National SCIENCE Challenges

SUSTAINABLE SEAS

Ko ngā moana whakauka

Development of a seafloor model of disturbance impacts on benthic structure in the Hawke's Bay

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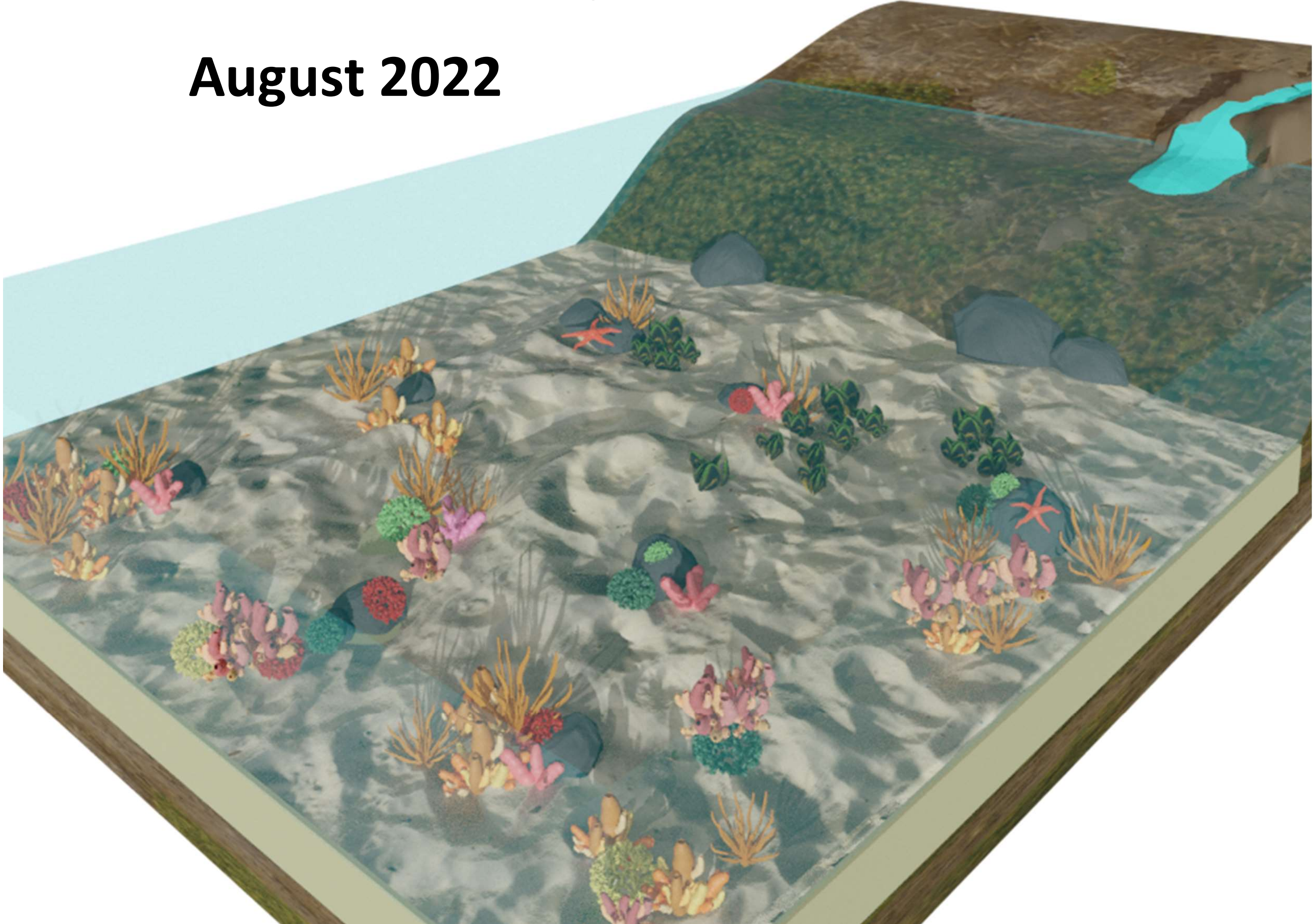
August 2022



Report for Sustainable Seas National Science Challenge project *Enhancing implementation of EBM in the Hawke's Bay (Project code S1)*

Authors

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For more information on this project, visit:
https://www.sustainableseaschallenge.co.nz/our-research/hawkes-bay-regional-study/

About the Sustainable Seas National Science Challenge

Our vision is for Aotearoa New Zealand to have healthy marine ecosystems that provide value for all New Zealanders. We have 60+ research projects that bring together around 250 scientists, social scientists, economists, and experts in mātauranga Māori and policy from across Aotearoa New Zealand. We are one of 11 National Science Challenges, funded by the Ministry of Business, Innovation & Employment.

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Cover image: Conceptual diagram of seafloor invertebrate communities (N. Yogesh).

Acknowledgements

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This model builds upon a model developed through significant funding from NIWA's Fishing Ecosystem Effects project, NIWA's Strategic Science Investment Fund, and Fisheries New Zealand contract ZBD200925. This model was further adapted for the Tasman and Golden Bays region to add sediment stressors for Sustainable Seas, project 5.1.2 Spatially explicit decision support tools (2015-2019).

Application of the model to the Hawke's Bay would not have been possible without the contributions of the project team from NIWA, Deliberate, Whetu, and Hawke's Bay Regional Council. We sincerely appreciate the many hours of volunteer time provided by the participants from the Hawke's Bay Marine and Coastal (HBMaC) group in learning about the Seafloor model and developing the Hawke's Bay scenarios. HBMaC and HBRC also provided much of the data underpinning the environmental layers used in the Seafloor model, including sediment/seafloor habitat maps for the Marine and Coastal Information Review (2016), HBRC consent data on sediments and multi-beam contracts.

Contents

Executive summary

Models are often used to explore potential changes in marine ecosystems under possible future scenarios when it is too difficult or too expensive to empirically test these scenarios at the temporal and spatial scale that is required to inform science and management. As part of the Hawke's Bay case study of the Sustainable Seas National Science Challenge, we applied a Seafloor model of disturbance and recovery dynamics to explore the implications of changes in the scale and intensity of different stressors for seafloor ecosystems. Exploratory scenarios, parameterised using local data on seafloor sediments and fisheries catch, were used to understand implications of individual stressors of land-based sediment inputs and of intensity of bottom impacts from trawl fisheries on benthic communities. A final set of scenarios was then designed by the Hawke's Bay Coastal and Marine Group to explore the outcome on seafloor communities when combinations of reductions in sediment and fishing stressors were applied. These scenarios varied three different levers: 1) reductions in sediment mud content on the seafloor; 2) reductions in fishing intensity; and 3) implementation of spatial closures (fishery restrictions).

Scenario results showcased the conditional ecosystem response to stressor reductions based on spatiotemporal variability in stressor-ecosystem relationships. For example, the potential positive impact of reductions in fishing intensity or implementation of spatial closures was dependent on where these measures were placed relative to the existing spatial footprint of fishing. If a fisheries measure or closure was placed in a location with only limited existing fishing effort, it was unlikely to result in a significant increase in benthic structure. Knowledge gaps in sediment were also apparent, such that while sediment inputs from individual rivers in the Hawke's Bay have been modelled, how the sediment is transported and deposited on the seafloor within the coastal environment is unknown, and the model simplistically assumed increases or reductions in sediment supply were equally distributed through the model area. The model also assumed a 1:1 ratio between changes in riverine sediment inputs and mud content on the seafloor, an assumption that has been used elsewhere in New Zealand, but has not yet been validated.

The model outputs highlighted the complexities of ecosystem-based management where multiple overlapping uses and stressors must be managed within a complex and dynamic system such as the Hawke's Bay coastal environment. Participants in the case study workshops found the Seafloor model to be useful at showcasing how seafloor ecosystems function and respond to fishing and sediment stressors. The scenario process allowed participants to explore the magnitude of restoration or reduction in impacts required to result in a positive change in seafloor ecosystem health.

Introduction

Ocean management is complex, and is challenged by increasing pressure from population growth, climate change, and a diversification of both new and historical resource uses (Long et al. 2015, Thrush et al. 2016). Ecosystems are highly variable, complex networks between interacting species and the physical environment, where changes in one part of the ecosystem may have cascading system-wide effects (Thrush et al. 2009, Snelgrove et al. 2014). Interactions between humans and natural systems also influence the system dynamics, and management must also consider trade-offs between economic, social, cultural and environmental objectives, and their effect on ecosystem resilience (Berkes 2012, Le Heron et al. 2016). The consideration of such large and highly connected socio-ecological systems is a key challenge for management (Gibbs 2009, Berkes 2012), and an understanding of scientific uncertainties is essential for accurate evaluation of potential outcomes and trade-offs.

Spatially explicit decision support tools (SEDS) are one set of approaches to inform ecosystem-based management (EBM), using a range of methods that visualise and/or incorporate spatially-explicit overlaps in resource use, stakeholder, community and Māori values, and environmental impacts (Smith et al. 2007, Centre for Oceans Solutions 2011, Lombard et al. 2019). Models are often used to explore potential changes in marine ecosystems under possible future scenarios when it is too difficult or too expensive to empirically test these scenarios at the temporal and spatial scale that is required to inform science and management. While models often cannot accurately predict real distributions of species with respect to disturbance, they can facilitate understanding of ocean ecosystems under different management scenarios.

One such tool is a model (hereafter the ‘Seafloor model’) developed to explore the impacts of disturbances on the communities of animals living on the seafloor (Thrush et al. 2005, Lundquist et al. 2013). This Seafloor model can be used to inform our understanding of the scale and magnitude of the impact of different stressors on seafloor community dynamics, including both natural and human-induced disturbances that cause ecological responses at different spatial and temporal scales. When these disturbances occur at large scales over areas of high environmental variability, it is difficult to assess impacts using either species richness or individual species distributions due to species-specific responses to environmental drivers (e.g., exposure, sediment, temperature) and species interactions (Hewitt et al. 2017). Instead, grouping species assemblages based on key functional groups (e.g., sediment bioturbators, three-dimensional biogenic structure) enables application across a large spatial scale (such as different regions), despite differences in species composition (Bremner et al. 2003, de Juan et al. 2009). This approach also provides a better indicator of ecological or functional resilience, which is critical for ecosystem health (Rodil et al. 2013). Typical seafloor disturbances to coastal ecosystems include bottom fishing impacts where trawl or dredging gear results in damage to seafloor communities, and land-based impacts resulting in sedimentation deposition and increased water column turbidity (Figure 1).

The Seafloor model was initially developed through funding to NIWA (Fisheries Ecosystem Effects, FRST Project C01X0212) (Thrush et al. 2005); further development has been funded by NIWA SSIF (Lundquist et al. 2010), Fisheries New Zealand (Lundquist et al. 2013), and the Sustainable Seas National Science Challenge (Bulmer et al. 2022, Stephenson et al. 2019). In Phase 1 of the Challenge, project 5.1.2 (Spatially explicit decision support tools) applied the Seafloor model to its Phase 1 (2015-2019) case study area in Tasman Bay and Golden Bay (TBGB), exploring responses of seafloor invertebrate communities to both bottom fishing impacts and land-based sediment inputs (Bulmer et al. 2022). The TBGB case study derived mechanistic relationships between fishing impacts and seafloor sediment (percent mud content) to parameterise the TBGB case study model (Bulmer et al. 2022).

