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Enabling conservation theories of change

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Global theories of change (ToCs) can provide broad, overarching guidance for conservation and sustainable use of Earth's ecosystems. However, broad guidance alone cannot inform how conservation actions will lead to desired socioecological outcomes. Here we develop a framework for translating a global-scale ToC into focused, ecosystem-specific ToCs that consider feasibility of actions, as determined by national socioeconomic and political contexts (that is, enabling conditions). We used coastal wetlands as a case study for developing the framework and identified six distinct multinational profiles of enabling conditions ('enabling profiles') for their conservation. For countries belonging to profiles with high internal capacity to enable conservation, we described plausible ToCs that involved strengthening policy and regulation. Alternatively, for profiles with low internal enabling capacity, plausible ToCs typically required formalizing community-led conservation. Our 'enabling profile' framework can be applied to other ecosystems to help operationalize the Kunming–Montreal Global Biodiversity Framework and meet sustainable development goals.

Theories of change (ToCs) have been used to describe how conservation interventions can achieve desired outcomes[1]. The Convention on Biological Diversity's Kunming–Montreal Global Biodiversity Framework (KM-GBF) has an overarching ToC for achieving a 2050 vision of 'humans living in harmony with nature' (ref. 2). However, the KM-GBF ToC is not described in detail despite recognition that a comprehensive ToC is necessary to achieve its goals and targets[3]. Operationalizing the KM-GBF ToC is further challenged by the scale and complexity of the conservation planning task; conservation actions will need to be implemented by a diverse set of actors working internationally, regionally and locally, including non-governmental organizations (NGOs), governments and communities[1,4]. Ultimately, many of these actors may benefit from well-defined ToCs that state how action can address drivers of ecosystem loss and degradation, dependent on socioeconomic and political factors that influence conservation feasibility (hereafter referred to as 'enabling conditions'). Enabling conditions are fundamental to the development of a meaningful ToC because ToCs will not be valid unless social, economic and political mechanisms are in place to enable conservation action[5].

We propose a framework for translating a global ToC into nested, ecosystem-specific ToCs informed by enabling conditions and drivers of ecosystem loss. Nesting regional or location-specific ToCs within an overarching ToC, such as the KM-GBF, can help to coordinate

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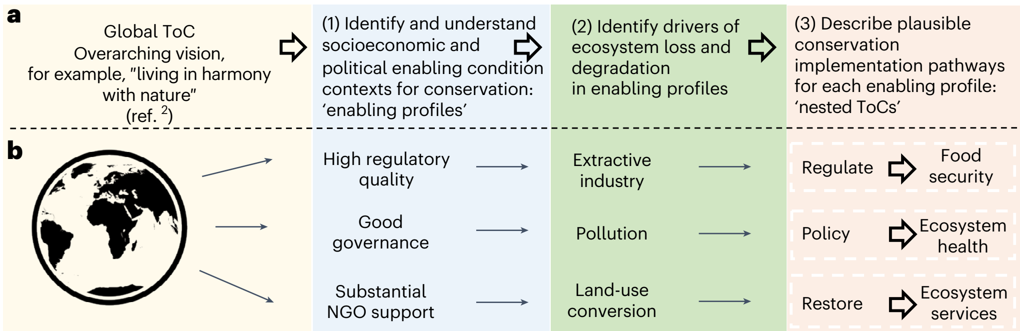

Fig. 1 | Operationalizing a global ToC. a, Steps to translate a global ToC into nested, ecosystem-specific ToCs informed by enabling conditions. **b**, Simplified example of three distinct enabling condition contexts (that is, enabling profiles), their primary drivers of ecosystem loss and nested ToCs. Note that in this example only one enabling condition and a driver of ecosystem loss or degradation are provided for illustrative purposes. In reality, there may be multiple, interacting enabling conditions and drivers of ecosystem loss and degradation that will need to be considered when developing a ToC.

multi-actor action towards global conservation goals[1]. Our approach involves three steps (Fig. 1a): (1) identify and understand 'enabling profiles', which represent unique socioeconomic and political enabling condition contexts for the conservation of a focal ecosystem, for example, national-scale differences in governance effectiveness, regulatory quality or NGO support (Fig. 1b); (2) identify drivers of ecosystem loss and degradation within each enabling profile, such as land use conversion, pollution or extractive industries (Fig. 1b); (3) describe plausible ToCs for each enabling profile, that is, conservation implementation pathways, ensuring that actions to address drivers of ecosystem loss, such as restoration, policy development or strengthening regulations (Fig. 1b) are feasible as determined by enabling conditions. Nesting of regional or location-specific ToCs within enabling profiles does not imply that ToCs should be developed from the 'top down'. Instead, enabling conditions can be used to determine the most effective combination of top-down (for example, national policy) and bottom-up (for example, community-led governance) approaches. Importantly, stakeholders representative of all spatial scales within a nested ToC pathway (for example, national to local) should be involved in its development to ensure just and equitable decision-making. This follows the recommendations by Ostrom et al.[6] for managing commonly owned resources via nested, cross-scale cooperation and governance, from local to global.

