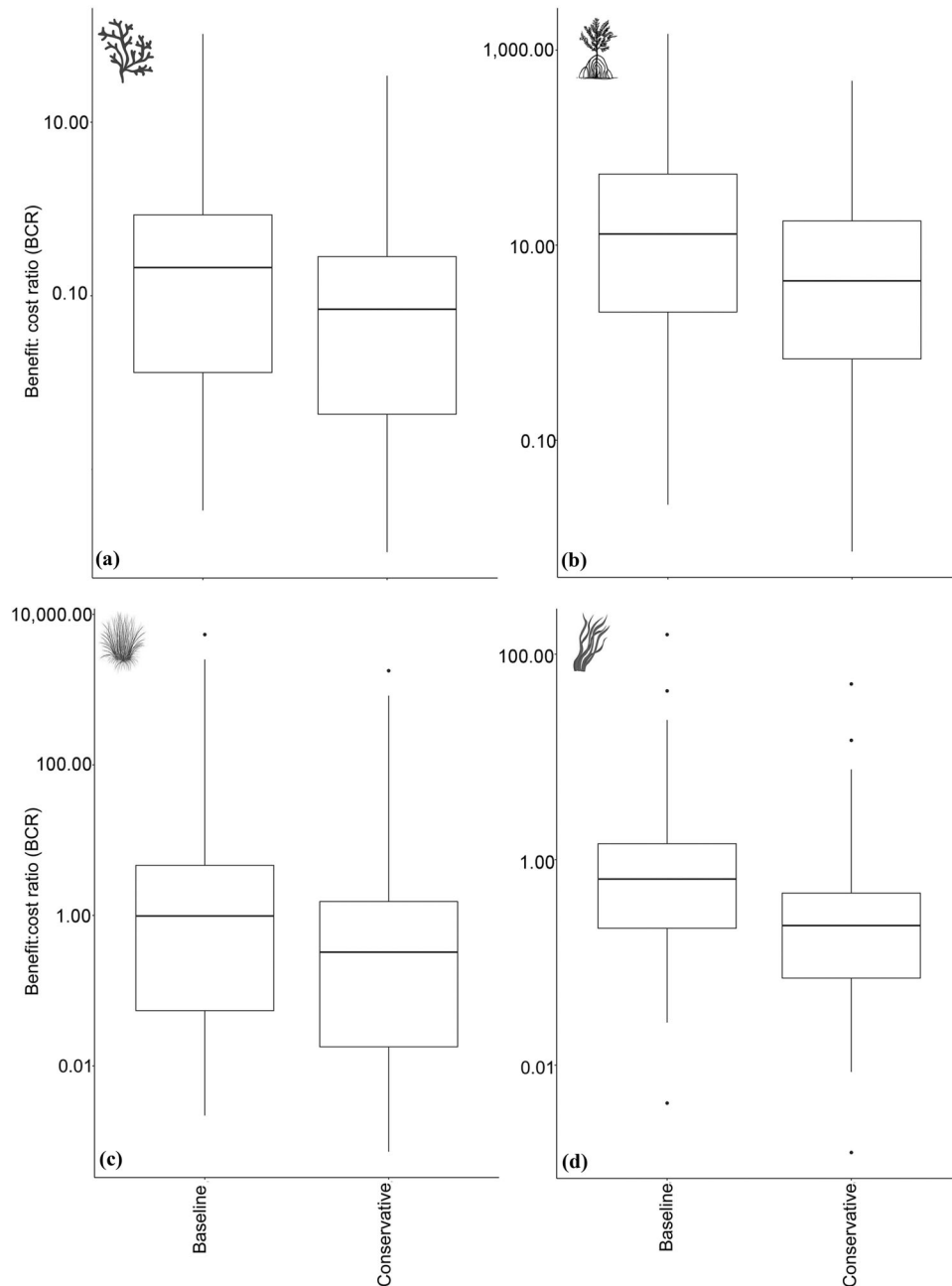


FIGURE 2 Cost–benefit analysis of restoration of (a) coral reef, (b) mangrove, (c) saltmarsh, and (d) seagrass ecosystems under baseline and conservative scenarios, where there are no significant differences in benefit:cost ratio between scenarios (horizontal lines, median; bars, interquartile range; whiskers, minimum and maximum)

ecosystem were mapped (details in Appendix S2). An ANOVA was then used to compare BCR between country income levels: high, upper middle, and lower middle (World Bank, 2019). There were no data for restoration in low-income countries.