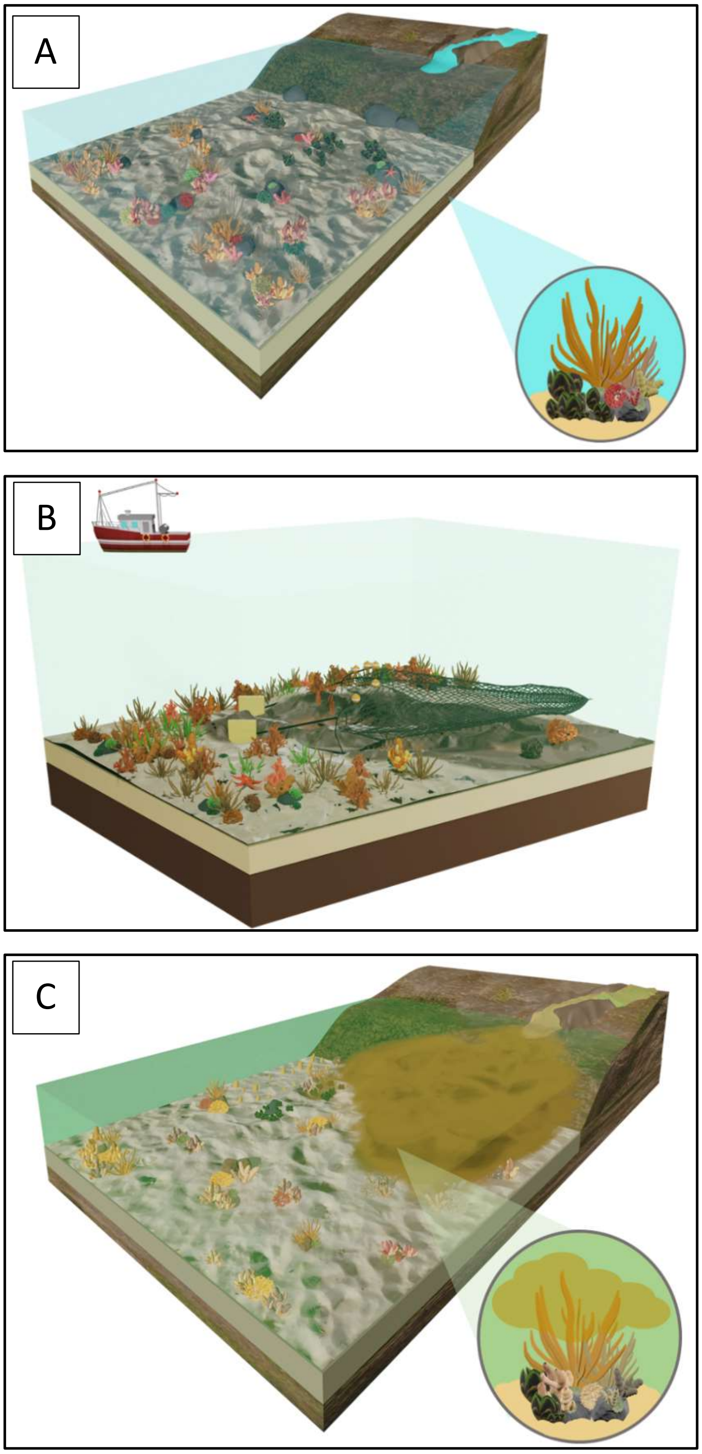

Figure 1: Conceptual diagrams of the impacts of fishing and sediment on three-dimensional benthic structure on the seafloor. A. Pristine seascape. B. Impact of bottom trawling gear. C. Impact of land-based sediment inputs.

While Sustainable Seas does not have the mandate to 'implement' EBM, its case studies provide underpinning research and tools to support the design and implementation of an EBM approach tailored to Aotearoa New Zealand. These case studies are designed to serve as proof of concept of EBM approaches and provide key lessons about putting theory into practice to further enable EBM in Aotearoa NZ. Partnering with central and regional government, industry, other stakeholders, and Māori is critical for the implementation of EBM and the success of the Challenge.

Here, we present the application of the Seafloor model to the Challenge's Phase 2 Hawke's Bay case study. Following an initial meeting in November 2018 between the Challenge and the Hawke's Bay Marine and Coastal Group (HBMaC), the Hawke's Bay case study was selected as one of the Challenge's Phase 2 case study areas for research on implementing ecosystem-based management in a real-world context using tools, processes and analyses developed within Challenge research. HBMaC is a non-statutory multi-stakeholder group established in 2016 in recognition of concerns over the apparent reduction of inshore finfish stocks and environmental degradation in coastal and marine areas of Hawke's Bay. HBMaC is comprised of representatives from local and central government councils and agencies, port company, tangata whenua, the forestry industry, and recreational and commercial fisheries.

Hawke's Bay is representative of a typical coastal marine ecosystem with sandy beaches, inter-tidal reefs, dunes, estuaries and subtidal reefs and soft sediments. The region has large river systems, fisheries, productive lands and ocean outfalls which can add stress to the marine system and impact on people's values for the coastal area. Two stressors (sediment delivery to the Hawke's Bay coastal marine area from land, and the effect of seabed disturbance through bottom contact activities) were identified as the focus of this case study project due to their perceived importance for the health and recovery of the Hawke's Bay marine ecosystem.

Historical increases in sediment inputs from land relative to pre-human times are comparable in the Hawke's Bay to those found in other regions of New Zealand, showing variation both temporally (intra- and inter-annually) and spatially with tidal creeks typically having higher sedimentation rates than the main bodies of estuaries and of coastal bays (Swales et al. 2009). Annual average sediment loads estimated using the SedNet tool (Dymond et al. 2016) in the Hawke's Bay range from 1.6 to 6.8 times greater sediment loads than pre-human times, which are comparable to Auckland estuaries, where a study of 30 sites suggested rates of sedimentation of up to an order of magnitude higher (i.e., 10 times higher) than prior to catchment deforestation, with rates approximately halved in deeper subtidal regions (Swales et al. 2002). Comparisons of bottom fishing trawl intensity with national data also showed high spatial variability with localised regions of high fishing effort as measured by the fishing footprint, the number of trawls, and the aggregated fishing area (Baird and Mules 2021). The national fishing footprint estimated a mean of 277 tows per 25 km^2 cell averaged from 1990-2019 for the national dataset, which is a similar order of magnitude to the Hawke's Bay region (mean 78 tows per 25 km^2, maximum 495 tows per 25 km^2).

In Stage 1 of the case study project, a System map was developed (Connolly et al. 2020). In Stage 2 of the project, the Seafloor model was applied to the Hawke's Bay region, focussing on one of the primary foci of the System map, benthic structure, which refers to the epifaunal communities living on the seafloor. This report describes the parameterisation of the Seafloor model. A companion report describes an Analogue simulation exercise (Connolly et al. 2022) that linked the outputs of the Seafloor model to the implications for societal, economic and cultural factors identified within the System map. A final project report summarises the case study project, including the three tools used in the project: the System map, the Seafloor model, and the Analogue simulation exercise (Lundquist et al. 2022). The Hawke's Bay case study illustrates a further application of decision-support tools in a place-specific context to explore ecosystem-based management.

Methods

Seafloor model parameterisation

The Seafloor model of disturbance and recovery dynamics allowed for exploration of a key element identified in the Hawke's Bay System map, benthic structure, and how benthic structure responds to the two stressors of interest (sedimentation from land and seabed disturbance through bottom contact activities). The disturbance model is a spatially explicit decision support tool (coded in Matlab programming software) that explores how the spatial extent and frequency of disturbances (by sediment or fishing) impact on the abundance and distribution of animals living on the seafloor. The model can be visualised as a grid of cells, each representing a habitat patch and the animals that live within it (Figure 2).

Functional groups

The model includes eight functional groups (FGs) of seafloor invertebrates that are commonly found in soft sediment seafloor ecosystems (examples on right hand side of Figure 2). Each functional group represents key functional aspects of seafloor ecosystems (i.e., ranging from small to large, early to late colonising, surface dwellers to burrowers, predators, scavengers, deposit and filter feeders). Life histories for each group (i.e., age of reproductive maturity, post settlement or adult dispersal from source cell, reproductive seasonality, maximum lifespan) were determined by expert opinion along with published studies on representative taxa for each group, where available (Lundquist et al. 2013). The focal group for the Hawke's Bay case study was the 3D biogenic structure group, consisting of habitat-structure forming epifaunal invertebrates (animals that live at and above the surface of the seafloor such as those that form sponge gardens, sea pen meadows, and bryozoan reefs). All model outputs in this report below refer to the recovery of only this functional group.

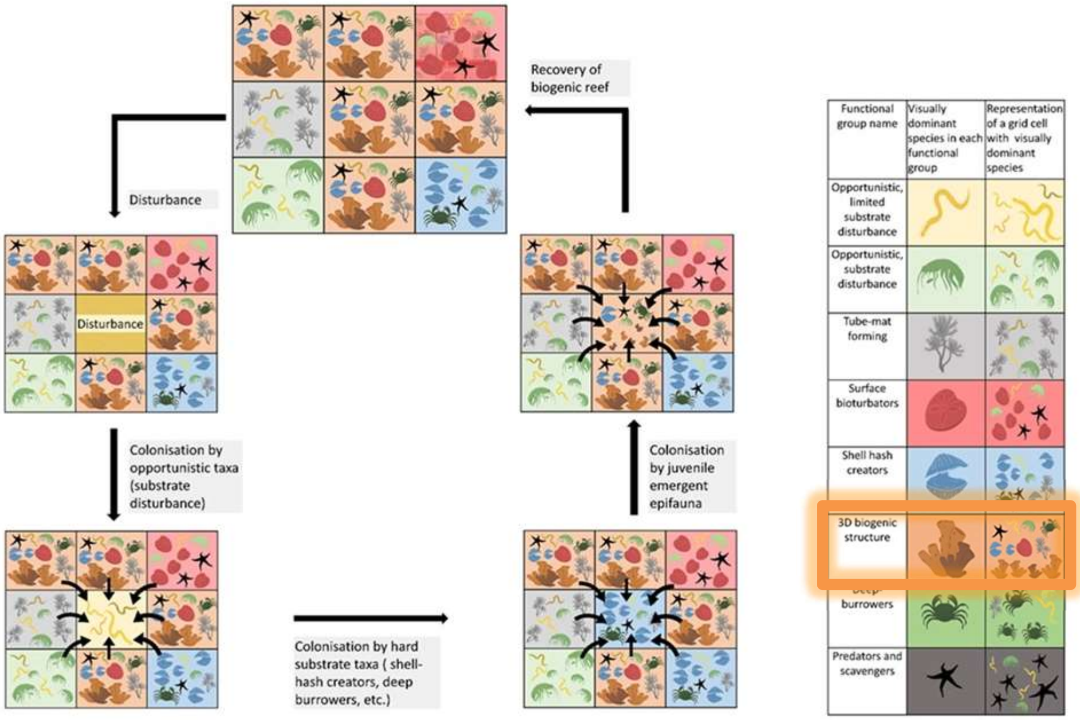

Figure 2: Conceptual diagram of the different types of functional groups of animals in the seafloor model, and a typical time cycle showing disturbance and recovery. Each functional group represents benthic species assemblages dominated by different types of animals, and are colour coded to show transition from a disturbed community (pale cells) through colonisation and growth/aging to a mature community (highlighted orange cells) dominated by benthic-structured organisms.

At each timestep in the model, natural processes (growth/aging, mortality, predation, and competition) and other disturbances (e.g., fishing, sedimentation) occur within each cell. Reproduction is determined by the 'age' of animals in each cell relative to an empirically estimated age of maturity for each group. Dispersal of larvae or recruits into adjacent cells is determined by estimated distances of planktonic larval dispersal that are specific to each group, and based on field or experimental data (Lundquist et al. 2010, Lundquist et al. 2013). Natural mortality or other disturbances (based on rates that are defined for each scenario) occur at each timestep, and result in impacts on the group in each cell. The response to stressors of each of the eight FGs is based on empirically-derived data representing the likelihood of mortality from a disturbance event (Bulmer et al. 2022). Once a disturbance occurs, a group may 'die', and the cell can be repopulated in later timesteps if colonists are available from neighbouring cells (Figure 2).

Dispersal and colonisation

Dispersal and colonisation processes are iterated each timestep to determine whether unoccupied cells are colonised by juveniles. The production of colonists for each FG only occurs in cells occupied by adults, and each FG only produces colonists during reproductively active seasons. The source neighbourhood for colonists varies based on FG, according to life history parameters (local to long-distance dispersal). The potential distance travelled from adults by colonists was represented by a square-shaped neighbourhood around the central dispersing cell, with the dimensions approximately twice the FG-specific dispersal distance. For simplicity, dispersal was assumed to be uniform in all directions, and decreased linearly with distance from an adult source, though complex circulation patterns, topography, larval behaviour and other physical and biological interactions are known to influence patterns of connectivity (Cowen and Sponaugle 2009). A linear decay function was used to calculate the number of potential colonists arriving from within the source neighbourhood; here, the probability of colonists reaching a cell decreased with increasing distance from a source adult, matching typical distance-based simplifications used in metapopulation theory (Hanski and Ovaskainen 2003, Kaplan et al. 2009, Lipcius et al. 2015). The number of colonists reaching a cell was calculated based on the cumulative contribution from all source cells within the dispersal range of the unoccupied cell. Colonisation success was determined stochastically, based on a random number being less than the ratio of the number of colonists divided by the maximum potential number of colonists that could reach that cell for that FG. Colonisation success was normalised to total seaward neighbourhood for cells that had land neighbours.