In this study, we use vegetated coastal wetlands—mangroves, seagrass, salt marshes—as a case study to demonstrate the proposed framework and summarize lessons learned as guiding principles for future application to other ecosystems ('Recommendations for operationalizing ToCs'). Vegetated coastal wetlands provide important services that support global environmental goals, such as action to regulate climate[7,8] and preserve biodiversity[9]. However, pressure on coastal ecosystems is increasing in all regions of the world[10], degrading these services and creating an urgent need for their conservation. Furthermore, coastal wetlands were underrepresented in global ecosystem assessments that informed the Convention on Biological Diversity's previous global ToC, the 'Strategic Plan for Biodiversity' (ref. 11), suggesting there is a need for more focused attention on their conservation. The current mechanism for implementing the KM-GBF are national biodiversity strategy and action plans[12] and so in our case study we consider how national enabling conditions relevant to coastal wetland conservation can inform the development of multinational enabling profiles and associated ToCs. Nested, subnational enabling profiles for coastal wetlands could also be established using information on regional (for example, state-based) and location-specific enabling conditions, thereby informing the development of locally relevant ToCs. In our case study, we only describe ToCs for seagrass and mangroves because global data on drivers of salt marsh loss were lacking.

Results

Identifying and understanding enabling profiles

From a database of 19 national socioeconomic and political enabling condition indicators (Supplementary Table 1), we used cluster analysis to identify six multinational enabling profiles for coastal wetland ecosystems (Fig. 2a). We then used classification trees to determine the relative importance of national indicators in differentiating enabling profiles (Fig. 2b) and how individual indicators define each profile (Fig. 2c). To aid interpretation, we categorized the 19 national indicators into the following groups: (1) policy—policy commitments and governance frameworks to facilitate conservation work (including international treaties); (2) regulation—active management of pressures and impacts to the environment; (3) engagement—active engagement with conservation, either through financial investment (domestic or foreign) or social interest (Fig. 2b,c).

Key indicators differentiating enabling profiles were the regulation of wastewater pollutants, regulation via environmental tax, the number of biodiversity-related projects funded by international aid, domestic conservation spending, Ramsar management and commitment to an international climate policy (nationally determined contributions (NDCs)) (Fig. 2b). Post hoc hierarchical cluster analysis revealed that enabling conditions in profiles 1 and 2 were less similar relative to profiles 3, 4, 5 and 6 (Fig. 2a). The majority, that is, 91%, of countries in profiles 1 and 2 were high-income countries, 77% of countries in profiles 3 and 4 were middle-income countries and 52% of countries in profiles 5 and 6 were low or lower middle-income countries (see Supplementary Fig. 1 for country income status and enabling profile designation).

Profiles 1 and 2 had high capacity to enable conservation through policy, regulation and domestic conservation investment relative to other enabling profiles; however, mangroves, seagrass and salt marshes were not included in their NDC climate mitigation and adaptation policy strategies (Fig. 2c). Profile 2 also had relatively low protection of vegetated coastal wetlands via the Ramsar convention, although implementation of management plans in Ramsar-protected areas was high (Fig. 2c). Profiles 3, 4, 5 and 6 generally had higher capacity for enabling conservation through engagement mechanisms linked to foreign aid and social interest, although profile 1 had relatively high NGO support for environmental projects and social interest in biodiversity. Conversely, policy and regulatory capacity in profiles 3, 4, 5 and 6 was typically lower, with the exception of NDC climate mitigation and adaptation strategies and Ramsar protection.

There were clear differences in the policy and regulatory capacity of profiles 3, 4, 5 and 6 (Fig. 2c). Specifically, profile 3 had moderate to high capacity for most policy and regulation indicators, whereas profile 4 had moderate to low capacity on most of these indicators (Fig. 2c). Profile 5 had relatively low policy capacity and moderate

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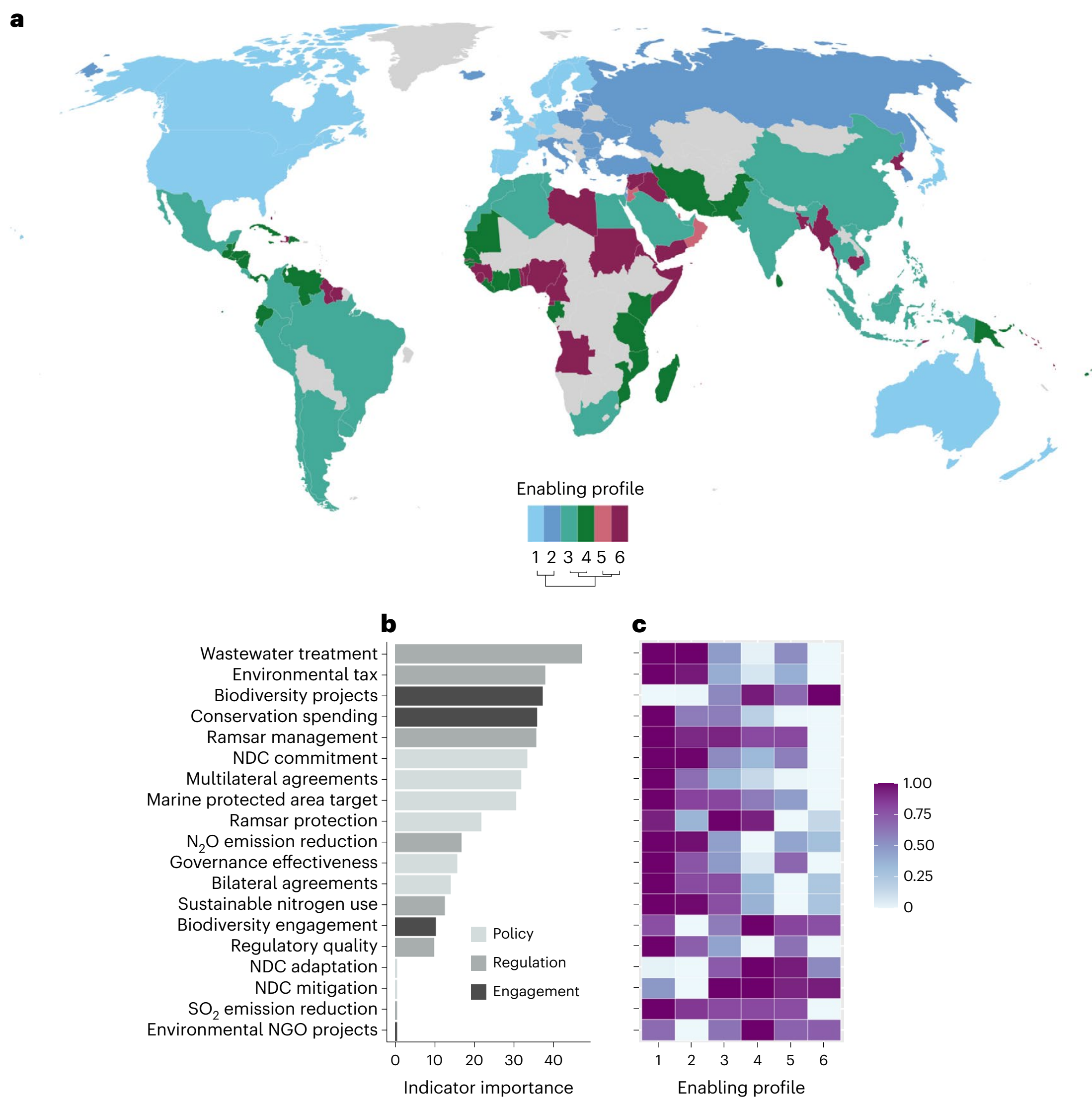

