Current Biology

Report

Ambitious global targets for mangrove and seagrass recovery

Highlights

- We estimated potential global recovery of mangroves and seagrass
- Protection reduces net losses and supports long-term recovery
- Restoration is critical to achieve net gains in ecosystem extent
- Both protection and restoration are required to achieve and sustain global recovery

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In brief

Conservation action is needed to maintain and recover mangrove and seagrass ecosystems world-wide. Scenario-based models can inform ambitious and achievable global targets for coordinated action. Buelow et al. demonstrate that only protection and restoration combined can support substantial gains in mangrove and seagrass extent into the future.

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Ambitious global targets for mangrove and seagrass recovery

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SUMMARY

There is an urgent need to halt and reverse loss of mangroves and seagrass to protect and increase the ecosystem services they provide to coastal communities, such as enhancing coastal resilience and contributing to climate stability.[1,2] Ambitious targets for their recovery can inspire public and private investment in conservation,[3] but the expected outcomes of different protection and restoration strategies are unclear. We estimated potential recovery of mangroves and seagrass through gains in ecosystem extent to the year 2070 under a range of protection and restoration strategies implemented until the year 2050. Under a protection-only scenario, the current trajectories of net mangrove loss slowed, and a minor net gain in global seagrass extent (~1%) was estimated. Protection alone is therefore unlikely to drive sufficient recovery. However, if action is taken to both protect and restore, net gains of up to 5% and 35% of mangroves and seagrasses, respectively, could be achieved by 2050. Further, protection and restoration can be complementary, as protection prevents losses that would otherwise occur post-2050, highlighting the importance of implementing protection measures. Our findings provide the scientific evidence required for setting strategic and ambitious targets to inspire significant global investment and effort in mangrove and seagrass conservation.

RESULTS AND DISCUSSION

Throughout the Anthropocene there has been rapid degradation and loss of ecosystems that support biodiversity and deliver benefits to humanity.[4] Increasing awareness of the importance of ecosystems and their services has triggered a wave of international conservation strategies and policies, such as the UN Strategic Plan for Biodiversity[5] (2011–2020) and the Paris Agreement[6] (climate policy initiated in 2015). These initiatives can enable action to conserve ecosystems, particularly if they are supported by achievable and ambitious ecosystem-based policy goals and targets.[7–9] Allowing science to underpin target setting is crucial, as many countries have committed to area-based targets that are unrealistically large and could result in perverse conservation outcomes if best restoration practices are sacrificed for short-term areal gains.[10,11] While unrealistic targets and perverse outcomes are undesirable, ambition is necessary to combat climate change and ecosystem degradation[2] and will stimulate the development of tools and practices that can effectively scale-up restoration and overcome logistical constraints to achieving targets. Scenario-based models can help set scientifically sound targets that balance realism with ambition, are quantifiable and scalable, and capture nuanced ecological processes—features that are critical to target effectiveness.[12,13]

Mangrove and seagrass ecosystems need robust global conservation targets to inspire coordinated action. In recent decades, improved conservation of mangroves has slowed rates of loss and imparted optimism for their future,[14] despite their extinction being once considered a possibility.[15] Global targets can support this bright future for mangroves; however, the rate at which protection and restoration need to occur nationally to achieve them has not been evaluated. This information will help synchronize continued action to recover lost mangroves and protect those remaining from ongoing and emerging anthropogenic threats, such as aquaculture and oil palm, respectively.[16] In contrast, seagrasses have not received substantial conservation attention globally[17] despite several regions being at high risk from anthropogenic threats, primarily increases in turbidity and destructive demersal fishing.[18] Without effective conservation action, the continued degradation and loss of mangroves and seagrass will compromise coastal livelihoods, food security, and culture through lost ecosystem services;[1] contribute to climate change through greenhouse gas emissions;[19–21] and negatively impact biodiversity.[22]

Global extent change of mangroves and seagrass with protection and restoration

We evaluated what gains in ecosystem extent could be achieved for mangroves and seagrasses globally through rapid and extensive protection and restoration efforts using scenario-based Markov projection models (Figures 1A and 1B). We projected mangrove and seagrass ecosystem extent change to 2030, 2050, and 2070 under intermediate and ambitious conservation scenarios (i.e., targets set to achieve substantial or near-complete recovery, respectively), compared to a baseline scenario of no additional conservation (Table 1). Conservation scenarios included protection, restoration, or a combination of both. We defined protection as activities on land or sea that halt existing ecosystem loss and restoration as activities that create new areas of mangroves or seagrass where loss or degradation has occurred (and so does not include afforestation). For coastal ecosystems (particularly seagrasses), protection could include action in catchments that slow or prevent ecosystem pressures, such as enhancing water quality or catchment-coast connectivity. We assumed best practice for protecting or restoring coastal ecosystems that ensures these actions do not impinge on indigenous peoples' and local communities' rights and livelihoods, and that they are inclusive and equitable.[23,24]