Adult-juvenile interactions were also included in the model to further influence whether successful colonisation resulted in successful settlement. Adult-juvenile interactions were evaluated as detrimental, neutral or beneficial for a potential juvenile settler within that cell, based on the occupancy of adults of other FGs within the cell; the selection and parameterisation of the functional groups by a team of expert marine soft sediment ecologists is described in Lundquist et al. (2013). Settlement success was determined by comparing the cumulative adult-juvenile interaction score to a random array based on the range of possible interaction scores. Settlement occurred if interaction scores were less than or equal to the random array score value. Following settlement, the age of the group within that cell increased by one unit per timestep, conditional on the cell not being impacted by either disturbance or natural mortality.

A further model complexity was included to represent the facilitation that shell-hash of species such as bivalves and gastropods provides as the primary settlement substrate for sessile epifaunal species. The fragmentation and removal of this hard substrate has been suggested as one possible reason for a lack of recovery in some structure-forming communities following disturbance events (Thrush et al. 2001, Cranfield et al. 2003). Here, the model was parameterised with the explicit assumption that the presence of shell-hash was obligate for benthic structure group to successfully settle. The presence of shell-hash and carbonate-creating species such as bivalves and gastropods was assumed to produce shell hash. Settlement of benthic structure-formers could occur if shell-hash was present either due to current occupation of a cell by the shell-hash group, or due to presence of dead shells following natural mortality. Fishing disturbance was assumed to remove all the shell debris, leaving a cell unsuitable for colonisation by benthic structure-formers until a cell was recolonised by the shell-hash group in subsequent time steps.

Model region

The case study region was selected to include Hawke’s Bay Coastal Marine Area, as well as the portion of Hawke Bay that is offshore of the regional council boundary (Territorial Sea) to represent a more ecologically continuous area. The Hawke’s Bay grid was created using ArcGIS, and converted into a raster grid of 184 x 147 cells each with dimension 500 m x 500 m. All land-based cells were excluded from the active model region. The southeastern boundary of the area includes a deepwater (>200 m) region that was retained in the model, though for simplicity and due to lack of data on benthic invertebrates in the region, we did not assume a different benthic community assemblage in this deepwater area.

Disturbance

Scenarios were used to explore how changes to two different stressors representing management interventions (e.g., changes in fishing intensity or the spatial distribution of fishing and reductions in land-based sediment impacts) might increase seafloor ecosystem health in the Hawke's Bay region. Hawke's Bay specific datasets on seafloor sediments, sediment inputs from land from each of the major rivers, and the bottom trawl fishing footprint were used to populate the tool for the Hawke's Bay case study.

Mortality of each group, when subjected to either sediment or fishing disturbance, was based on empirical data relating either the number of fishing events (trawls on the seafloor in a grid cell within a time step), or the sediment mud content, to likelihood of mortality occurring within that time step (Bulmer et al. 2022) (fishing stressor illustrated in Figure 3; sediment stressor illustrated in Figure 4). Empirical data for functional group-sediment relationships was based on field and laboratory studies of New Zealand soft sediment ecosystems, and relationships between functional groups and fishery impacts were based on New Zealand and global reviews of seafloor fishing impacts (e.g., Cummings et al. 2020, Hewitt and Norkko 2007, Lundquist et al. 2013, Tuck et al. 2017, Sciberras et al. 2018).

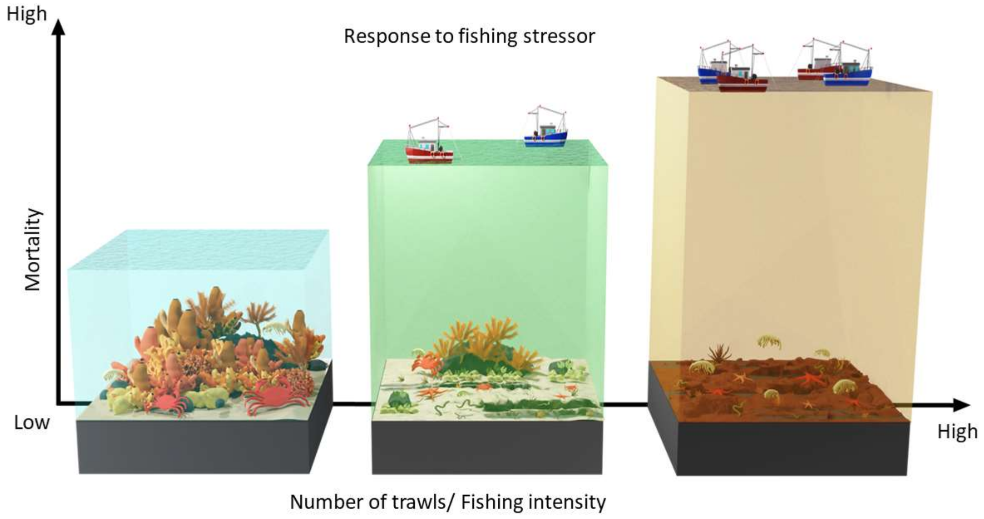

Figure 3: Conceptual diagram of application of fishing stressor maps in the seafloor disturbance model. Example aquaria showcase changes in benthic structure with increasing fishing in each grid cell.

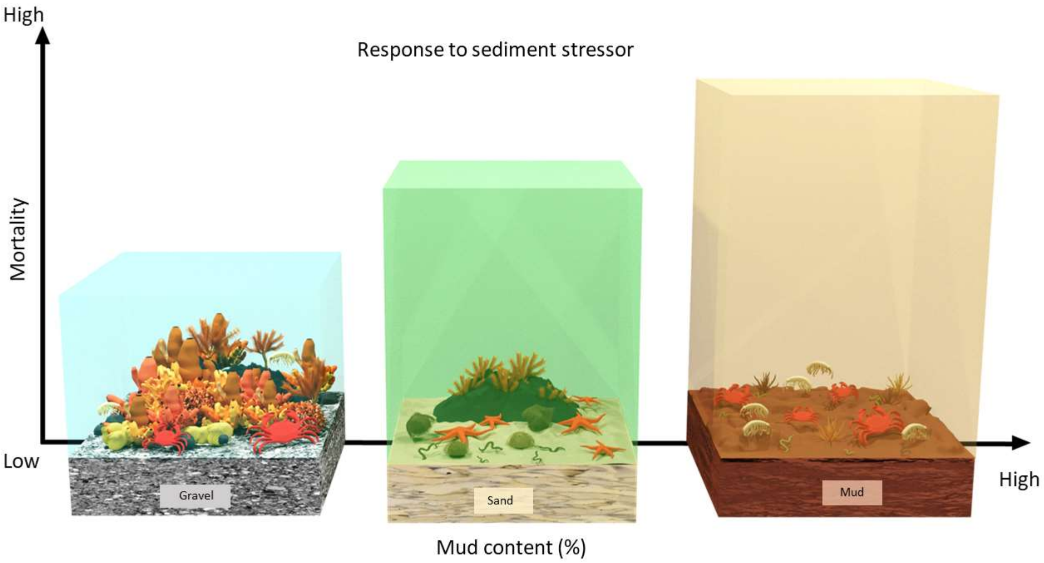

Figure 4: Conceptual diagram of application of sediment stressor maps in the seafloor disturbance model. Example aquaria showcase changes in benthic structure with increasing sediment mud content in each grid cell.

Disturbance – Sedimentation

Percent mud content was used as an indicator of the impact of land-based sediment inputs on the seafloor. The relationship between percent mud content and the probability of FG survival was calculated based on a combination of expert opinion and empirical data on sensitivity of seafloor invertebrates to sediment grainsize/mud content. Datasets from two locations in New Zealand (Tasman and Golden Bays and the Hauraki Gulf), including a total of 499 paired mud/macrofauna samples, were used in regression analyses (binned 90th percentile regressions) to determine relationships between sediment mud content and the probability of survival of different FGs (Figure 5; Bulmer et al. 2022). The Hauraki Gulf dataset provided greater spread of values across differing mud content, whereas the Tasman and Golden Bays dataset was clustered towards high mud content values (mean mud content 60%). As empirical data were likely confounded by other factors such as fishing impacts, expert opinion and relevant literature were used to further revise curves to reflect anticipated ecological responses (reviewed in Bulmer et al. 2022).

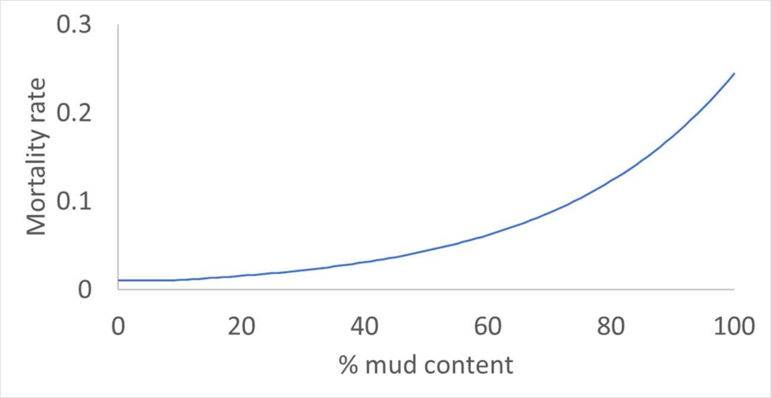

Figure 5: Relationship between sediment mud content and the mortality rate of the 3D biogenic structure group based on empirical data.

To incorporate sediment stressors in each timestep, the likelihood of FG survival was calculated for each cell based on the seafloor mud content and associated survival probability. A random number generator was used for each cell and compared to an array of values based on each FG's likelihood of survival with respect to a percent mud content. Survival of the FG occurred if the random number was greater or equal to the survival array score. To simulate scenarios with changes in percent mud content, the mud content value was increased or decreased across the full model grid by a set percent increase (numerical) in each time step. The model parameters allowed for input of a maximum (e.g., 100% mud content) or minimum mud content below which no further increases or decreases in mud content were deemed ecologically sensible. In the scenarios used in this project, a minimum of 5% mud content was used based on approximate values from the validated point records of the coarse sediment regions in the model area.

The sediment lever allows for multiple pieces of information that could result in reductions in land-based sediment inputs. First, the start year, and total number of years of the sediment intervention could be varied. Second, the annual percent increase or decrease in sediment mud content could be varied. The model assumed a constant rate of change across the years of intervention, i.e.., a 10% decrease in sediment over 10 years was measured as a 1% decrease per year over 10 consecutive years. Further, the model assumed all sediment inputs are comprised of muddier sediments, on par with estimates of the SedNet modelling tool which provided sediment loads of terrestrial fine sediments (Dymond et al. 2016). The model further assumes that increases or decreases in sediment inputs could be directly translated (1:1 ratio) to a percent change in mud content on the seafloor. This assumption has been used by other models, but has not been validated in the Hawke's Bay or elsewhere in New Zealand

Disturbance – Fishing

The relationship between fishing intensity (number of trawl events per timestep) and the probability of functional group survival was calculated based on a literature review of trawling impacts on benthic species survival (Figure 6; Sciberras et al. 2018, Bulmer et al. 2022). The fishing layer for Hawke's Bay was obtained from Fisheries New Zealand based on the average distribution of trawling events within the region (over the fishing seasons 2007/2008-2018/2019), which was used to inform the number of boats (and corresponding trawl events) per time step within each cell of the model. Data were extracted from the Trawl Catch Effort Return (TCER) and Trawl Catch Effort and Processing Return (TCEPR) landing statistics database held by the New Zealand Ministry for Primary Industries (MPI) (Baird and Mules 2021, Baird and Wood 2018). At each timestep, the likelihood of FG survival was calculated for each cell based on the number of boats operating within that cell, and the resulting number of trawls per timestep, and associated survival probability. Survival of that FG occurred if survival scores were less than or equal to a random number. Stressor response curves were calculated based on a global review of responses of seafloor taxa to bottom fishery impacts (Figure 6; Sciberras et al. 2018), assigning all taxa in the review to their corresponding FG in the Seafloor model.