Fig. 2 | Enabling profiles for conserving coastal wetland ecosystems. **a**, Enabling profiles for vegetated coastal wetland ecosystems (seagrass, mangroves and salt marshes) ordered by their overall similarity (see the dendrogram below the profile legend). **b**, Relative importance of national indicators for defining enabling profiles. **c**, Relative ranking of national indicator thresholds across enabling profiles (low = 0 and high = 1). For ease of interpretation, national indicators are grouped as most relevant to policy, regulation or engagement. Mapped national boundaries are from Belgiu[43].

regulatory capacity (Fig. 2c). Profile 6 included countries affected by internal conflict (for example, Somalia) and international sanctions (for example, North Korea) (Fig. 2a), and had moderate to low capacity for most policy and regulation indicators, with the exception of including vegetated coastal wetlands in NDC climate change mitigation and adaptation strategies (Fig. 2c).

Identifying drivers of ecosystem loss

We identified drivers of ecosystem loss within enabling profiles for mangroves and seagrass only because global data on drivers of salt marsh loss were not available. For mangroves, the main drivers of loss within enabling profiles were non-productive conversion or erosion, although for profile 3, agriculture and aquaculture accounted for a substantial proportion of loss (Fig. 3). Profile 2 countries did not intersect with the global distribution of mangroves and so are absent from Fig. 3.

For seagrass, catchment processes (for example, coastal development, erosion, flooding) were a driver of loss common to all enabling profiles, while boating-related losses were unique to profile 1 (Fig. 4). Climate and storms were also drivers of loss for profiles 1 and 3; aquaculture and fishing drove seagrass loss in profiles 1, 2, 3 and 4; and disease drove seagrass loss only in profiles 1 and 4 (Fig. 4). Profile 5 countries did not intersect with the global seagrass change data and so are absent from Fig. 4.

Describing plausible, nested ToCs

We described a plausible ToC for conserving mangroves or seagrass in each enabling profile. Our ToC descriptions were formalized as causal statements of how action can address drivers of loss and lead to desired conservation outcomes (ref. 5; Fig. 5 and Supplementary Table 2 for a detailed description of all ToCs and case studies providing qualitative validation). In enabling profiles 1 and 5, non-productive conversion (for example, vegetation dieback from nearby human development such as mines and roads, harvesting of mangrove trees for timber) was a main driver of mangrove loss, but ToCs differed (Fig. 5 and Supplementary Table 2). In profile 1, improved monitoring of indirect negative effects on mangroves could inform improved policy and regulations to reduce mangrove dieback[13,14] (Fig. 5 and Supplementary Table 2). Alternatively, in profile 5, mangrove clearing for fuel or timber could be reduced if