Our projections suggested that without additional conservation action there would be global net loss of mangrove and seagrass extent equal to 1,122 km^2 (0.8% of total observed extent [TOE]; Figure 1C) and 55 km^2 (0.5% of TOE; Figure 1D), respectively, by 2070. Protection of mangroves could reduce the amount of loss but would not be sufficient to negate net loss in global extent (Figure 1C), while protection of seagrass could allow small net gains in global extent by 2050 and 2070 (Figure 1D). Considerable net gains in global extent of mangroves and seagrass, however, were possible under both the restoration ("R") and combined protection and restoration scenarios ("PR"; Figures 1C and 1D). This suggests that in addition to protecting extant mangroves and seagrasses, restoration is a critical conservation action, as protection alone will not reverse current trends of net extent loss. The importance of restoration has been formalized in international resolutions such as the UN Decade on Ecosystem Restoration[30] (2021–2030), with both governments and civil society facilitating on-the-ground action. For example, the World Wildlife Fund has recently launched conservation programs that aim to implement new protected areas, enhance existing protection, and restore 10,000 km^2 of mangrove forest across a number of countries, including Colombia, Madagascar, Fiji, and Mexico, and 25 km^2 of seagrass in the United Kingdom by 2050.[31,32] While NGOs can facilitate conservation action, governments will need to provide policies that support their ongoing protection and restoration.

The greatest net gains in global extent were projected to occur under the combined ambitious protection and restoration scenario ("PR(A)"), with recovery of 8,006 km^2 of mangroves (5.5% of TOE; Figure 1C) and 3,625 km^2 of seagrasses (34.9% of TOE; Figure 1D) by 2050. The estimate for mangroves is comparable to an estimate of total global restorable area (8,120 km^2);[33] however, a global estimate of restorable area is not yet available for seagrass. Without continued restoration efforts after the year 2050, net gains in ecosystem extent by 2070 were reduced by 1,128 km^2 for mangroves and 13 km^2 for seagrasses, due to continued losses in both ecosystems (Figures 1C and 1D). Reductions in net gains by 2070 were even greater under the restoration only ("R") scenario (Figures 1C and 1D), underlining the importance of protection for maintaining both extant ecosystems and gains in extent achieved through restoration by reducing losses from human pressures. For mangroves, protected area expansion is the preferred management action because it is generally less expensive and more efficient than restoration,[16] and some mangrove conservation strategies such as carbon crediting show high potential return on investment globally.[34] Further, protection allows ecosystem services, such as carbon sequestration, to accrue.[35] However, restoration remains important to achieving future targeted gains in extent because, even with ambitious protection effort, some losses are expected to continue.

We did not model potential losses or gains of mangroves and seagrass due to climate change (although we did include losses due to extreme weather events; Table S2). Projections for mangroves and seagrass were highly sensitive to the initial restorable area and restoration success (Figure S1), both of which could change substantially with processes related to climate change, such as relative sea-level rise. For example, scenario-based models of mangrove and seagrass extent change under sea-level rise have demonstrated that both continued loss and expansion are possible trajectories, dependent on whether there is sufficient space for landward migration, if sediment accretion allows shoreline progradation, or if water quality management is sufficient to mitigate seagrass losses.[36,37] Projections of extent change were moderately sensitive to annual rates of loss and expansion (Figure S1), which will likewise be influenced by sea-level rise,[37] climatic variation,[38] and other geo-political and economic factors that determine coastal development and "coastal squeeze."[39] Seagrass extent change estimates at the national level may also be biased, either positively or negatively, in countries with few observations (see Table S3 for the number of observations in each country). Projections were less sensitive