Predictors of variation in BCR

We constructed boosted regression trees (BRT) (Elith et al., 2008) to measure the correlation between BCR of blue restoration in each ecosystem (under the baseline scenario) and six pre-

dictor variables: scale (size of project in hectares), survival (percentage of restored organisms alive at the end of the project), duration (length of project in years), restoration technique, ecosystem subservice, and protected status of the ecosystem. More information on construction of BRT is in Appendix S2

RESULTS

The costs of restoration were highest for coral reefs, followed by seagrass, saltmarsh, and mangrove restoration. There was a

TABLE 1 Median (SD) costs and benefits of restoration in 2010 US\$ ha⁻¹ year⁻¹

	Coral reef (<i>n</i> = 29)	Mangrove (<i>n</i> = 53)	Saltmarsh (<i>n</i> = 70)	Seagrass (<i>n</i> = 58)
Costs	117,220 (28,585,926)	896 (19,167)	66,189 (979,712)	74,594 (400,512)
Benefits	1131 (3222)	882 (2206)	902 (273,723)	1912 (9877)

very large standard deviation of costs for each ecosystem, due to outliers with very high costs (Table 1). Seagrass ecosystems had the greatest median benefit, followed by coral reefs, saltmarsh, and mangroves. As with costs, there was a large standard deviation in ecosystem benefits, due to outliers with very high benefit values (Table 1).

Sensitivity analyses

The sensitivity analysis that compared CBA of restoration under nine different models was robust to changes in discount rate and time frame; there were no significant differences between these models (ANOVA for coral reef $p = 0.67$, mangrove $p = 0.79$, saltmarsh $p = 0.81$, and seagrass $p = 0.52$) (Figure 1). From these, we chose the moderate model, E, to run future CBA scenarios for all ecosystems. Under model E, costs and benefits were discounted under a declining discount rate over 60 years.

Uncertainty analyses

Overall, ecosystem restoration had higher benefits than costs in all ecosystems. As expected, BCRs were higher under the baseline scenario than the conservative scenario. However, there was no significant difference ($p > 0.05$) between results of the cost–benefit analyses under the baseline and conservative scenarios for any of the ecosystems (Figure 2). As such, we used the baseline scenario under model E (see above) for all further analyses.

Cost–benefit analyses

The mean BCR under the baseline scenario was highest for saltmarsh (BCR = 232), followed by mangroves (BCR = 87), seagrass (BCR = 5), and coral reef restoration (BCR = 4). However, there was a large range, so these values had high uncertainty (Figure 2).

All ecosystems had a large range for time to return on investment (from 1 year to more than 100 years). The mean time to return on investment was lowest in mangrove restoration at 18 years, followed by saltmarsh in 57 years. The longest time to return on investment was in seagrass and coral reef restoration, after 71 and 79 years, respectively.

Spatial cost–benefit analyses

Restoration in high-income countries had lower net benefits than restoration in countries with lower-middle and higher-middle incomes (Figure 3). In mangrove restoration, this pattern was significant (ANOVA, $p < 0.01$), whereas in coral reef restoration, the pattern was present but not significant ($p = 0.67$). We excluded saltmarsh and seagrass restoration from this analysis because all projects in the database were conducted in high-income countries.

Coral reef restoration produced net benefits in the coral triangle (Indonesia, Thailand, and the Philippines) and on the Great Barrier Reef in Australia (Figure 4a), but there were no net positive benefits outside of this region. Conversely, mangrove restoration generally produced net benefits; the greatest net benefits (BCR > 100) were in Vietnam and Thailand (Figure 4b). There were no clear spatial patterns in benefits of saltmarsh restoration (Figure 4c). Similarly, seagrass restoration was performed only in the United States and Australia. There were no clear spatial patterns in the United States but in Australia, there may be subnational differences in net benefits (Figure 4d).