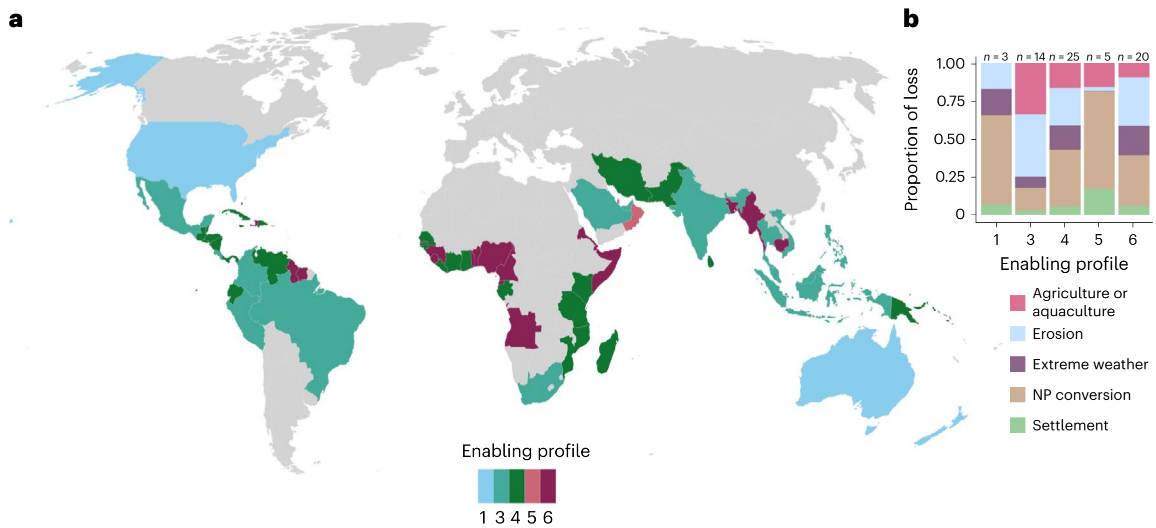

Fig. 3 | Drivers of mangrove loss in enabling profiles. a, Intersection of enabling profiles with countries where drivers of recent mangrove loss (that is, agriculture and aquaculture, erosion, extreme weather events, clearing and human settlement) have been mapped[40]. **b**, The proportion of mangrove loss attributed to each driver within each enabling profile (n = number of countries). Mapped national boundaries are from Belgiu[43]. NP, non-productive.

NGOs are engaged to support the development of community-based sustainable management of mangroves and ensure this is recognized in government policy[15] (Fig. 5). For seagrass, ToCs to address the loss driven by aquaculture or fishing differed between profiles 2 and 4 (Fig. 5). In profile 2, policy could be established to ensure aquaculture is not placed near seagrass[16]. In profile 4, external support and funding to establish payments for seagrass ecosystem services could provide an alternative source of income that incentivizes the reduction of destructive fishing practices that negatively impact seagrass[17] (Fig. 5).

Discussion

Our framework for operationalizing a global ToC ensures that enabling conditions underpin action-based pathways towards goals related to conservation and sustainable use of the planet, thereby increasing the likelihood of achieving desired outcomes[5]. Multinational enabling profiles, such as those developed in our coastal wetland case study, offer a platform for knowledge transfer between nations that have similar enabling conditions and drivers of ecosystem loss and degradation. In an era of rapid and complex global change, sharing knowledge about how to effectively implement sustainable management practices is important. Our framework could also encourage testing of conservation actions under similar or different enabling condition contexts, thereby encouraging experimental adaptation of ToCs[18].

ToCs for coastal wetland ecosystems

We identified six distinct multinational enabling profiles to inform nested ToCs for globally coordinated conservation of coastal wetland ecosystems. Profiles 1 and 2 generally had high capacity to enable conservation via policy, regulation and domestic funding relative to other profiles. Many countries in profiles 1 and 2 belong to the European Union where multilateral environmental agreements (for example, the Water and Marine Strategy Framework Directives) have improved water quality and led to recovery of lost seagrass[19]. Alternatively, in profiles 3, 4, 5 and 6, capacity to leverage support for conservation via engagement with external actors was relatively high (see Supplementary Table 2 for a detailed description of enabling conditions in each profile). In the past, external actors such as NGOs have had an important role in prompting governments of countries in these profiles, for example, Mexico and South Korea, to effectively implement Ramsar protection of wetlands[20]. We used enabling condition contexts unique to each profile to describe plausible ToCs for addressing dominant drivers of mangrove and seagrass loss (Fig. 5), and used examples of recent conservation interventions to validate proposed implementation pathways (Supplementary Table 2). Our coastal wetland ToCs are most relevant to actors developing and coordinating conservation actions internationally, but subnational data on enabling conditions could be used to develop ToCs relevant to regional and local scales.

Our case study had several limitations that impose constraints on the robustness of the enabling profiles and ToCs developed. Of primary importance is the lack of comprehensive data on indicators for some of the enabling conditions, for example, 'conservation spending', 'Ramsar management', 'biodiversity projects' and 'environmental NGO projects', which may bias construction of the enabling profiles. Furthermore, ToCs may not address all the important drivers of seagrass loss and degradation in each enabling profile because these are also not based on globally comprehensive data (see Supplementary Table 3 for a detailed description of all caveats). Our case study also lacked a systematic process for developing ToCs that engages stakeholders. In the next section, we make recommendations to guide future application of our framework to other spatial scales or ecosystems that is systematic and reproducible.

Recommendations for operationalizing global ToCs

Constructing enabling profiles that are representative of all conditions relevant to implementing conservation for a specific ecosystem will require compiling a comprehensive database of appropriate indicators. Where possible, indicators should be chosen systematically by first reviewing the literature for enabling conditions and management actions relevant to the conservation of a focal ecosystem, and then by asking stakeholders or external experts to (1) confirm the relevance of each indicator identified in the review to enabling conservation action and (2) rank the relative importance of relevant indicators to enabling actions against different drivers of ecosystem loss and degradation. In cases where there are several suitable indicators to represent an enabling condition, sensitivity analysis could be used to determine whether results are robust regardless of which indicator is chosen or whether greater consideration is needed to choose between competing indicators. Rankings of the relative importance of each enabling condition could be used to tailor enabling profiles to the most important