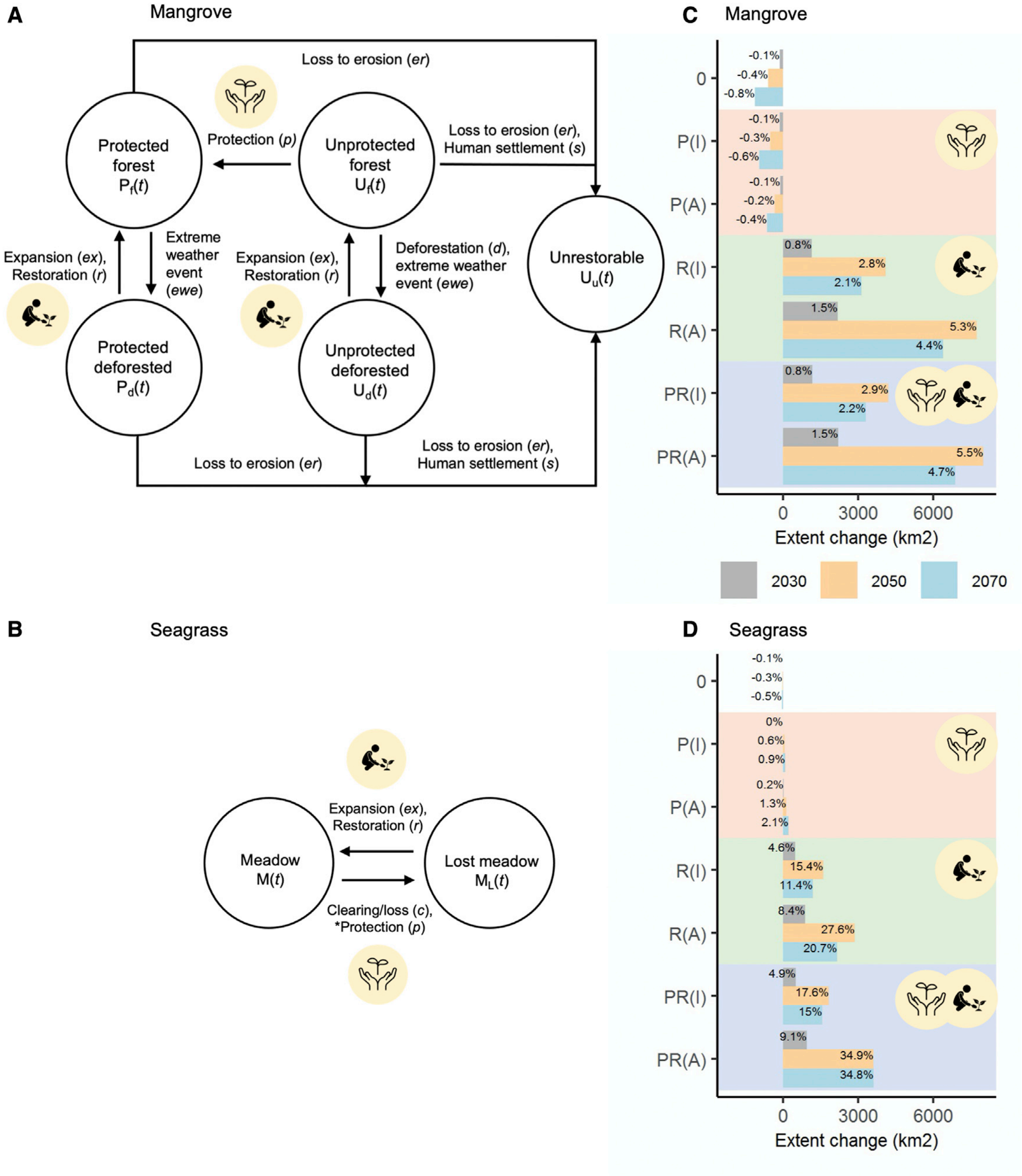

Figure 1. Model states and transitions and projected global net change in ecosystem extent (km^2)

(A and B) States are represented by circles and state-state transitions by arrows for (A) mangroves and (B) seagrass. The processes underpinning state-state transitions are listed adjacent to each arrow (see STAR Methods for further description of model states and transitions and Tables S1 and S2 for an explanation of the model assumptions and caveats, respectively). Due to lack of global data on seagrass extent change and drivers of loss, we were unable to explicitly model protected, unprotected, and unrestorable states for seagrass; however, the probability of transitioning from meadow to lost meadow can vary according to whether protection measures are implemented (i.e., *p).

(C and D) The models were used to quantify global net change in ecosystem extent for the years 2030, 2050, and 2070 for (C) mangroves and (D) seagrass under baseline (0; white), protect (P; pink), restore (R; green), and protect and restore (PR; blue) scenarios. Intermediate and ambitious scenarios are denoted by “I” and “A” in parentheses (see Table 1 for scenario descriptions). Total net losses and gains were calculated from the year 2023 and percentages represent net loss or gain relative to total observed extent. Total observed extent for mangroves was mapped via remote sensing from 1996 to 2016[25] and total observed seagrass extent was obtained from observations collated in a literature synthesis, with observations starting in 1879.[26] Note that data used for projecting seagrass extent change were not globally comprehensive and therefore estimates only represent what can be achieved with protection and/or restoration at the 349 study sites. See Figures S1 and S2 for sensitivity of model projections.