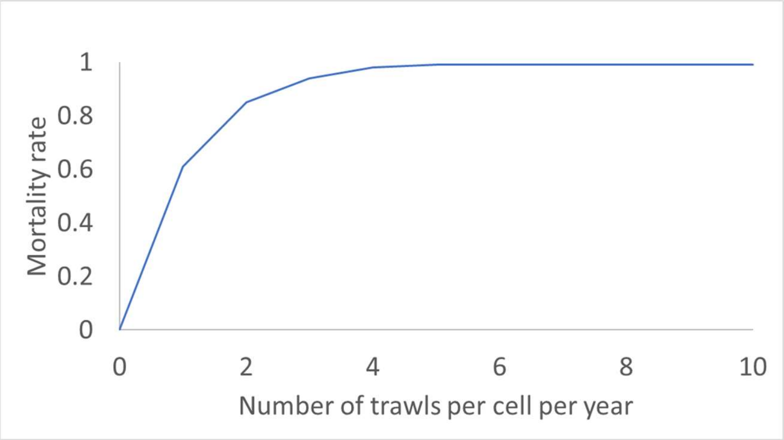

Figure 6: Relationship between number of trawls and the mortality rate of the 3D biogenic structure group based on empirical data.

Model process

Within a model simulation, a start-up or initialisation stage occurred, followed by implementation of a 50-year period of historical stressors based on the map of current sediment mud content, and the average recent fishing footprint (Figure 7). This model period provided an estimated 'current' state of benthic structure on the seafloor. During the intervention period, different stressor options were applied, and the change in benthic structure followed for 50 years (Figure 7). The model is stochastic (involving processes that are described by random probability distributions), and random variations such as high mortality or high recruitment events that do occur naturally, could occur.

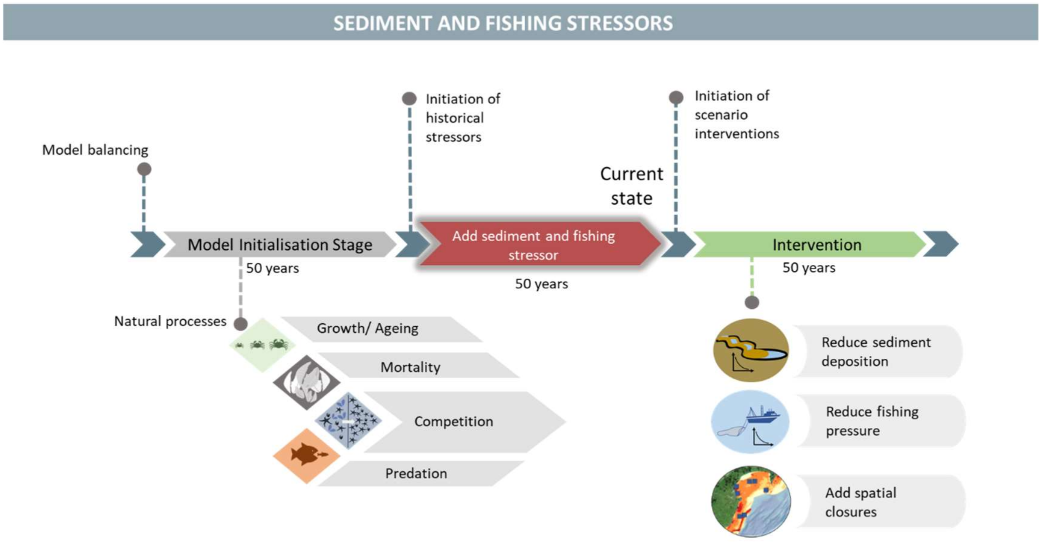

Figure 7: Flowchart illustrating model flow and processes applied during a model scenario.

Sediment and fisheries data

Sediment datasets included spatial maps from the Hawke's Bay marine and coastal review (Haggitt and Wade 2016) representing abiotic habitats (mud, sand, etc.) (Figure 8). These maps were converted into values representing the percent mud content at the seafloor using Hawke's Bay Regional Council sediment surveys of raw point records of sediment grainsize within each sediment type; these include raw point records from the HBRC Subtidal Habitat Inventory of sites, HBRC Sediment monitoring (2007, 2014, 2019), the Marine Hotspot – Sediment Characterisation survey (2018, 2019), Hastings DC outfall, and the Port of Napier Dredge Spoil Disposal survey (2019) and multi-beam surveys of the Wairoa Hard and the Clive Hard (NIWA 2018, 2019) (Figure 9). Sediment maps were updated based on these empirical data and multi-beam surveys (Figure 10).

Sediment riverine inputs were available from estimates using the SedNet[1] tool, which provides annual loading from each of the major rivers, as well as estimates of pre-human sediment loads (Figure 11). These estimates allowed HBMaC participants to see relative contributions of individual rivers within the Hawke's Bay region to seafloor sediment inputs, to help inform where management intervention might be most effective. However, this higher resolution detail on sediment inputs from each river/catchment was not used due to lack of information currently available on high resolution current flow to estimate sediment plume dispersion and spatial distributions of sediment deposition from each river. In other words, the sediment load and known change in sediment inputs from pre-human to contemporary sediment loads are accurately estimated (Figure 11), but it is unknown how rates of sediment transport and disposition vary once sediments enter the bay. The majority of the sediment load (>50%) is from the Wairoa and Mohaka Rivers near the centre of the bay (Figure 11), suggesting equal rates of sediment dispersion across the bay was a reasonable assumption, in the absence of high-resolution sediment transport information.

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[1] http://tools.envirolink.govt.nz/dsss/sednet/

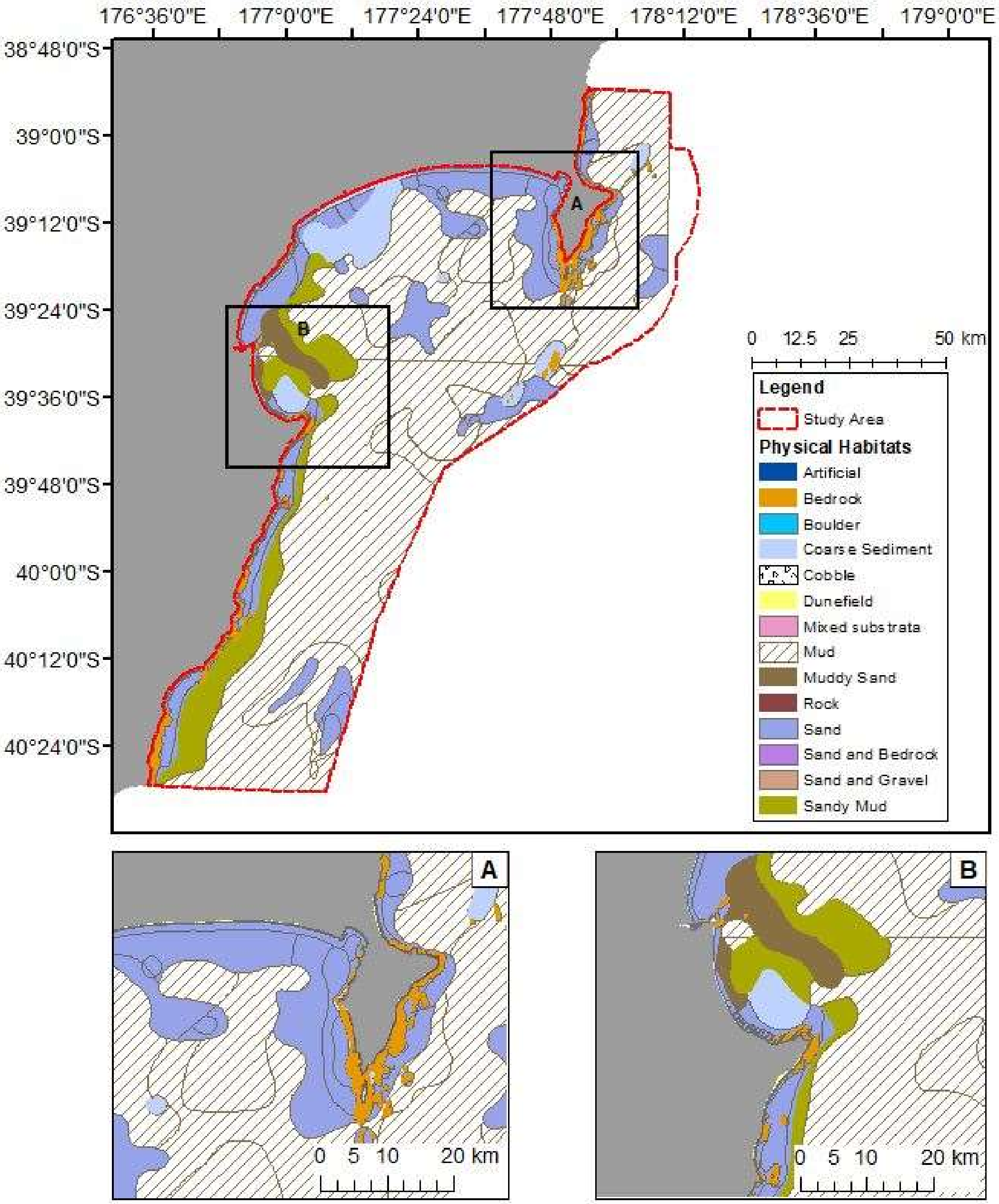


Figure 8: Distribution of abiotic habitats represented by sediment types, adapted from Lundquist et al. (2020) based on data from Hawke's Bay information review (Haggitt and Wade 2016).

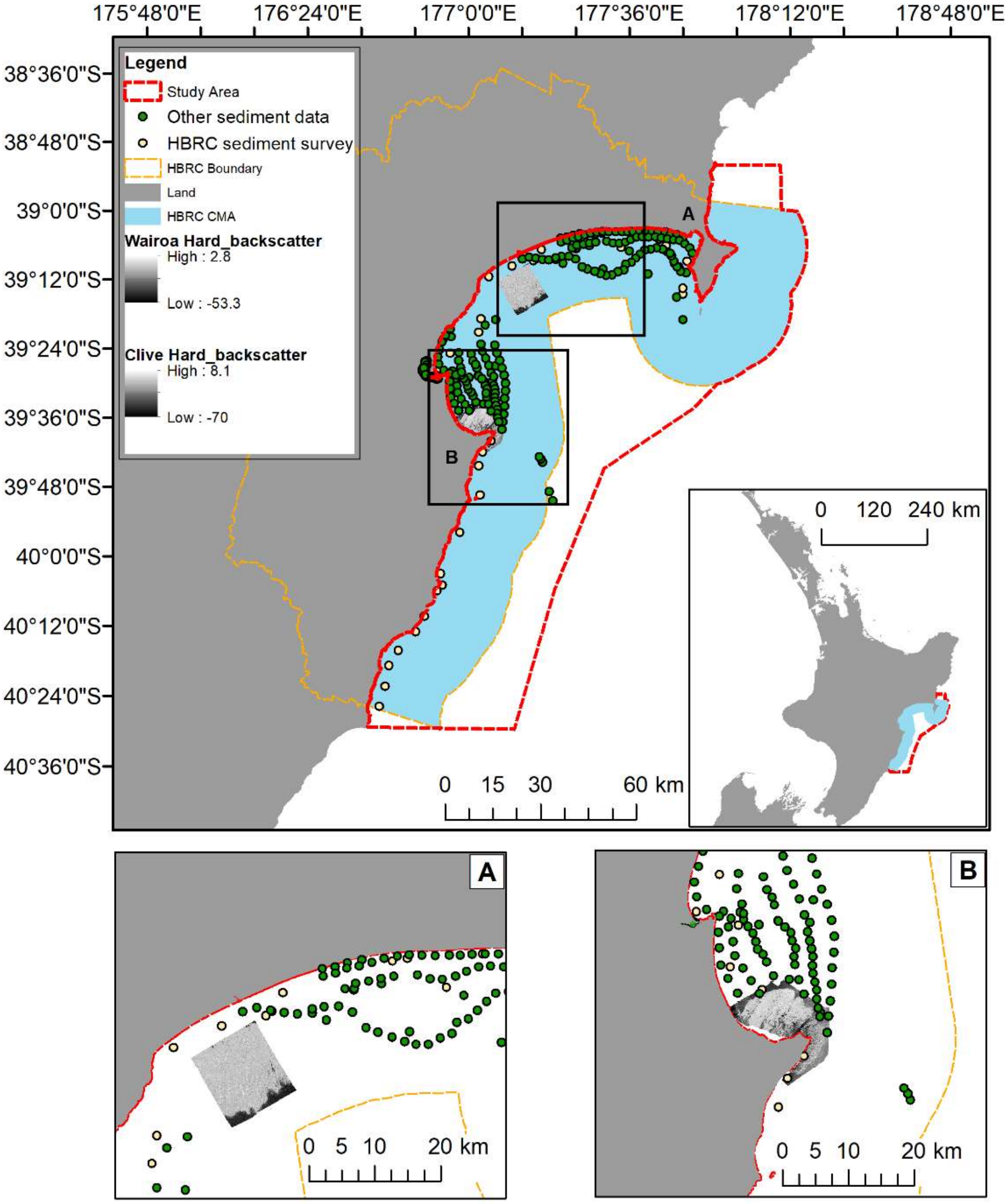


Figure 9: Locations of additional sediment grainsize point records and multi-beam ground truthing to update and parameterise the sediment map in the Seafloor model.