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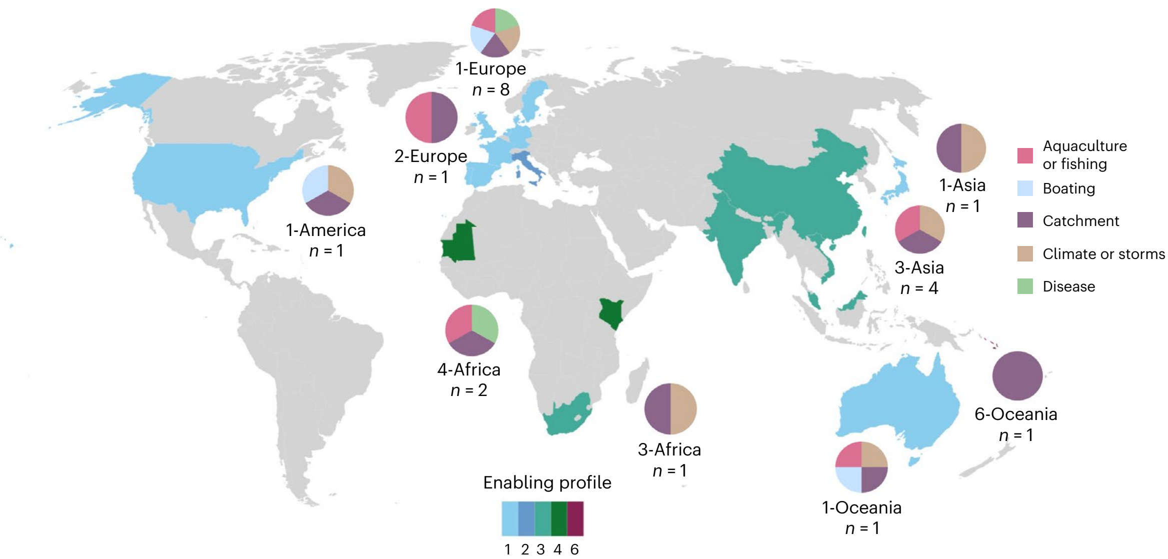

Fig. 4 | Drivers of seagrass loss in enabling profiles. Countries where seagrass drivers of loss (that is, aquaculture and fishing, boating, catchment processes, climate and storms, and disease) have been identified, coloured according to enabling profile. The pie charts represent the drivers of seagrass trends identified in each continent and enabling profile (n = number of countries). Seagrass driver data represent sites where seagrass drivers were identified via a synthesis of peer-reviewed literature[41] rather than the entire global distribution of seagrasses. Mapped national boundaries are from Belgiu[43].

drivers of ecosystem loss and degradation. For example, in our case study, enabling condition indicator scores could be weighted according to their importance for enabling action against dominant drivers of coastal wetland loss in each country. Finally, robust enabling profile construction may be hindered by lack of comprehensive data for indicators of enabling conditions, in which case the limitations this imposes on interpretation of enabling profiles should be communicated to end users, and effort should be made to fill indicator data gaps in the future to improve enabling profile robustness.

Ideally, effective actions to conserve focal ecosystems will be identified via systematic review of the literature and consultation with stakeholders or experts (see the recommendations in the previous paragraph). Plausible ToCs will describe how specific actions can feasibly address drivers of ecosystem loss given the enabling conditions. Guidelines for developing conservation ToCs have been developed comprehensively elsewhere[1,5], and so we do not provide specific recommendations for this process in this article. However, we suggest that, where possible, pathways for implementation should be tested quantitatively by relating enabling conditions to successful conservation interventions, thereby ensuring that ToCs are robust (see Williamson et al.[21]). Alternatively, in data-sparse contexts, real-world examples of conservation interventions can provide a qualitative alternative for justifying proposed ToCs, for example, our case study validations. We also suggest that where a range of competing plausible implementation pathways are developed, they could become testable hypotheses and form a basis for experimental adaptation of ToCs[18]. If experimentation cannot be used to choose from competing implementation pathways, the heuristic 'mitigation and conservation hierarchy' could help differentiate priority actions (that is, refrain, reduce, restore, renew)[4].

There is no 'one-scale-fits-all' ToC. For example, the nested ToCs that we have described in our case study may not have sufficient detail or local context for actors working to implement conservation on the ground. To overcome this, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has recognized the need for multi-scale conservation planning[22]. Future applications of our framework could be extended to support multi-scale conservation planning by establishing multi-level, hierarchical enabling profiles that represent enabling condition contexts operating at different spatial scales (for example, subnational enabling profiles nested hierarchically within multinational enabling profiles). To be relevant to local-scale conservation practitioners, ToCs could be developed using a participatory framework (see Reed et al.[23]) that engages actors working across sectors and scales, from local practitioners to international policymakers, and ensures that ToCs are just and equitable. It is also important to recognize that human behaviour can have an important role in whether ToCs will achieve the desired outcomes. Tacit working models of how human behaviour and conservation relate to one another could be used to integrate this understanding into ToC development[24]. Finally, ToCs will be dynamic, requiring adaptation as enabling conditions and drivers of loss change through time. In our coastal wetland case study, for example, rapidly developing middle- and low-income countries may acquire greater internal capacity for facilitating conservation and rely less on international aid[25], causing them to shift from enabling profiles 3, 4, 5 or 6 to profiles 1 or 2. Their ToCs could be adapted based on what has or has not worked for other countries belonging to profiles 1 or 2.

Nested ToC's could inform the development of globally coordinated National Biodiversity Strategies and Action Plans (NBSAPs), which are the current mechanism for implementing the Kunming–Montreal Global Biodiversity Framework[12]. The effectiveness of NBSAPs is challenged in part by a lack of specific guidelines and accountability for their development[12]. If adopted, our approach provides a quantitative framework that allows NBSAP developers to (1) incorporate enabling conditions and drivers of ecosystem degradation into conservation action pathway development (that is, ToCs), and (2) co-create nested ToC pathways with actors working subnationally, allowing opportunities for collaboration towards collective national and global conservation goals to be more easily identified. In this way, our framework for nested ToC development acts as a mechanism for cross-scale conservation action. This is especially important for resources such as coastal wetlands, which are typically communally owned and threatened by global, regional and local-scale processes, making effective cross-scale coordinating mechanisms, such as nested ToCs, essential[6,26].