Table 1. Conservation scenarios for mangroves and seagrass

Scenario	Target-setting	Relevance	Mangroves	Seagrass
Baseline—0	no additional protected area expansion or restoration	–	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and assuming no further protection or restoration	seagrass extent was projected to 2070 at each site using current annual rates of loss/expansion and assuming no further protection or restoration
Protect				
Protect—P(I)	intermediate—effectively protect 30% by 2030	nature compact[27]	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and yearly expansion of forest area under effective protection ($km^2 year^{-1}$) to reach a target of 30% protected by 2030, if protection is implemented in 2023	seagrass extent was projected to 2070 at each site using current annual rates of loss/expansion and yearly implementation of protection measures on either land or sea that abate loss at 30% of seagrass sites by 2030, if protection is implemented in 2023
Protect—P(A)	ambitious—effectively protect 50% by 2030	nature needs half[28]	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and yearly expansion of forest area under effective protection ($km^2 year^{-1}$) to reach a target of 50% protected by 2030, if protection is implemented in 2023	seagrass extent was projected to 2070 at each site using current annual rates of loss/expansion and yearly implementation of protection measures on either land or sea that abate loss at 50% of seagrass sites by 2030, if protection is implemented in 2023

(*Continued on next page*)

Table 1. ***Continued***

Scenario	Target-setting	Relevance	Mangroves	Seagrass
Restore				
Restore—R(I)	intermediate—restore 50% of loss by 2050	substantial recovery (i.e., 50%–90%[29])	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and restoration rates (km^{2}year^{-1}) required to restore 50% of loss since 1996 by 2050, if restoration is implemented in 2023	seagrass extent was projected to 2070 at each site using current annual rates of loss/expansion and restoration rates (km^{2}year^{-1}) required to restore 50% of known historical loss at each site by 2050, if restoration is implemented in 2023
Restore—R(A)	ambitious—restore 90% of loss by 2050	complete recovery (i.e., >90%[29])	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and restoration rates (km^{2}year^{-1}) required to restore 90% of loss since 1996 by 2050, if restoration is implemented in 2023	seagrass extent was projected to 2070 at each site using current annual rates of loss/expansion and restoration rates (km^{2}year^{-1}) required to restore 90% of known historical loss at each site by 2050, if restoration is implemented in 2023
Protect and restore				
Protect and restore—PR(I)	intermediate—effectively protect 30% by 2030 and restore 50% of loss by 2050	nature compact,[27] substantial recovery (i.e., 50%–90%[29])	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and intermediate action to protect and restore (described above) beginning in 2023	seagrass extent was projected to 2070 for each site using current annual rates of loss/expansion and intermediate action to protect and restore (described above) beginning in 2023
Protect and restore—PR(A)	ambitious—effectively protect 50% by 2030 and restore 90% of loss by 2050	nature needs half,[28] complete recovery (i.e., >90%[29])	mangrove extent was projected to 2070 for each country using current annual rates of loss/expansion and ambitious action to protect and restore (described above) beginning in 2023	seagrass extent was projected to 2070 for each site using current annual rates of loss/expansion and ambitious action to protect and restore (described above) beginning in 2023

Targets for each scenario were chosen for their relevance to current global initiatives and proposed mangrove and seagrass recovery timelines. Projections for mangroves and seagrass were based on trends estimated across the years 2010–2016 and 2000–2010, respectively. 0, baseline (white); P, protect (pink); R, restore (green); PR, protect and restore (blue); I, intermediate; A, ambitious.