Predictors of BCR

Predictors of BCRs varied among ecosystems. For coral reefs, the majority of the variation was due to restoration technique (71.6%) (Figure 5). Coral reef restoration techniques that had a positive relationship with net benefits were coral gardening (with a nursery phase) and direct transplantation. Techniques associated with decreased net benefits were larval enhancement and substrate addition (Figure 5). In mangrove restoration, the benefits provided by ecosystem services were the best predictor of net benefits; reduction of damage during extreme events and fish nursery services produced the greatest net benefits (96.8%) (Figure 5). Similarly, saltmarsh restoration technique (34.8%) and provision of ecosystem services (37.9%) had the largest effects on net benefits. Hydrological restoration and construction techniques had positive impacts on benefits, whereas planting saltmarsh directly negatively affected benefits of restoration. Water purification services were also provided the greatest net benefits for saltmarsh restoration (Figure 5). In seagrass restoration, however, the duration of projects was the most important factor in determining the BCR, which increased steeply when projects were longer than 2–3 years (70.9%) (Figure 5).

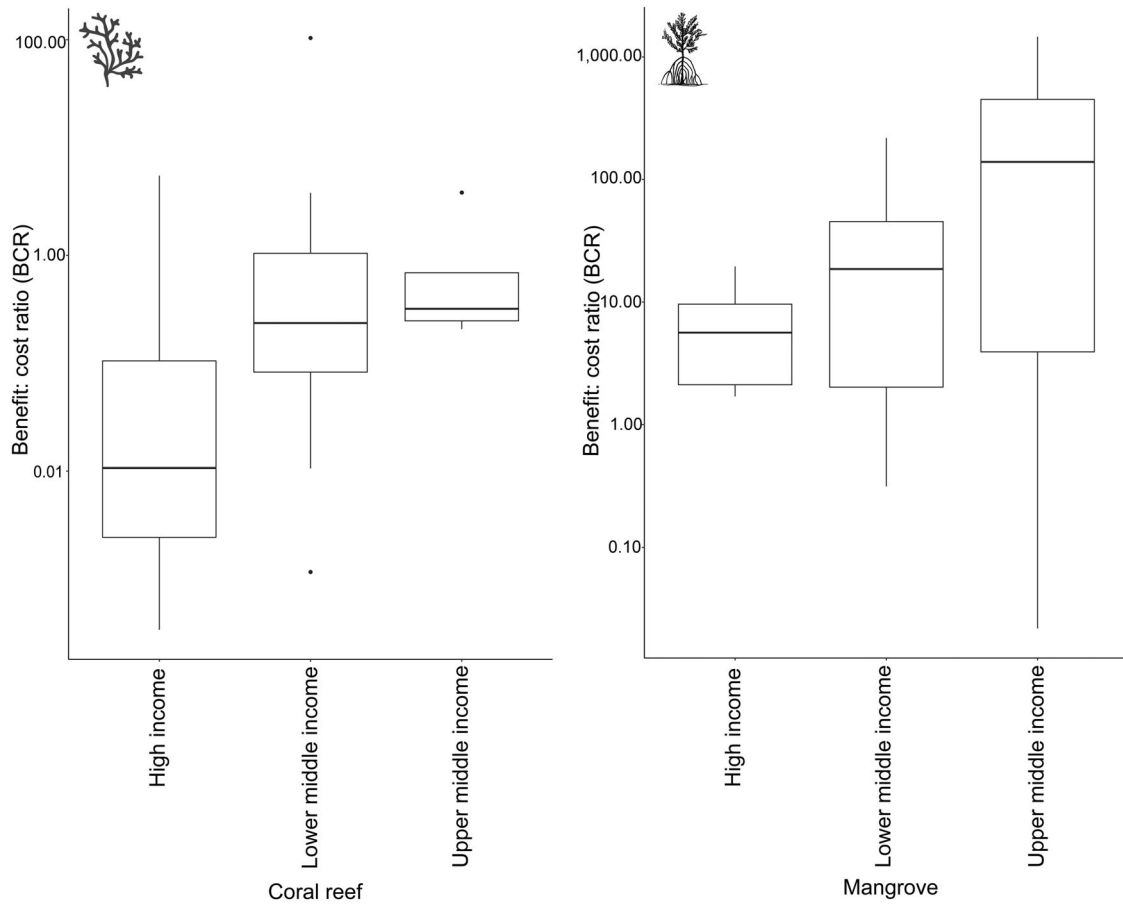


FIGURE 3 Benefit:cost ratio of coral reef and mangrove restoration in countries of high, low middle, and upper middle incomes (horizontal lines, median; bars, interquartile range; whiskers, minimum and maximum)