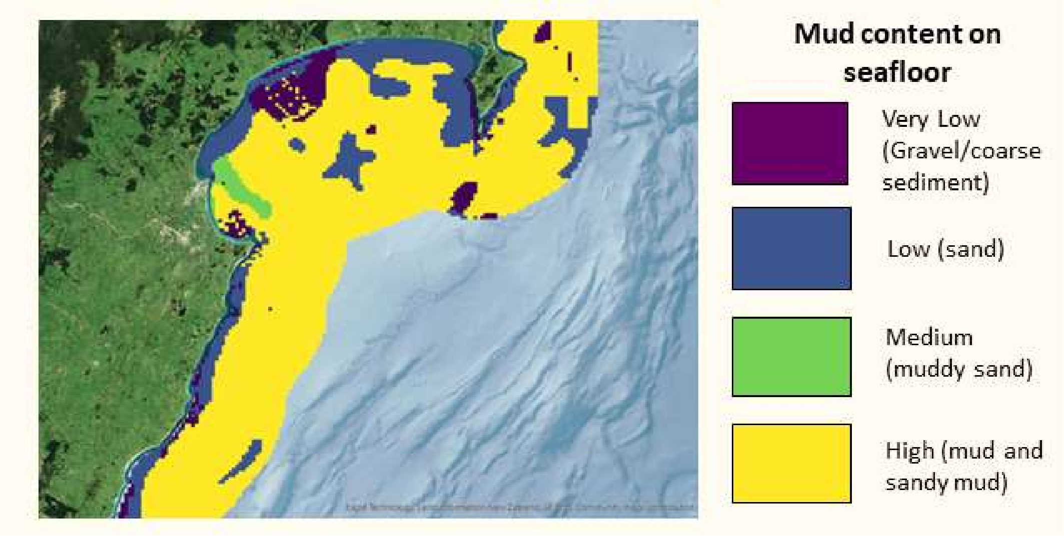


Figure 10: Sediment map used in Seafloor model following additional ground truthing using regional council data and sidescan information. Coarse sediments (purple) indicate locations of the Wairoa Hard and Clive Hard, for example.

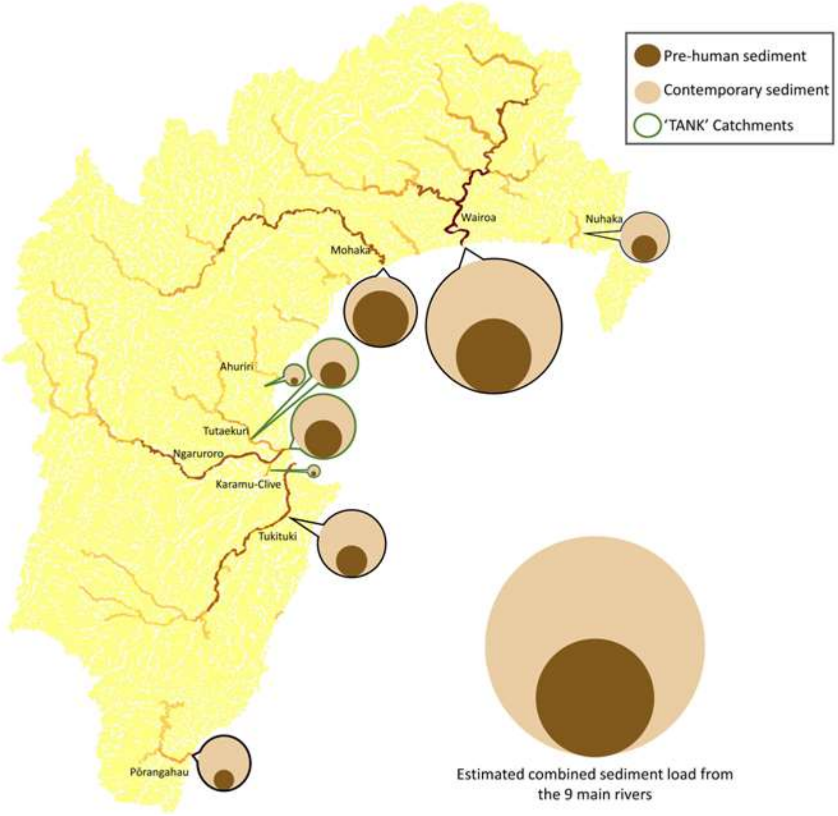


Figure 11: Estimated sediment inputs from nine major catchments in the Hawke's Bay region, showcasing variability in sediment inputs. As an indicator of scale, the Ngaruroro catchment pre-human sediment load is approximately 200,000 t/yr, whereas the Wairoa contemporary sediment load is approximately 2.5 million t/yr. The Karamu-Clive value was increased by an order of magnitude to allow it to be seen on the map.

Fisheries data were provided by Fisheries New Zealand and represented an annual average fishing footprint (converted from number of trawls per km^2 to match model grid cell resolution; Figure 12). Existing spatial closures (e.g., Clive Hard, Mahia Peninsula, Wairoa Hard, Te Angiangi Marine Reserve) were determined to be adequately represented as closed areas within the fishing footprint, as trawl counts were zero within these areas. Other seasonal spatial closures were detailed by HBMaC participants, but were not included as closed areas, as these areas still experienced significant bottom fishing during some parts of the year.

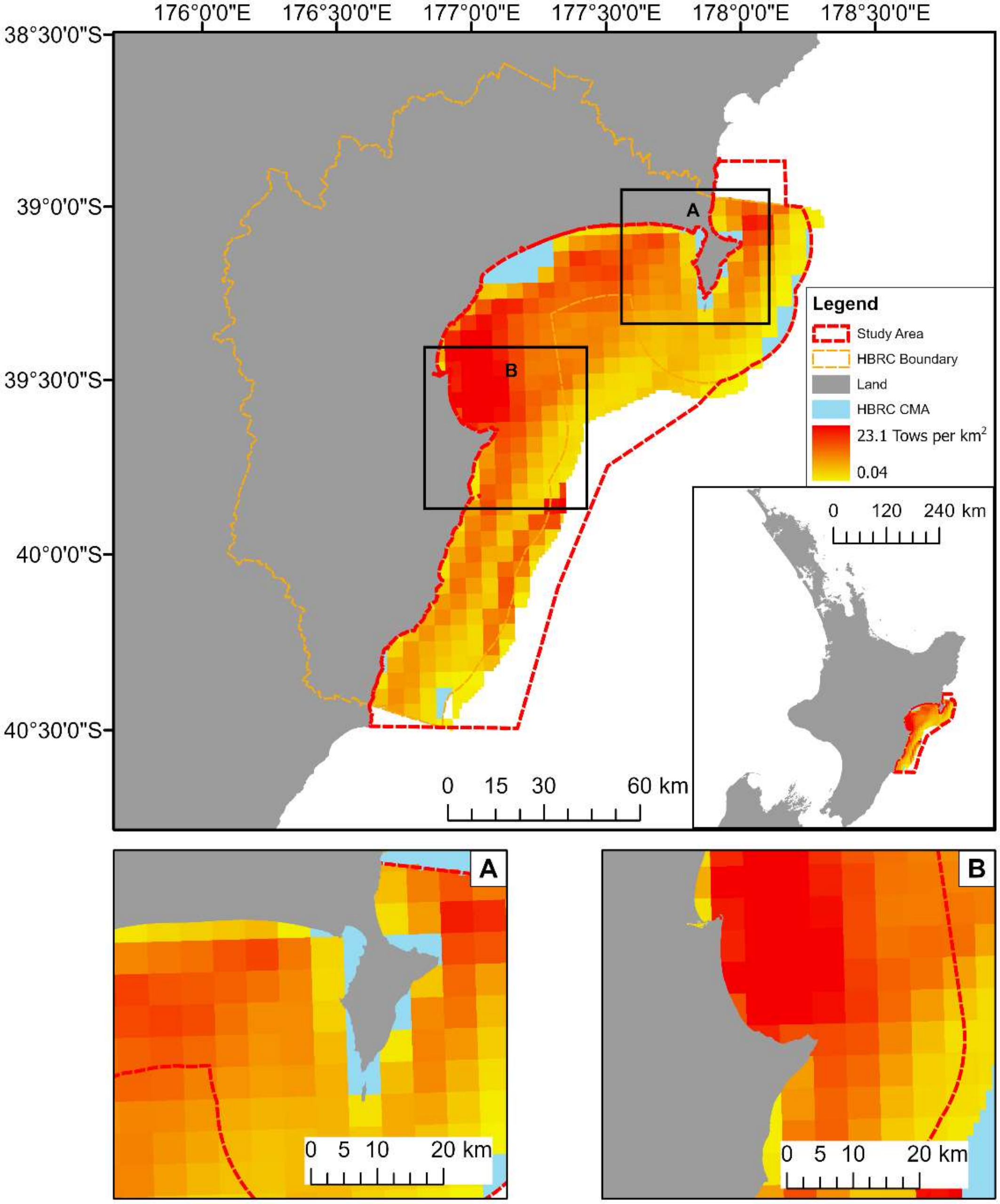


Figure 12. Average tow count in the Hawke’s Bay region based on fisheries seasons 2007/2008 – 2016/2017. Red line indicative of study area used in key ecological areas review (Lundquist et al. 2020).

HBMaC participants suggested that recent years might have potentially different spatial fishing footprints compared to the trawl history, and two additional years of fishing data were requested from FNZ to include the most recently compiled fishery statistics available. Data from 2019/2020 2020/2021 were not yet available to inform the model. Inter-annual comparisons indicated consistent spatial patterns of fishing effort (Figure 13). While the most recent available year (2018/2019) did show indications of declines relative to the immediately preceding years, it was well within the typical range of variability of fishing effort in the region over the 2007/2008 to 2018/2019 fishing seasons, which ranged from -19.1% to 15.6% around the mean of aggregated swept area, -17.7% to 16.0% around the mean of annual number of trawls, and -15.3% to 11.4% around the mean of the annual footprint (Table 1).

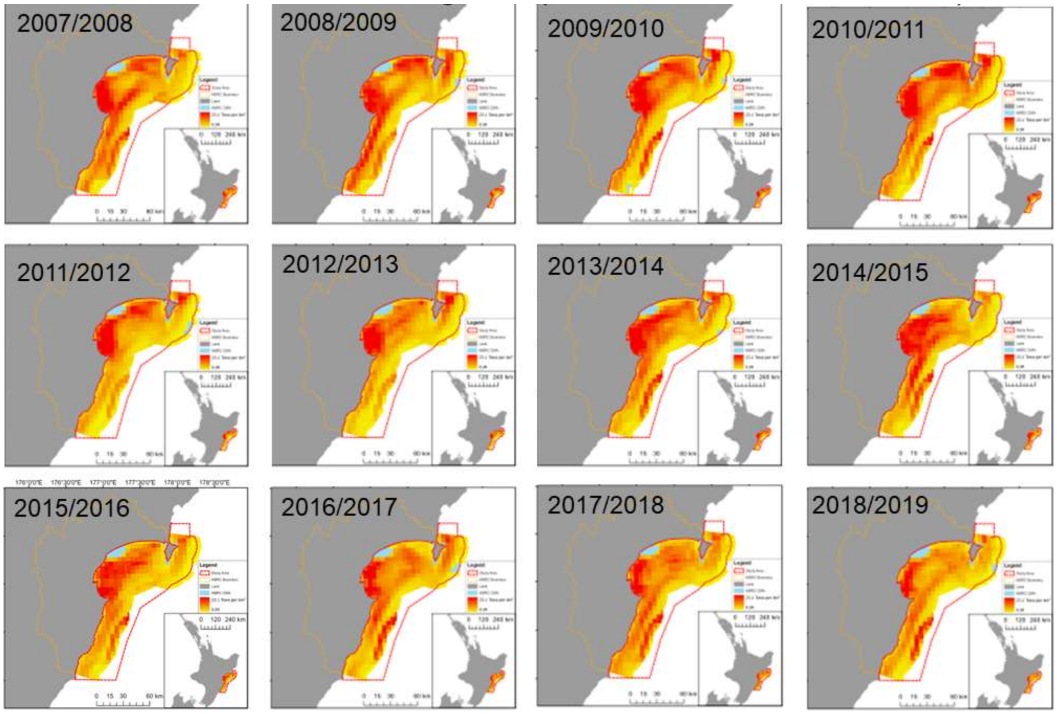


Figure 13. Interannual comparison of tow count from trawl footprint analysis. Red line indicative of study area used in key ecological areas review (Lundquist et al. 2020).