A public platform for sharing knowledge could facilitate communication and cooperation between actors working at different levels of a nested ToC pathway or, alternatively, between actors in different enabling profiles that are working to address the same drivers

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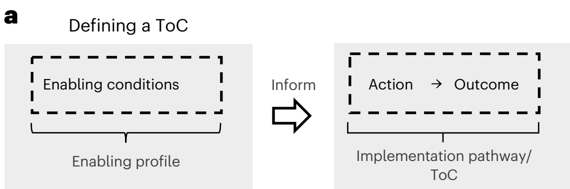

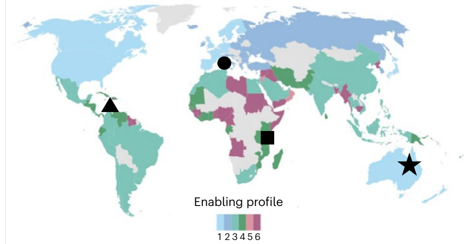

b Examples where mangrove loss is driven by non-productive conversion

Enabling profile	Enabling conditions	Implementation pathway/ nested ToC	Case study validation
1	Capacity to enable conservation via policy, regulation and domestic funding is high	Monitor indirect effects of development on mangroves → Tailor policy and regulations to mitigate indirect effects → Decreased mangrove dieback	Australia: mangrove dieback from herbicide run-off ★
5	Capacity to enable conservation via policy, regulation and domestic funding is generally low, but moderately high governance effectiveness	External NGO supports development of community-based sustainable management of mangroves with well-defined resource-use rights → Government establishes policy that recognizes communities as management authority → Reduced mangrove clearing for fuel and timber	St. Lucia: community-based sustainable management of mangroves ▲

c Examples where seagrass loss is driven by aquaculture or fishing

Enabling profile	Enabling conditions	Implementation pathway/ nested ToC	Case study validation
2	Capacity to enable conservation via policy, regulation and domestic funding is high	Establish policy that prevents fish farms from being established near seagrass → Reduced loss of seagrass to anoxia associated with fish farm pollution	Cyprus: seagrass recovers after strategic fish-farm placement ●
4	Capacity to enable conservation via policy, regulation and domestic funding is generally low	External support and funding secured to incentivize community-based management of fishing threats through payments for ecosystem services → Decreased loss and degradation of seagrass from fishing	Kenya: seagrass payments for ecosystem services ■

Fig. 5 | Enabling conditions inform nested ToCs. a, How to define a ToC. **b**, Selected mangrove case study ToCs. **c**, Selected seagrass case study ToCs. A comprehensive set of ToCs for each enabling profile and coastal wetland ecosystem is provided in Supplementary Table 2, along with a detailed description of supporting case study examples. An interactive visualization of the enabling profiles and all case studies is available at https://github.com/cabuelow/enabling-profiles-app. Mapped national boundaries are from Belgiu[43].

of ecosystem loss. A Web-based tool would not only make sharing information and coordinating actions easier, but could also serve as a monitoring, adaptation and accountability platform to ensure that progress towards conservation goals is made[27]. The platform would report on the enabling conditions and conservation plans, actions and outcomes of all contributing parties to the global ToC through time. Ideally the platform would also allow direct integration with NBSAP development and reporting, such as through the NBSAP online forum (https://www.learningfornature.org/en/nbsap-forum/). Making enabling profiles and ToCs underpin NBSAPs publicly available in an online platform where progress can be tracked could help improve transparency and accountability in NBSAP development.

Operationalizing a global ToC with our proposed framework could be challenged by lack of information on enabling conditions and effective conservation actions, and the technical expertise required to gather and analyse data to construct enabling profiles and develop ToCs. International NGOs, intergovernmental organizations and philanthropists can have a role in providing resources to overcome these challenges. Furthermore, effectively coordinating actions by actors working at different scales and institutions may also require the development of new cooperative mechanisms that increase information exchange and build capacity for achieving common conservation and sustainable development goals.

Global conservation planning and mapping has been criticized for lacking a clear ToC[28]. While global ToCs are at risk of failing to achieve goals if they are not translated effectively into tangible and discrete pathways for implementing action, our framework for operationalizing a global ToC ensures that conservation efforts are at the forefront in developing robust implementation pathways. Adoption of our framework as a coordinating mechanism for global action towards sustainable use of the Earth's ecosystems will help reduce rates of loss and degradation.

Methods

Database of national enabling condition indicators

We compiled a database of national values for 19 policy, regulation and engagement indicators representative of enabling conditions for vegetated coastal wetland conservation in 138 countries, that is, 70% of all countries with an oceanic coastline. To identify countries with these wetlands, we intersected the exclusive economic zone (EEZ) boundaries of countries that have an oceanic coastline[29] with the global distributions of mangroves[30], seagrass[31] and salt marshes[32]. Our enabling condition indicator database was developed via Web-based searches for suitable, publicly available global datasets providing information on policy, regulation and engagement, and whose relevance to coastal wetland conservation was informed by previous research[33,34] (see Supplementary Table 1 for literature supporting our choice of indicators). A caveat of our analysis is that we considered enabling condition indicators and drivers of loss to be static through time (Supplementary Table 3), using indicators with variable temporal ranges (Supplementary Table 1). Ideally, enabling condition indicators will be based on contemporary data and ToCs will be updated accordingly as new information becomes available.