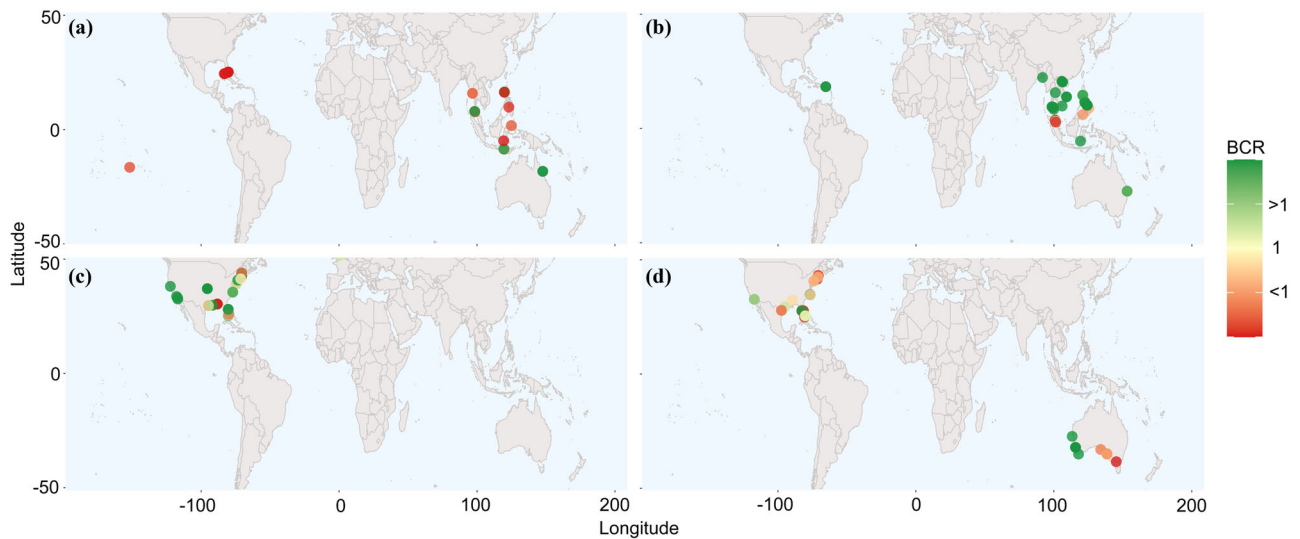


FIGURE 4 Benefit:cost ratio (BCR) of restoration of (a) coral reefs, (b) mangroves, (c) saltmarsh, and (d) seagrass from 1980 to 2018. The benefit:cost ratio was calculated over 60 years with a 3.5% discount rate declining after 30 years to 3% (green, restoration benefits are higher than costs [i.e., $BCR > 1$]; red, restoration benefits are lower than costs [i.e., $BCR < 1$])

FIGURE 5 Benefit:cost ratio (BCR) of restoration predictor variables that contribute >50% to the boosted regression tree model: (a) coral reef restoration technique has a relative contribution of 71.6%, (b) mangrove restoration ecosystem services have a relative contribution of 96.8%, (c) saltmarsh restoration technique has a relative contribution of 34.8%, (d) saltmarsh restoration ecosystem services have a relative contribution of 37.9%, and (e) seagrass restoration duration has a relative contribution of 70.9%. All other predictor variables were nonsignificant. The fitted function is the difference between the actual y -axis value and the mean response value

DISCUSSION

Profitability of blue restoration

Our benefit:cost analyses showed that blue restoration can be an economically beneficial strategy that could help reduce or reverse the degradation of the four key marine ecosystems assessed. However, the BCR varied among ecosystems and with factors associated with their restoration.

We found higher BCRs for restoration than prior researchers. For example, the estimated net benefits (i.e., when benefits > costs) of coral reef and seagrass restoration were higher than in prior studies (BCR of 4 and 5, respectively, compared with 0.05 in De Groot et al. [2013]). The greatest net benefits were in saltmarsh and mangrove restoration, which was in line with prior studies, where these ecosystems had the greatest absolute benefits (i.e., net present value) of restoration of all ecosystems assessed (De Groot et al., 2013).

The higher BCRs we found were due to lower cost estimations because we used the same source for benefit values (Van der Ploeg & De Groot, 2010) and discount rates were comparable (−1% to 8% in De Groot et al. [2013]). Further, the estimated costs of coral reef, mangrove, saltmarsh, and seagrass restoration have declined over time; median values reported here were all lower than those reported for restoration up until 2014 (Bayraktarov et al., 2016). Thus, any further reductions in the costs of restoration are likely to further increase the net benefits of restoration and increase confidence in restoration investment.