Table 1: Change in fishing effort relative to mean value based onf fisheries seasons from 2007/2008-2016/2017.

Fishing season	Aggregated swept area (change relative to mean)	Annual # trawls (change relative to mean)	Annual area of footprint (change relative to mean)
2007/2008	15.4%	9.3%	11.4%
2008/2009	15.6%	6.8%	8.1%
2009/2010	15.3%	9.3%	7.2%
2010/2011	14.2%	16.0%	9.0%
2011/2012	-12.9%	-6.7%	-12.3%
2012/2013	-19.1%	-13.7%	-15.3%
2013/2014	-1.7%	2.8%	-1.4%
2014/2015	1.8%	3.7%	0.6%
2015/2016	-7.0%	-4.0%	-2.2%
2016/2017	-2.8%	-4.7%	0.9%
2017/2018	-0.5%	-0.9%	5.3%
2018/2019	-18.2%	-17.7%	-11.3%

Decreases in fishing intensity were modelled as changes in the number of boats that were fishing in the model, and thus a reduction in the total number of fishing events. The model could use a random, a constant, or a spatially variable fishing footprint (i.e., reflecting hotspots of high value areas for fishing activity). When fishing intensity was decreased, the total number of fishing events across the model area decreased, but the fishing events were allocated across the same spatial footprint, such that hotspots of fishing activity may still appear as having high relative impact on 3D biogenic structure, even if a large (e.g., 30%) decrease in activity occurs across the full model area.

Spatial closures could be included within the model as areas where fishing events were restricted, for example spatial blocks representing new or existing closures in the model where fishing boats were not allowed to be active (examples spatial configurations shown in Figure 14). If spatial closures were added, it was possible to either reduce the total fishing intensity based on removal of the portion of the fishing footprint within the newly closed area, or to instead allocate the same fishing intensity across the remaining area open to fishing. Fishing intensity parameters were based on number of trawls per cell, converted to the number of active boats per timestep. Fishing stressor variables included the number of boats, and the start and finish year of fishing activity, with finish year allowing for exploration of time to recovery. As deepwater fisheries representatives were not represented in HBMaC, the participants largely agreed to retain the deep area (>200 m) within the model, but not implement any fishing restrictions in this area.

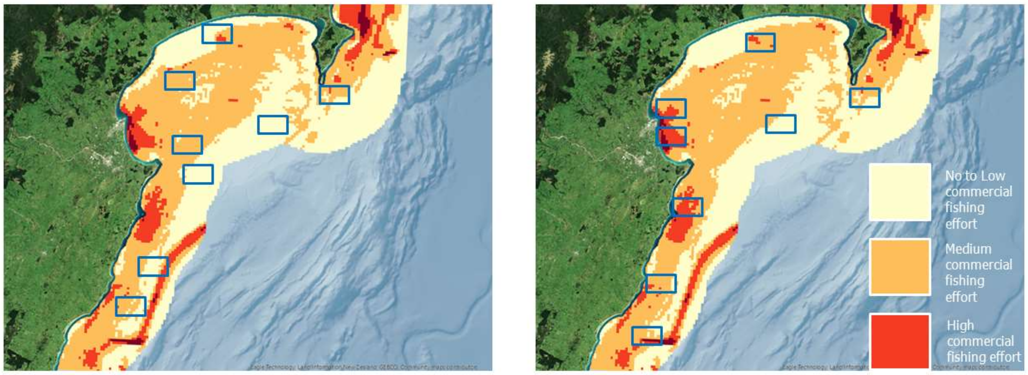


Figure 14. Example of random allocation of 10% of model area into spatial closures. Depending on closure location (the blue boxes), these can result in either minor (left) or significant (right) reductions in access to priority fishing ground, and associated implications for potential reductions in fishing effort.

Exploratory stressor scenarios

Exploratory scenarios were performed to determine potential impacts of changes in the two stressors (sediment and fishing), and to explore implications of adding spatial closures (i.e., areas where bottom trawling was restricted). Exploratory scenarios for fishing stressors included reductions of 10-50% in fishing intensity (number of trawl events) (Figure 15A). Exploratory scenarios for sediment inputs included exploratory scenarios that varied the rate of change of a one-off sediment reduction (e.g., 1%, 3%, … 30% reduction in sediment mud content) (Figure 15B). Random number generators were used to create randomly distributed maps of spatial closures for 5 and 10% (e.g., Figure 14), to explore how the location of a closure may impact the impact on benthic structure (Figure 15C).

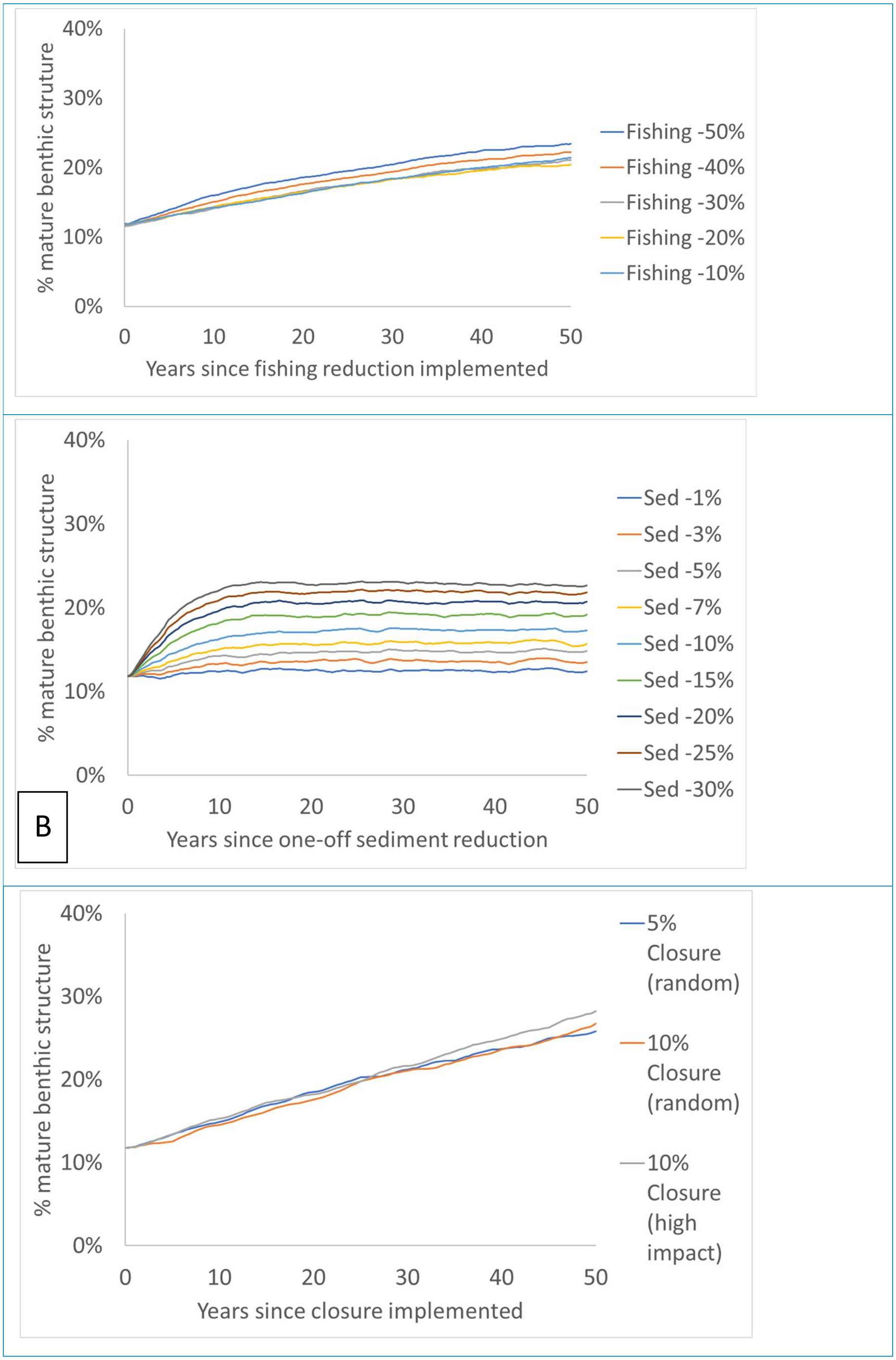


Figure 15. Comparison of exploratory scenarios with A. varying fishing stressor. B. varying sediment stressor. C. varying spatial closure.

HBMaC Scenario development

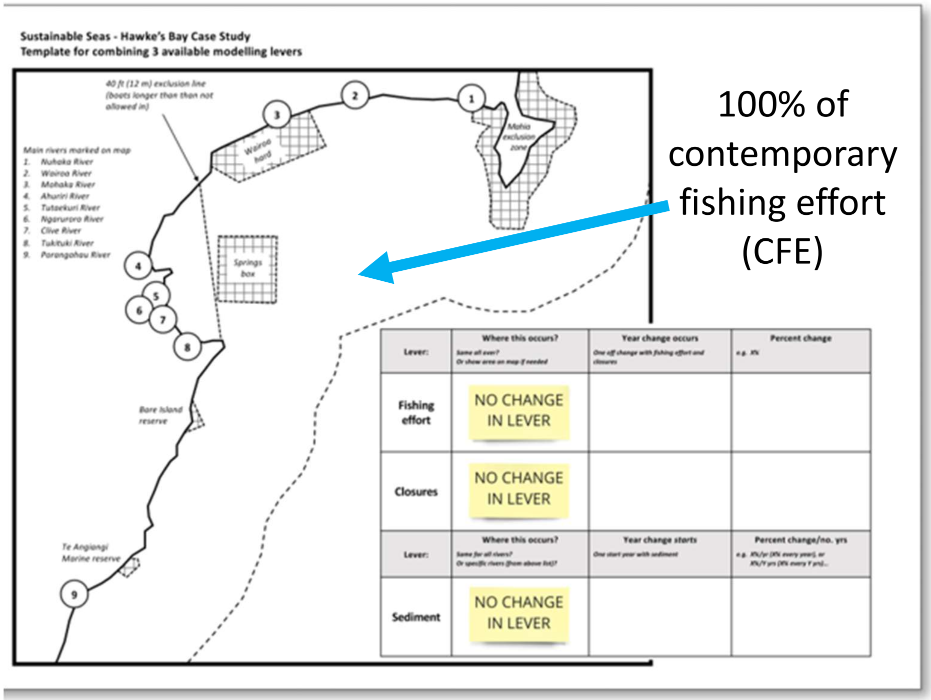
Scenario options were selected by HBMaC to represent different ways in which the group perceived that sediments or fishing could be changed within the region. Four scenarios (three change scenarios and one baseline scenario) were modelled to reflect reductions in sediment inputs into the Hawke's Bay, and reductions in fishing disturbance to the seafloor through either reduction in fishing intensity or addition of spatial closures (Table 2). The baseline scenario represented no reduction in stressors from the current state (Table 2).