We used national indicators to classify countries into global enabling profiles that represent similar policy, regulation and engagement settings for conservation. We first used a Bayesian latent variable model (LVM) to gap-fill missing indicator values before classification[35]. The LVM estimates correlations among all indicators across countries and leverages these correlations to interpolate missing values. The model assumes that values are 'missing at random', conditional on the other indicators. The model was formulated as:

$$\log(\mu_{ij}) = \theta_{0j} + \mathbf{z}_i^T\theta_j \quad (1)$$

where μ_{ij} is the mean response at country i for indicator j, θ_{0j} is the indicator-specific intercept, $\mathbf{z}_i$ are the vectors of latent variables and

θ_j are their corresponding indicator-specific coefficients[35]. We set the number of latent variables in our model to nine (approximately half the number of indicators), which provided accurate estimates of indicator responses (see Appendix 1 in the Supplementary Information for a detailed description of model settings). Before fitting the LVM, continuous indicator response variables were log-transformed and *z*-score standardized (mean = 0, s.d. = 1). We then used equation (1) to predict indicator values to all countries, including interpolating to those countries with missing values. Where indicators had values missing not at random, we fitted an additional LVM without these indicators to check that our predictions were robust.

Eleven indicators had missing values that were interpolated (see Supplementary Table 1 for the percentage of missing values for each indicator, ranging from 0% to 46%, and Supplementary Fig. 2 for assessment of the model fit). Data for the 'conservation spending' indicator were only available for countries that were signatories to the Convention on Biological Diversity or the sustainable development goals[36]. However, only one country (the United States) was missing a value for this reason; all other missing values were due to insufficient data[36]. The 'Ramsar management' indicator also had non-random missing values because countries without coastal wetland Ramsar sites were designated as 'NA' (Supplementary Table 1). Although there were non-random missing values in these indicators, this did not necessarily violate assumptions of the LVM because it assumes missing at random, conditional on other indicators. Furthermore, predictions from LVMs fitted with and without each indicator were positively correlated (Supplementary Figs. 3 and 4), demonstrating that parameter estimates were robust. We also performed a simulation study to measure the interpolative capacity of LVMs under scenarios where response variables have large proportions of values missing not at random (that is, 30%, 40% and 50%). Under each scenario, we simulated 100 datasets with 20 response variables ($n = 100$) by randomly drawing values from a multivariate normal distribution (correlation strength varying between −0.5 and 0.5). We then manipulated each simulated dataset so that one variable had large proportions of values missing not at random (that is, values above the 50th, 60th and 70th percentiles were missing). We used LVMs to interpolate missing values for response variables with missing values and found sufficient correlation between simulated data and the LVM predictions under all scenarios (median $R^2 = 0.65–0.72$) to justify the inclusion of variables with high proportions of values missing not at random in our case study (Supplementary Fig. 5). Supplemental methods for fitting models are also provided in Supplementary Appendix 1.

Classification of countries into global enabling profiles

We performed a cluster analysis on the gap-filled, standard-normal indicator values obtained from the LVM to group countries into enabling profiles. Specifically, we used *k*-medoid clustering with the 'partitioning around medoids' algorithm on a Euclidean distance matrix of indicator values. Standard-normal indicator values were rescaled to the minimum and maximum values of the indicator with the narrowest range before clustering to reduce the leverage of indicators with exceptionally large ranges (that is, binomial response variables: NDC commitment, NDC adaptation, NDC mitigation and Ramsar protection). We investigated a range of clustering configurations ($n = 5–10$) to identify the number of clusters that best represented country-level variability in indicator values, while also identifying general patterns useful for informing coastal wetland conservation. We used the average silhouette width[37] to measure the quality of each clustering configuration (that is, cluster cohesion and separation). All configurations were of similar quality, so we chose six clusters as the final configuration because it best balanced national indicator variability with generalizable patterns across countries. We assessed the robustness of clusters by re-evaluating the cluster analysis across the full distribution of indicator values predicted by the LVM (see Supplementary Figs. 6 and 7 for an assessment of the robustness of the final clustering configuration). We also tested the robustness of cluster configurations to the removal of variables with high proportions of missing values (that is, conservation spending and Ramsar management) by calculating the proportion of cases where pairwise clustering differed for each country with removal of these indicators (Supplementary Fig. 8). Overall, the pairwise clustering of most countries was robust to removal of the conservation spending indicator (pairwise clustering of more than 50% countries differed in less than 20% of cases) and Ramsar management (pairwise clustering of more than 50% of countries differed in less than 10% of cases) (Supplementary Fig. 8). Finally, we used post hoc hierarchical cluster analysis of cluster medoids to group and order enabling profiles according to their similarity and we used principal components analysis to visualize country-level variability within enabling profiles.

Indicators defining global enabling profiles

We used classification trees to determine (1) the relative importance of national indicators in the classification of enabling profiles and (2) how individual indicators define each profile. Classification trees are non-parametric, supervised machine-learning models that use recursive partitioning to generate decision rules that relate predictor variables (that is, indicator values) to response variables (that is, enabling profiles)[38]. Observations are repeatedly split into subgroups by predictor variables, aiming to minimize heterogeneity of observations in each subgroup of the final tree[38].

To measure the relative importance of indicators, we fitted a classification tree using indicator values as predictors of enabling profiles. Indicator importance was measured as the sum of the Gini goodness of split measure where the indicator was a primary splitting variable in the classification tree. Gini goodness of split is measured as the inverse of Gini impurity, an estimate of the probability of misclassification[39]. We also used decision rules generated by individual classification trees, where each indicator was the sole predictor of enabling profiles, to identify indicator thresholds that defined each profile. To minimize the influence of outliers on threshold definition, we fitted individual classification trees using only indicator values within the interquartile range of each enabling profile. Threshold values were rescaled from 0 to 1 to provide a relative measure of indicator scores defining each profile, where 0 = low and 1 = high.