Investment in longer term monitoring and maintenance of restoration in all blue ecosystems will lead to increased net benefits. Blue restoration projects are usually short term (1–2 years), whereas the estimated time to reach a state similar to reference sites is 20–30 years (Bayraktarov et al., 2016; Duarte et al., 2020). This discordance is highlighted here as the time to return on investment (i.e., when benefits from ecosystem services outweigh the costs): 18 years in mangrove and more than 70 years in seagrass and coral reef restoration.

Spatial patterns in net benefits

The benefits of coral reef restoration were the greatest in the coral triangle (Indonesia, Thailand, and the Philippines) and on the Great Barrier Reef in Australia. These areas were identified as having other covariates related to producing benefits, such as lower income countries and use of low-cost restoration techniques (see below). Globally, mangrove restoration is economically viable. The greatest net benefits were produced by mangrove restoration in Vietnam and Thailand, neither nation is high income (correlated with low net benefits—see below). Restoration in these nations also produced high-value ecosystem services, such as provision of fish nursery services and reduction in damage during extreme events, respectively.

Net benefits were higher in lower income nations, where restoration is cheaper and benefits gained from livelihood services may be more valuable. In mangrove restoration, net benefits were greatest in Vietnam and Thailand (Lewis, 2001), which are categorized as having lower-middle and upper-middle incomes (World Bank, 2019). This relationship was still present but not significant in coral reef restoration, which had high net benefits (BCR = 3) in the Philippines (a lower middle-income country [Cruz et al., 2014]). Conversely, coral reef restoration projects in the United States (high-income country) were all net cost (i.e., costs outweighed benefits [Spurgeon & Lindahl, 2000; Miller & Barimo, 2001; Spurgeon, 2001]). However, these projects used expensive techniques (substrate addition and stabilization) (see “Predictors of net benefits”).

Predictors of net benefits

We hypothesized that net benefits of restoration may be associated with different predictor variables of restoration projects. In coral restoration, the greatest benefits were produced by

coral gardening with a nursery phase (Shaish et al., 2008; Levy et al., 2010) and with direct transplantation (Yeemin et al., 2006). Techniques with low BCRs, such as larval enhancement and substrate addition or stabilization, were not frequently used in coral reef restoration (1.3% and 25% of all coral reef restoration projects, respectively [Boström-Einarsson et al., 2020]). Conversely, techniques with high BCRs, such as transplantation, represented a much higher proportion (68%) of studies (Boström-Einarsson et al., 2020). This could indicate that the coral reef restoration industry may already be gravitating toward more economically viable techniques. However, it may also indicate there is higher reporting of less expensive techniques (e.g., transplantation) and shows the need for greater monitoring of blue restoration projects.

The type of ecosystem service provided was important in mangrove and saltmarsh restoration. In mangrove restoration, provision of fish nursery services in Australia (Saenger, 1996) and Vietnam (Adger et al., 1997; Lewis et al., 2003) led to high net benefits, whereas reduction of damage during extreme events produced high net benefits from mangrove restoration in Thailand (Lewis, 2001). In saltmarsh restoration, hydrological restoration and construction techniques had positive impacts on benefits, for example, in the United States (Milano, 1999; Minello et al., 2012). Similarly, water purification services produced high net benefits, as exemplified by the restoration of saltmarsh in Silver Springs, Maryland (USA) (Spurgeon, 1999), which was associated with water purification services worth ~US\$820,000 ha^{−1} year^{−1} (Van der Ploeg & De Groot, 2010). Comparatively, hunting and fishing services associated with saltmarsh restoration in the U.S. northeast only produced benefits of approximately US\$900 ha^{−1} year^{−1} (Louis Berger & Associates, Inc., 1997). These results suggest that consideration of which ecosystem services will be provided when planning saltmarsh restoration projects is important because some services are more economically viable than others.

In seagrass restoration, the most important predictor of net benefits was project duration in Australia (Paling & van Keulen, 2002; Stowers et al., 2006), which could be due to spread of costs over a longer time frame. After initial outlays when setting up a restoration project, costs may decrease; minimal amounts may be required for maintenance and monitoring (De Groot et al., 2013). These results suggest that planning and implementation of long-term projects can increase the net benefits provided by restoration.