Sediment scenarios varied in the percent reduction of mud content and the time period over which reductions occurred (Table 2). Sediment scenarios assumed a direct correlation between increases or decreases in land-based sediment inputs and mud content on the seafloor, though empirical data to parameterise this relationship is not available (MBIE Programme: Oranga Tangata, Oranga Taiao, personal communication with A. Madarasz-Smith). Fishing varied substantially between scenarios, based on closure location and spatially defined reductions in fishing (Table 2). Reductions in sediment mud content are more realistically represented by percent change over a longer time period, as sediment reductions are unlikely to occur immediately due to logistical implications of activities required to reduce freshwater sediment inputs. Thus reductions in mud content were phased through time throughout the model. Fishing stressors, in contrast, could be immediately implemented through changes in fishing effort or spatial closures. However, it is important to recognise that ecological responses to changes in sediment and fishing stressors can often show time lags after implementation of a restoration or management activity. Thus, while the model provided an absolute time of reduction in a stressor, recovery periods based on life history characteristics of benthic invertebrates in the Seafloor model often resulted in decadal or longer recovery periods before a reduction in stressor resulted in a perceived increase in benthic structure.

The baseline scenario assumed a static sediment mud content (i.e., no increase or decrease in seafloor mud content), and implemented the current average fishing footprint for 50 years (Table 2, Figure 16A). Scenario 1 implemented a sediment reduction of 10% over 25 years, a spatial closure to fishing for all coastal areas within 2 nm of shore, and a 5% reduction in fishing elsewhere with the exception of the deepwater zone (>200 m) (Table 2, Figure 16B). Scenario 2 implemented a large reduction in fishing effort (30%) within Hawke Bay and inshore near Porangahou, and a moderate reduction of 10% elsewhere (with the exception of the deepwater zone) (Table 2, Figure 16C). The sediment intervention in scenario 2 included a 15% reduction over 30 years. Scenario 3 included a moderate reduction in fishing effort of 15% throughout the model area (with the exception of the deepwater zone), and a 25% reduction of sediment inputs over 40 years (Table 2, Figure 16D). Changes in fishing intensity and spatial closures for each of the scenarios can be seen in Figure 17.

Table 2: Details of management interventions parameterised in scenarios designed by HBMaC.

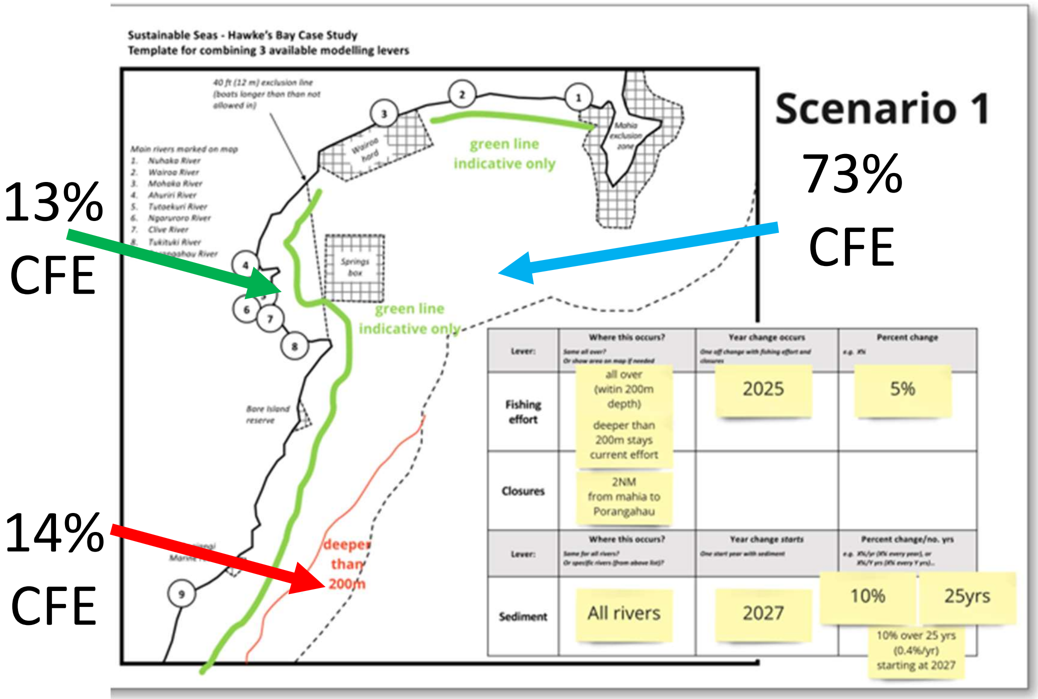
Parameter	Baseline scenario	Scenario 1 5% reduction	Scenario 2 Mixed 30/10% reduction	Scenario 3 15% reduction
Sediment change start	n/a	2027	2027	2027
Sediment change end	n/a	2052	2057	2067
Years sediment reduction occur	n/a	25	30	40
Total % reduction	0	10	15	25
Annual % reduction	0	0.4%	0.5%	0.625%
Fishing change start	n/a	2025	2025	2025
Fishing change description	Existing fishing footprint, with existing spatial variability in fishing effort	Reduction in fishing effort by 5% (excluding 200 m+ depths and spatial closures). Fishing effort allocated spatially across existing fishing footprint (excluding deepwater)	Reduction in fishing effort in two areas: 1) Reduction of 30% within the inshore Hawke Bay and nearshore area (2 NM) offshore of Porangahou; 2) Reduction of 10% elsewhere, excluding deepwater.	Reduction in fishing effort by 15% (excluding 200 m+ depths and spatial closures). Fishing effort allocated spatially across existing fishing footprint (excluding deepwater)
Fishing change in Deepwater area (>200 m)	None	None	None	None
Combined relative % reduction in effort compared to current fishing footprint for the entire region noting that each scenario enacted spatial differences in fishing changes (see Figure 15 for indicators of the relative proportion of contemporary fishing effort in each area of the model	0%	17%	12%	13%
Closure areas	Current spatial closures	Current spatial closures plus extension of Mahia Peninsula coastal closure to Porangahou (width ~3 km/2 NM)	Current spatial closures	Current spatial closures



Sustainable Seas - Hawke's Bay Case Study
Template for combining 3 available modelling levers

100% of contemporary fishing effort (CFE)

Lever:	Where this occurs? Same all over? Or show area on map if needed	Year change occurs One off change with fishing effort and closures	Percent change e.g. X%
Fishing effort	NO CHANGE IN LEVER		
Closures	NO CHANGE IN LEVER		
Lever:	**Where this occurs?** Same for all rivers? Or specific rivers (from above list)?	**Year change starts** One start year with sediment	**Percent change/no. yrs** e.g. X%/yr (X% every year), or X%/Y yrs (X% every Y yrs)...
Sediment	NO CHANGE IN LEVER		



Sustainable Seas - Hawke's Bay Case Study
Template for combining 3 available modelling levers

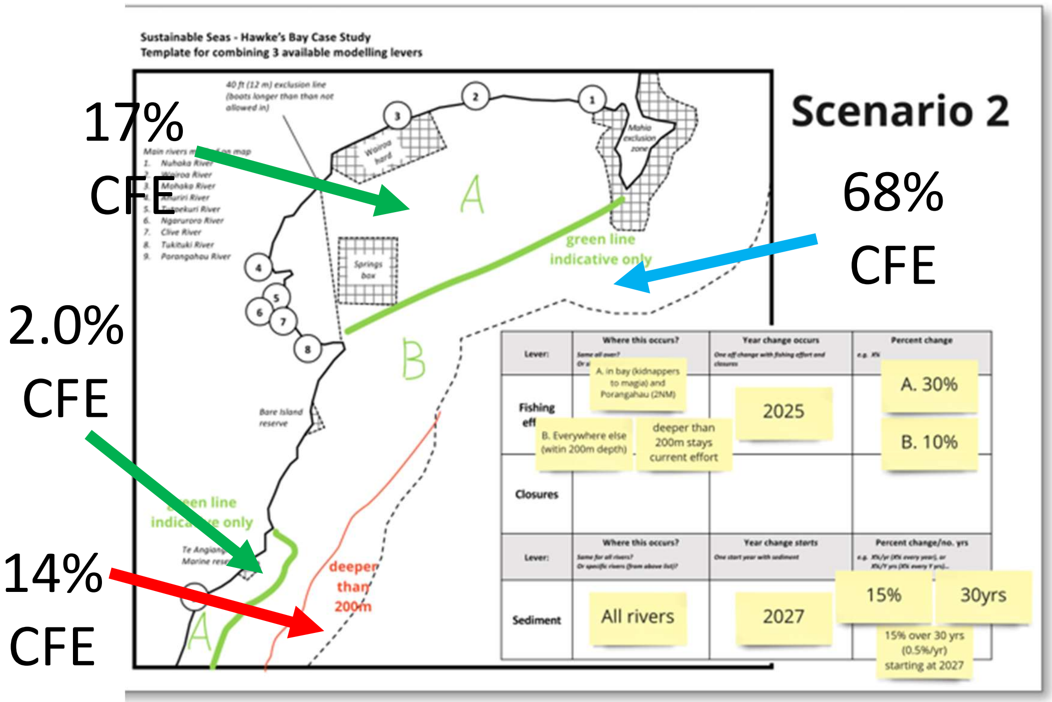
Scenario 1

73% CFE

13% CFE

14% CFE

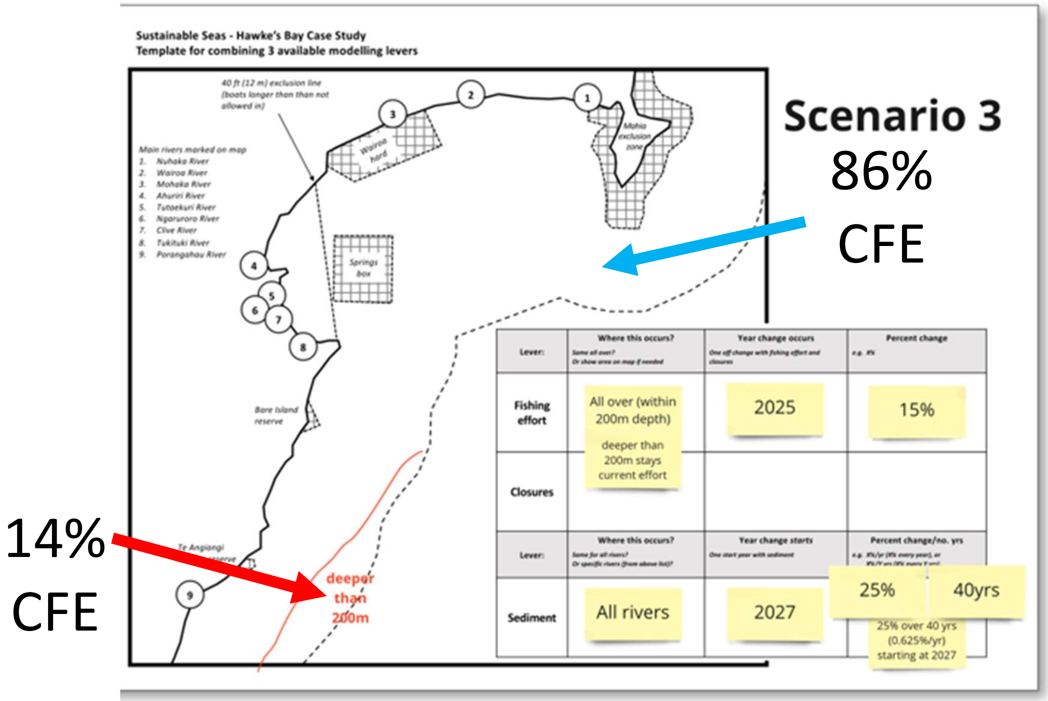
Lever:	Where this occurs? Same all over? Or show area on map if needed	Year change occurs One off change with fishing effort and closures	Percent change e.g. X%
Fishing effort	all over (witin 200m depth) deeper than 200m stays current effort	2025	5%
Closures	2NM from mahia to Porangahau		
Lever:	**Where this occurs?** Same for all rivers? Or specific rivers (from above list)?	**Year change starts** One start year with sediment	**Percent change/no. yrs** e.g. X%/yr (X% every year), or X%/Y yrs (X% every Y yrs)...
Sediment	All rivers	2027	10% 25yrs 10% over 25 yrs (0.4%/yr) starting at 2027



Sustainable Seas - Hawke's Bay Case Study
Template for combining 3 available modelling levers

Scenario 2

Lever:	Where this occurs? Same all over? Or show area on map if needed	Year change occurs One off change with fishing effort and closures	Percent change e.g. X%
Fishing effort	A. in bay (kidnappers to magia) and Porangahau (2NM) B. Everywhere else (witin 200m depth) deeper than 200m stays current effort	2025	A. 30% B. 10%
Closures			
Lever:	Where this occurs? Same for all rivers? Or specific rivers (from above list)?	Year change starts One start year with sediment	Percent change/no. yrs e.g. X%/yr (X% every year), or X%/Y yrs (X% every Y yrs)...
Sediment	All rivers	2027	15% 30yrs 15% over 30 yrs (0.5%/yr) starting at 2027



Sustainable Seas - Hawke's Bay Case Study
Template for combining 3 available modelling levers

Scenario 3

Lever:	Where this occurs? Same all over? Or show area on map if needed	Year change occurs One off change with fishing effort and closures	Percent change e.g. X%
Fishing effort	All over (within 200m depth) deeper than 200m stays current effort	2025	15%
Closures			
Lever:	Where this occurs? Same for all rivers? Or specific rivers (from above list)?	Year change starts One start year with sediment	Percent change/no. yrs e.g. X%/yr (X% every year), or X%/Y yrs (X% every Y yrs)...
Sediment	All rivers	2027	25% 40yrs 25% over 40 yrs (0.625%/yr) starting at 2027

Figure 16: Visual interpretations of each scenario. A. baseline. B. Scenario 1. C. Scenario 2. D. Scenario 3. Arrows indicate percent of contemporary fishing effort (CFE) within each area identified within a particular scenario.