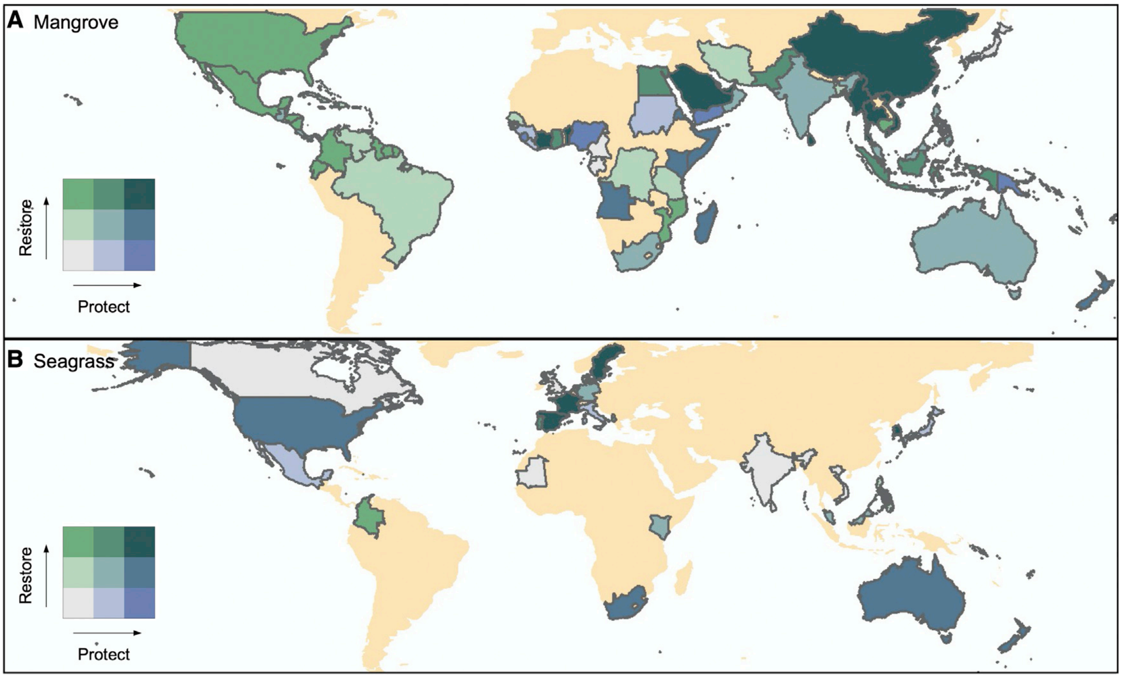

Figure 2. Relative importance of protection and restoration, nationally, for global conservation targets
Bivariate classification of countries according to the proportion of total observed ecosystem extent required to be protected or restored by the years 2030 and 2050, respectively, in each country to achieve global conservation targets for (A) mangroves and (B) seagrass under the ambitious protect and restore scenario (Table 1). Arrows on the legend axes indicate increasing amounts of protection or restoration, relative to total observed ecosystem extent in each country, and beige indicates no data. Total observed extent for mangroves was mapped via remote sensing from 1996 to 2016[25] and total observed seagrass extent was obtained from observations collated in a literature synthesis, with observations starting in 1879.[26] Note that the seagrass data are not globally comprehensive, so countries without data should not be considered as areas not in need of conservation action.

to assumptions regarding protection, i.e., effectiveness of protection and loss of protection over time (e.g., protected area downsizing, de-gazettement, or downgrading [PADDD]), leakage (i.e., displacement of threats to unprotected areas), and whether protection is targeted at areas with high rates of ecosystem loss (Figure S2).

National contributions to global targets

Projections of mangrove and seagrass extent change were evaluated at the country level to quantify national contributions to global targets. Mangrove and seagrass extent was projected to increase by 2070 in all countries under an ambitious scenario of combined protection and restoration, and the net gain in extent was either equal to or greater than that expected for protection-only or restoration-only scenarios. Under the baseline scenario of no additional conservation measures, Indonesia had the highest projected net loss in mangrove extent (504 km^2 between 2023 and 2070), but with ambitious protection and restoration a net increase of 1,518 km^2 could occur by 2070. For seagrass, the United States had the highest projected net decline in extent under the baseline scenario of no conservation (120 km^2 between 2023 and 2070), but with ambitious protection and restoration a net increase of 725 km^2 could occur by 2070.

The extent of mangrove protection and restoration required each year to achieve ambitious conservation targets ranged nationally from 0 to 969 km^2/year and 0 to 76 km^2/year, respectively. For seagrass, required national protection and restoration rates ranged from 0 to 86 km^2/year and 0 to 74 km^2/year, respectively. When compared to what has been pledged by some countries, these estimates are plausible. For example, the Indonesian government has set targets to restore 6,000 km^2 of mangroves by 2024,[40] which is far greater than the amount required by 2050 in Indonesia to reach our ambitious restoration scenario (i.e., 2,073 km^2). However, large-scale mangrove restoration efforts are typically unsuccessful,[16] so improved restoration practices are important to achieve success. Large-scale restoration of seagrass is possible, as demonstrated by the successful recovery of 36 km^2 *Zostera marina* in the United States over a 19-year period (1999–2018).[41] However, the current speed of seagrass recovery is not fast enough to achieve what is required under our ambitious conservation scenario. Given the increase in successful marine conservation action globally and advances in restoration technology and practices, the scale and rate of successful restoration efforts could advance rapidly.[29,42,43]