Limitations

There are limited data availability and high levels of uncertainty for both benefits and costs used in our cost–benefit analyses. The ESVD database, although extensive (Van der Ploeg & De Groot, 2010), lacks data on many ecosystem services for each ecosystem, with data on an average of only 12 services per biome out of a possible 22 (De Groot et al., 2012). Each benefit estimation here typically refers to a single ecosystem service, whereas in reality a habitat will produce benefits from

many ecosystem services. As such, it is likely that the values we assigned to restoration projects here underestimate the full value of benefits derived from all ecosystem services. There are also potential benefits from blue restoration we did not consider, such as job creation, that would add greatly to the full picture of this analysis.

The costs we estimated had a huge range, even within ecosystems, as noted in prior analyses of costs (Bayraktarov et al., 2016), and reflected a range of factors, including incomplete and underreporting of many costs. Consequently, there were large uncertainties in these analyses that could be improved with more detailed accounting surveys of practitioners. Blue restoration is a relatively new field, meaning high costs often relate to small-scale pilot or experimental studies (median <1 ha for coral reefs, saltmarsh, and seagrass [Bayraktarov et al., 2016]). Reductions in costs from prior estimates were observed (Bayraktarov et al., 2016), and costs may reduce in the future as bottlenecks driving higher costs are identified.

Ideally, each observation would have information available for both benefits and costs. However, in the databases published in Bayraktarov et al. (2020), only 17% of coral reef, 40% of mangrove, 56% of saltmarsh, and 32% of seagrass restoration projects had information on costs, and none of these had estimates of the monetary value of benefits. We used the best available techniques for value transfer, but such exercises should be repeated as the availability of benefits data improves. In a review of studies that valued ecosystem services of mangroves, saltmarsh, and seagrass, Himes-Cornell et al. (2018) found that many (20%) used global estimates and applied these to their particular case study, and only one third used values from the same country, as we did here. None of the studies in the review ($n = 527$) used adjusted unit value transfer as we did.

We found that blue restoration could be economically viable in all of the ecosystems we considered, even in those previously labeled as cost prohibitive, such as coral reefs (De Groot et al., 2013). Mangrove and saltmarsh restoration produced the greatest net benefits of the ecosystems we considered, and although benefits were lower in seagrass and coral reef restoration, these projects still produced net benefits on average. Restoration in lower income countries may be more economically worthwhile than in high-income countries, most likely due to lower costs and greater benefits to local communities. The factors influencing net benefits of restoration varied by ecosystem, but clearly demonstrated that future consideration of the technique used in restoration and the ecosystem services provided are important when planning blue restoration projects


Although these results are encouraging, there was large variation in data, and many data gaps leading to exclusion of valuable information. In the future, longer term monitoring and more comprehensive reporting of data on the costs and benefits of blue restoration would contribute to clarity of the overall economic value of restoration. Further, although we see the economic viability of blue restoration generally increasing over time, integration of restoration efforts with other resilience-based management strategies (e.g., protected areas) will strengthen the efficacy and positive returns.

Longer projects will provide larger net benefits; however, these depend on securing funding that includes resources for maintenance and monitoring over the long term. Our results provide new insights into the economic costs and benefits of blue restoration and indicate that investment in restoration is worthwhile and could increase future benefits.

ACKNOWLEDGMENTS

We acknowledge the local Indigenous people, who are the traditional custodians of the lands under consideration. We thank the many individuals who contributed to the development of this article through their insights and edits, including H. Possingham, G. E. Stewart-Sinclair, M. S. Ward, and M. Davey. Finally, we acknowledge those who contributed to the development of the restoration costs databases, including E. Bayraktarov and A. van Herwaarden.

ORCID

Phoebe J. Stewart-Sinclair  <https://orcid.org/0000-0002-1569-4274>

Carissa J. Klein  <https://orcid.org/0000-0002-6299-6451>

Ian J. Bateman  <https://orcid.org/0000-0002-2791-6137>

Catherine E. Lovelock  <https://orcid.org/0000-0002-2219-6855>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Stewart-Sinclair PJ, Klein CJ, Bateman IJ, Lovelock CE. Spatial cost-benefit analysis of blue restoration and factors driving net benefits globally. *Conservation Biology*. 2021;35:1850-1860. <https://doi.org/10.1111/cobi.13742>