Drivers of ecosystem loss in each enabling profile

We identified drivers of coastal wetland loss and degradation in each enabling profile using (1) data on drivers of mangrove areal loss derived from satellite data[40] and (2) data on the drivers of seagrass areal loss from a meta-analysis of in situ and remote sensing data[41]. Global data on drivers of salt marsh loss was not available[11]. We use the term 'drivers' to refer to environmental stressors (both human and natural) that can cause ecosystem loss and degradation. This is unlike the well-known Driver–Pressure–State–Impact–Response framework, first elaborated in the European Environment Agency programme and later on adopted for other environmental issues in Europe[42], which refers to human environmental stressors as 'pressures'. However, our terminology is consistent with the literature for mangroves[40] and seagrass[41].

Global drivers of mangrove loss from 2010 to 2016 were: erosion; extreme weather events; commodities (that is, agriculture or aquaculture); non-productive conversion (including clearing and dieback from indirect effects of human development); and human settlement[40]. We calculated the proportion of mangrove loss attributed to each driver in each country and then averaged these proportions across enabling profiles. This statistic standardizes for differences in overall mangrove area across different countries. Seagrass study locations from ref. 41 were intersected with country EEZ and enabling profile boundaries; drivers of trends were identified for each enabling profile and continent to determine opportunities for conservation.

Seagrass data were not globally comprehensive and so the identification of ecosystem loss drivers was limited to countries where peer-reviewed studies identified drivers of trends in seagrass meadow area. Primary drivers were identified from original sources in one of two ways: (1) attribution by visual (aerial imagery or graphical) or inferential (statistical) methods; or (2) the driver that was described and discussed most frequently[41]. We opted to exclude the 'invasive species' driver from our analysis because invasive fauna, such as disturbance by tunicates, crabs and lugworm, were not reported in the peer-reviewed literature, which may misrepresent the distribution and influence of this driver. Note that absence of these invasive fauna in the peer-reviewed literature may be due to lack of classification or nomenclature. For example, lugworm disturbance has been identified as a driver of seagrass loss, but the lugworm was not classified as an invasive species[41]. A complete description of mangrove and seagrass drivers is provided in Supplementary Table 4.

Nested ToCs for each enabling profile

We described nested ToCs for each enabling profile as causal statements that define how actions can lead to the desired conservation outcomes for mangroves and seagrass. Descriptions of plausible implementation pathways were informed by grey and peer-reviewed literature documenting effective action against drivers of ecosystem loss. We used case study examples to qualitatively validate nested ToCs.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All input data used in analyses were obtained from published sources cited in the Methods and Supplementary Information. They are stored on GitHub (https://github.com/cabuelow/enabling-theories-of-change) and archived on Zenodo (https://doi.org/10.5281/zenodo.8125788).

Code availability

The code to run the analyses and reproduce the figures is available on GitHub (https://github.com/cabuelow/enabling-theories-of-change), including an interactive application for exploring the profiles (https://github.com/cabuelow/enabling-profiles-app). The code is archived on Zenodo (https://doi.org/10.5281/zenodo.8125788).

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Author contributions

C.A.B., C.J.B., R.M.C., L.G. and V.J.D.T. conceived the project. C.A.B., C.J.B., R.M.C., L.G., V.J.D.T., B.H., J.C.D., S.Y.L., B.G.M., P.S.M., R.M.P., A.R., M.S., A.I.S., M.P.T. and J.V.-R. contributed to the methodology. L.G., C.A.B. and B.H. collected the data. C.A.B. and C.J.B. analysed the data. C.A.B. wrote the first draft of the manuscript. C.J.B., R.M.C., L.G., V.J.D.T., B.H., J.C.D., S.Y.L., B.G.M., P.S.M., R.M.P., A.R., M.S., A.I.S., M.P.T. and J.V.-R. contributed to revising the manuscript. C.J.B., B.G.M. and R.M.C. resourced the project.

Competing interests

The authors declare no competing interests.

Additional information

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Policy information about availability of computer code

Data collection	No software was used.
Data analysis	Code to run analyses and reproduce figures is available on Github (https://github.com/cabuelow/enabling-theories-of-change) and archived on Zenodo (https://doi.org/10.5281/zenodo.8125788) using R (version 3.5.2) and the following R packages: {boral}, {cluster}, and {rpart}.

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Study description	We compiled a database of national values for 19 policy, regulation, and engagement indicators representative of enabling conditions for vegetated coastal wetland conservation in 138 countries. We first used a Bayesian latent variable model (LVM) to gap-fill missing indicator values prior to classification. We then used a cluster analysis on the gap-filled, standard-normal indicator values obtained from the LVM to group countries into enabling profiles that represent similar policy, regulation, and engagement settings for conservation. Classification trees determined 1) the relative importance of national indicators in the classification of enabling profiles, and 2) how individual indicators define each profile. Drivers of coastal wetland loss and degradation in each enabling profile were identified using 1) data on drivers of mangrove areal loss derived from satellite data10, and 2) data on the drivers of seagrass areal loss from a meta-analysis of in-situ and remote sensing data. Finally, we described nested ToCs for each enabling profile as causal statements that define how actions can lead to desired conservation outcomes for mangroves and seagrass. We used case-study examples to qualitatively validate nested ToCs.
Research sample	Publicly available datasets, listed in Supplementary Table S1.
Sampling strategy	N/A
Data collection	Publicly available datasets, listed in Supplementary Table S1.
Timing and spatial scale	Temporal range of indicators is variable and documented in Supplementary Table S1. The spatial scale is global.
Data exclusions	N/A
Reproducibility	Scripts and data are provided to make all analyses reproducible.
Randomization	N/A
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