The relative proportions of mangrove and seagrass required to be protected or restored to achieve global conservation targets vary by country. In some countries, protection will make relatively larger contributions to global conservation targets than restoration, while the reverse is true in others (Figure 2). In China and Myanmar, for example, the proportions of total mangrove extent (including deforested areas) required to be protected or restored were both relatively high (Figure 2A). Combined protection and restoration are typical of countries where the proportion of mangrove forest currently protected is low and the area of forest that has been lost historically is large. Alternatively, in countries such as the United States and Mexico, which have protected a large proportion of mangrove extent but also have large areas of historical loss, the proportion of mangrove extent required to be restored was substantial, while the proportion requiring new protection was low (Figure 2A). Likewise, for seagrass in Colombia, the proportion of total extent required to be restored was high due to large areas of historical loss, but protection was not a priority given low rates of loss relative to other countries (Figure 2B). In contrast, several European countries that have experienced large amounts of seagrass loss at high rates required combined protection and restoration (Figure 2B).

While global targets are useful for coordinating action across countries, long-term success requires that demands on individual countries are equitable, discourage poor conservation practice, and positively support coastal communities and livelihoods.[23] For example, large area-based targets can lead to perverse outcomes[16,44] such as land or ocean grabbing[45] or failed mangrove planting projects on seagrass meadows.[46] Systematic conservation planning at local and regional scales can identify priority sites for restoration and protection while considering the feasibility of conservation actions,[47] and leadership by indigenous and local communities whose culture and livelihoods depend upon mangrove and seagrass ecosystem services will help to ensure conservation benefits both people and nature.[24,48,49] Future research could also determine what actions are necessary to achieve additional, complementary targets such as adequate representation of species and habitat diversity[50,51] and improved ecosystem function and service delivery.[46,52] Our interpretation of conservation outcomes for mangroves and seagrass is limited to the select scenarios investigated here (Table 1). However, outcomes under other conservation targets could be explored using our model in a user-friendly web app.

Conclusions

We have demonstrated that a general modeling framework, coupled with ecosystem extent trend data, can help to set ambitious targets for global conservation, which require both the protection and management of extant wetlands, and the restoration of these ecosystems throughout their distributions. The sheer magnitude of net gains in mangrove and seagrass extent needed to achieve recovery goals will require large-scale and coordinated investment in ecosystem restoration, supported by protection to conserve gains in extent into the future. Adopting these conservation actions will pay dividends for nations that will benefit from secure ecosystem goods and services and contribute to multiple global targets such as the UN Sustainable Development Goals (including goals 13 – Climate action, 14 – Life below water, and 15 – Life on land[53]) and the Post-2020 Global Biodiversity Framework, which envisions a future where humans live in harmony with nature.[54]

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2022.02.013.

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AUTHOR CONTRIBUTIONS

Conceptualization, C.J.B., R.M.C., D.A.A.-B., T.A.W., and C.A.B.; methodology, C.J.B., C.A.B., R.M.C., M.P.T., J.C.D., D.A.F., S.Y.L., M.F.A., G.N.A., D.A.A.-B., P.B., S.W.J.C., C.E.L., E.C.M., R.M.P., M.S., A.I.S., and T.A.W.; formal analysis, C.A.B., C.J.B., and M.P.T.; writing, C.A.B., C.J.B., R.M.C., M.P.T., J.C.D., D.A.F., S.Y.L., M.F.A., G.N.A., D.A.A.-B., P.B., S.W.J.C., C.E.L., E.C.M., R.M.P., M.S., A.I.S., and T.A.W.; funding acquisition, R.M.C. and C.J.B.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Global mangrove extent and rates of expansion	[25]	https://doi.org/10.3390/rs10101669
Seagrass meadow extent and rates of expansion/loss	[26]	https://doi.org/10.1111/gcb.15684
World Database on Protected Areas	[55]	https://www.protectedplanet.net/en
Country land and exclusive economic zone (EEZ) boundaries	[56]	https://doi.org/10.14284/403
Rates of mangrove loss (2010-2016) by natural and anthropogenic drivers for individual countries	[57]	https://doi.org/10.1111/gcb.15275
Data and code from this study	This study	https://doi.org/10.5281/zenodo.5889512
Software and algorithms		
R	[58]	https://www.r-project.org/
ArcGIS Pro	[59]	https://www.esri.com/en-us/arcgis/products/arcgis-pro/resources
R package 'sp'	[60,61]	https://cran.r-project.org/web/packages/sp
R package 'sf'	[62]	https://cran.r-project.org/web/packages/sf
R package 'raster'	[63]	https://cran.r-project.org/web/packages/raster
R package 'doParallel'	[64]	https://cran.r-project.org/web/packages/doParallel
R package 'foreach'	[65]	https://cran.r-project.org/web/packages/foreach

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by Lead Contact, Christina A. Buelow (c.buelow@griffith.edu.au).

Materials availability

This study did not generate unique reagents.

Data and code availability

Original code has been archived at Zenodo and the DOI is listed in the key resources table. All data used in the analyses are publicly available and are linked to in the key resources table. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Mangrove and seagrass study systems

Mangrove ecosystems have been mapped extensively via satellite remote sensing, allowing for accurate estimates of extent and change.[66] We quantified the current and deforested extent of mangrove forests and rates of expansion in each country using the most accurate available data on global mangrove distribution from 1996-2016.[25] To estimate rates of mangrove loss, we used global data that attributes loss to natural and anthropogenic drivers (i.e., erosion, human settlement, extreme weather events, commodities, and non-productive conversion (i.e., mangrove loss within a 5.5km radius of human settlements and roads).[57] Data layers of extent and expansion[25] were not spatially congruent with the layer of loss;[57] for countries with missing data, we used average rates of loss to each driver calculated for their respective marine province(s).[67]

While globally comprehensive datasets on seagrass distribution exist,[68–70] there are no corresponding time-series. Therefore, extent change could not be estimated globally. Instead, we modeled seagrass conservation scenarios at 349 sites where rates of expansion and loss have been estimated for the decade 2000-2010 from a time-series of seagrass area observations beginning as early as 1879.[18,26,71] We chose to use trends estimated for 2000-2010 because it was the most recent decade with the greatest global coverage of sites.[26] Site-level results were aggregated by country to evaluate national trends in seagrass extent change over time.

Prior to projecting extent change for both mangroves and seagrass, we considered countries and sites with an annual rate of change greater than +3 or less than −3 standard deviations from the mean (i.e., z-score) as outliers. Countries and sites identified as potential outliers likely had extreme high or low annual rates of change due to possible remote sensing data or observational errors. Annual rates of change for these countries or sites were set to a maximum (if z-score > 3) or minimum (if z-score < −3) annual rate of change value across all locations within the +3 or −3 z-score range.

METHOD DETAILS

Projected extent change

We projected extent change of mangroves and seagrass in predefined states over time using Markov projection models[72] (Figures 1A and 1B). Mangroves were classified into five 'states': unprotected forest (U_f), protected forest (P_f), unprotected deforested (U_d), protected deforested (P_d) and unrestorable area (U_u) (Figure 1A). We defined the processes underpinning transitions between mangrove ecosystem states as: protection (*p*), restoration (*r*), expansion (*ex*), deforestation (*d*), loss to extreme weather events (*ewe*), loss to erosion (*er*), and loss to human settlement (*s*) (Figure 1A). Erosion (*er*) and human settlement (*s*) were classified as drivers of unrestorable loss, while deforestation (*d*) included drivers of restorable loss, i.e., commodities, and non-productive conversion (e.g., mining). Protection could be via protected areas (PAs) or other effective area-based conservation measures (OECMs), both of which were assumed to be effective at abating loss to deforestation (*d*) and human settlement (*s*). Restoration was assumed to follow best-practice guidelines (e.g., the use of native species and suitable locations according to social and physical factors that influence restoration success[46,73]).

We classified seagrass into meadow (M) or lost meadow (M_L) and defined the processes associated with transitions between seagrass ecosystem states as: protection (*p*), restoration (*r*), expansion (*ex*), and clearing/loss (*c*) (Figure 1B). The seagrass model had fewer states and transitions than for mangroves owing to the lack of high resolution data on the drivers of loss.[26] Sites with the highest rates of loss were selected for protection. Similar to mangroves, restoration in seagrass was assumed to follow best practice guidelines, which include large-scale planting of native, foundation species that are in close proximity to donor beds.[74] Conceptual models of ecosystem state categories and transition rates for both mangroves and seagrass (Figures 1A and 1B) are *sensu* Possingham et al.,[75] Adams et al.,[76] and Kuempel et al.[77]

Initial conditions (states and transition rates) for Markov projection models were parameterized at the country level for mangroves and at the individual site level for seagrass (see Table S4 for description of data sources and processing). To project the extent of mangrove and seagrass in different states through time, we used a vector of initial states and a matrix of state-state transition probabilities for each country or site. Transition probabilities (*pr*) are the probability that a state will transition to another state from time *t* to time *t* + 1, and were calculated with the formula:

$$pr = 1 - e^{-r} \qquad \text{(Equation 1)}$$

where *r* is the annual transition rate corresponding to each state transition process defined in Figure 1. Where multiple transition processes mediate a single state-state transition we summed individual transition rates before calculating *pr*. For mangroves, both protection (*p*) and restoration (*r*) were assumed to occur as a constant fixed area in each year, as opposed to proportional to the area of the habitat available, and so were excluded from the transition probability matrix and instead included as additive terms at each time step of the Markov projection model (see Equation 2 below). For seagrass, restoration (*r*) was included as an additive term and protection (*p*) was modeled by setting the annual 'clearing/loss' transition rate (*c*) to 0 when a site became protected.

Protection and restoration rates for mangroves were calculated by quantifying proposed targets for 2030 or 2050 (Table 1) based on projected extent in 2023 and interpolating linear rates ($km^2 year^{-1}$) required to meet those targets. Restoration rates for seagrass were calculated similarly but, for protection, seagrass sites with the highest annual 'clearing/loss' rates were selected to be protected (e.g., a target of 'protect 30%' means that we selected 30% of seagrass sites with the highest annual rates of loss) and assigned a 'protection year'. 'Protection year' was allocated so that sites were protected additively each year to reach a cumulative total equal to the protection target by 2030. This also meant that seagrass sites with the highest annual rates of loss were protected in the first year of conservation intervention, while sites with the lower annual rates of loss were protected in the following years.

Following construction of the transition probability matrix and calculation of protection and restoration rates, we multiplied a country or meadow's initial state vector values at time *t* by the matrix of transition probabilities. If appropriate, we also added protection and restoration variables to determine the amount of habitat in each state at time *t* + 1, defined in matrix notation as:

$$N_{t+1} = A_t N_t + P + R \qquad \text{(Equation 2)}$$

where *N* is a vector of habitat states, *A* is the transition matrix, *P* and *R* are the amount of protection and restoration in kilometres-squared per year, respectively. To project the amount of ecosystem in each state to 2070 under baseline and conservation scenarios (Table 1) we repeated the process of matrix multiplication (Equation 2).

Conservation scenarios

Conservation scenarios included protection and restoration targets set for the years 2030 and 2050, respectively, and align with priority actions recommended for mangroves and seagrass that are based on recent literature and data syntheses[29] and milestone years for the Post-2020 Global Biodiversity Framework[54] (Table 1). We set conservation interventions to begin in 2023, allowing for a two-year initial implementation lag between the time of analysis (i.e., 2021) and the start of conservation projects on the ground. We projected forward from the end of each data series (2016 for mangroves and 2010 for seagrass) to 2023 assuming no additional protection or restoration, and then projected forward to 2070 assuming protection and restoration targets for each scenario defined in Table 1. Note that we projected twenty years beyond the restoration target year of 2050 to quantify outcomes after conservation actions to achieve targets has been completed.

Sensitivity analyses

We conducted sensitivity analyses for rates of expansion and loss, and the initial condition of restorable area to determine their influence on projected outcomes. We also tested sensitivity of model projections by varying initial assumptions so that: 1) there was deforestation of mangroves in protected areas from illegal activities, 2) seagrass protection was only effective at abating a percentage of loss, instead of all loss, 3) mangrove protection was not permanent (e.g., downgrading, downsizing, or de-gazettement could occur), 4) restoration success was variable, 5) increased protection of mangroves caused displacement of deforestation activities elsewhere (i.e., leakage), and 6) seagrass protection was not targeted at sites with high annual rates of loss, but instead was targeted either randomly or at sites with low rates of loss.

QUANTIFICATION AND STATISTICAL ANALYSIS

All analysis and spatial data processing was completed in R version 3.5.2[58] or ArcGIS Pro version 2.5.0.[59] Spatial data processing in R used the following packages: ‘sp’[60,61], ‘sf’[62] and ‘raster’[63]. Where required, parallel processing was conducted using the R packages ‘doParallel’[64] and ‘foreach’[65]. A web application for exploring projections of ecosystem extent under conservation scenarios can be found here: https://github.com/cabuelow/target-setting-app