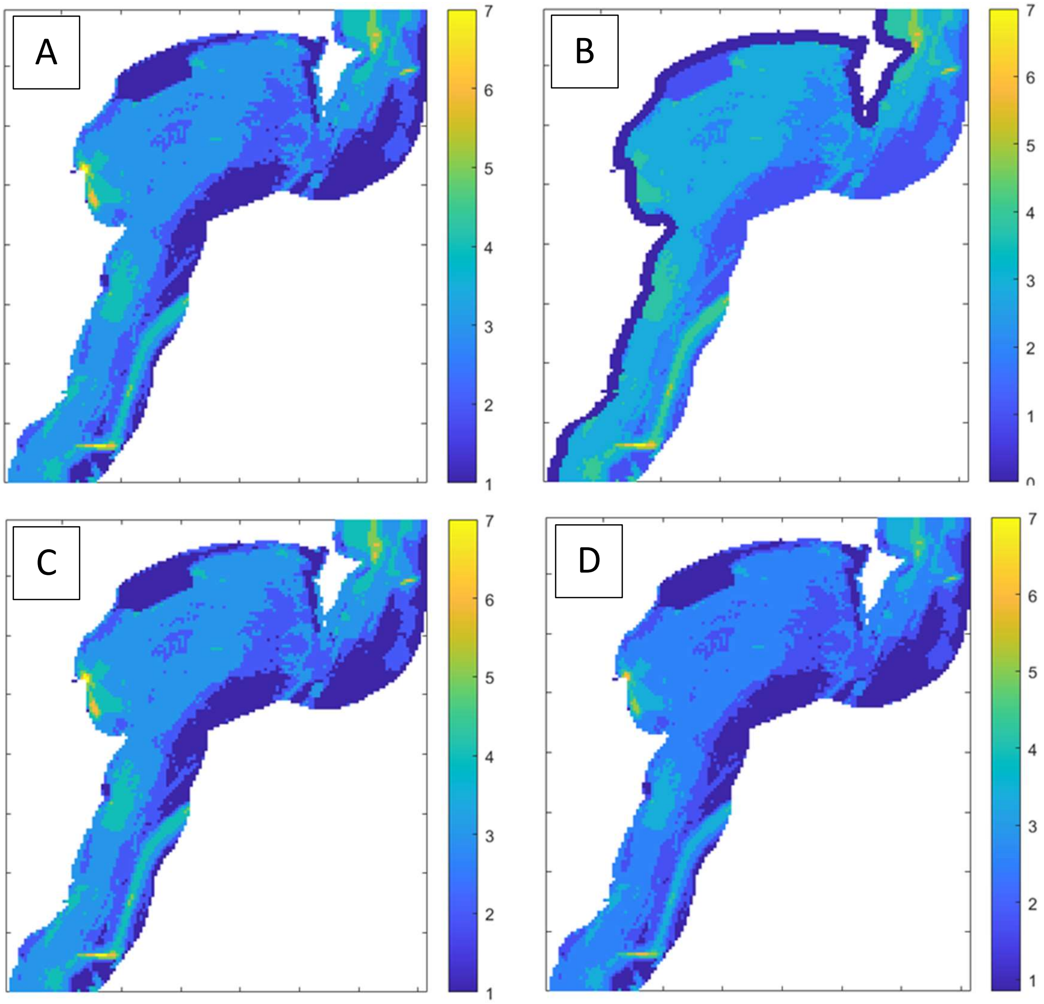


Figure 17. Fishing intensity compared across the four scenarios. A. Baseline. B. Scenario 1. C. Scenario 2. D. Scenario 3. Fishing intensity is represented by the number of fishing events per 500 m x 500 m cell.

To facilitate comparison between scenarios, the change in benthic structure over time was presented as an average across the model area (Figure 18). An estimate of 40% mature benthic structure was estimated for the system for a pristine, pre-European catchment and no commercial bottom trawling, based on exploratory scenarios presented at early Phase 2 workshops with HBMaC. Surprisingly, scenarios showed similar behaviour after 50 years; while not intuitive due to perceived changes in fishing, quantification of actual changes of fishing effort based on the different spatial interventions showed similar total reductions in fishing across the model area. Similarly, sediment scenarios, though different in magnitude, were of similar annual decreases (0.4-0.6%) (Table 2).

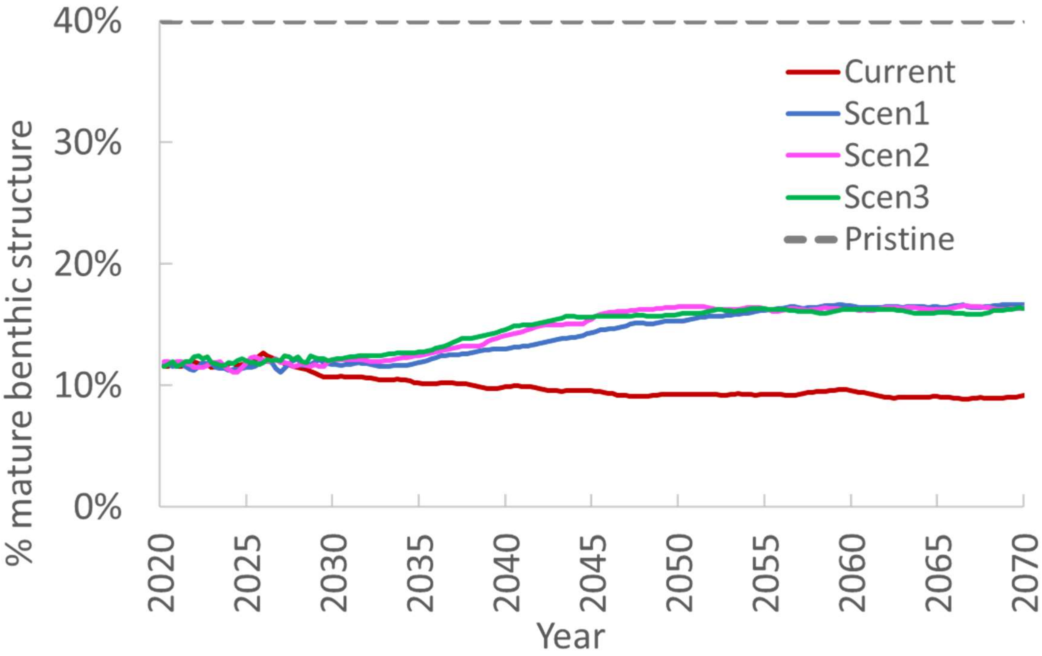


Figure 18. Predicted changes in benthic structure following implementation of different scenario options. Dashed line represents estimated percent (40%) of mature benthic structure for a pristine, pre-European catchment and no commercial bottom trawling.

Discussion

While the model has been previously applied to the Tasman Bay and Golden Bay (TBGB) case study as part of the Sustainable Seas National Science Challenge, this exercise was the first time that the Seafloor model was more directly used within a stakeholder participatory process (Lundquist et al. 2022). The seafloor disturbance model was initially developed by NIWA to explore disturbance recovery dynamics in marine ecosystems. The TBGB application facilitated further model development through the addition of sediment and fishing stressors, and parameterisation of the model with empirically derived relationships between stressors and survival rates of different benthic functional groups. However, the TBGB application was part of a broader exploration of EBM tools, and researchers developed tools and presented them to stakeholders without direct selection of the model scenarios by stakeholders.

The involvement of stakeholders (as well as team members without modelling expertise) provided a learning experience for the modelling team, recognising that terminology differs between disciplines, and highlighted the importance of clear definitions and good communication. Many visual aids and conceptual diagrams were developed to facilitate communication of how the Seafloor model works, and how stressors impact on seafloor ecosystems. Further, while the conceptual model is easy to explain to a broad audience, challenges emerged in explaining technical details to those who were interested, but lacked programming expertise. As with any participatory process, trust is required both between and within stakeholders and research teams. There was a potential that relatively complex ecological interactions and associated technical programming that can be difficult to understand and communicate resulted in a lack of trust in how the model worked. This lesson is useful to remember, as often technical experts can at times be unaware when others do not understand technical aspects and rely on trust in what others may perceive to be a black box of modelling detail.

Substantial effort was spent in creating visual infographics to support the modelling to assist stakeholders and other project team members in understanding the Seafloor model's capabilities. These visuals assisted in painting a picture of what seafloor ecosystems look like, both in pristine and in degraded states, as well as how stressor footprints are distributed spatially across the seascape. These valuable resources will have a life well beyond this project. Their development was also supported by Sustainable Seas project 1.1, which is also applying the Seafloor model in Phase 2 of the Challenge to explore cumulative effects in coastal environments. HMBaC participants commented on how much learning occurred via the Seafloor model in terms of learning how seafloor ecosystems work, and how they are impacted by stressors.

The modelling exercise showcased the significant data limitations that are typical of coastal ecosystems in Aotearoa New Zealand. While the System map report (Connolly et al. 2020) documented metadata on data available to parameterise different elements of the System map, many of the datasets did not have the detail necessary to include them in the Seafloor model. For example, maps of sedimentary habitats were available in the Hawke's Bay marine information review (Haggitt and Wade 2016), however these maps consisted of expert-derived polygons, rather than comprehensive seafloor surveys, and little data was available to ground truth them. Council data was used to convert shape files to estimates of seafloor mud content, and side scan images used to further approximate boundaries of known coarser substrates (i.e., the Wairoa Hard). These point records were limited to few surveys, and information was not available to ground-truth the majority of the Hawke's Bay Coastal Marine Area. A consistent challenge in Aotearoa New Zealand is the lack of validated sediment information, even in the Coastal Marine Area, and the further lack of samples of seafloor community assemblages to provide information on benthic structure and other fauna and flora that contribute to ecosystem function. Available invertebrate data was previously reviewed in Lundquist et al. (2020), showcasing the very limited point records available in the Hawke's Bay to inform spatial mapping of seafloor habitats and benthic invertebrate assemblages; modelled distributions were also evaluated, and national scale species distribution models were assessed as poor representations of known areas of high and low invertebrate species distributions and species diversity in the Hawke's Bay (Lundquist et al. 2020).

Fisheries data, while available, showcased a time lag between fisher perceptions of declines in fishery catch and reported declines in catch in the last two years (due to the pandemic, or other unknown reasons); data were only available to quantify a decrease in the 2018/2019 fishing season, though this decrease was within the level of variability seen across 12 years of fisheries data. More recent data since 2019 was not available due to the delayed release of finalised data following data compilation and analysis at the end of a fishing season. Further, only recently did inshore fishery trawls require information on both trawl start and finish positions. There are known inaccuracies in deepwater fishing footprints, which are further exaggerated in inshore fisheries which have a shorter history of detailed trawl information (Baird and Mules 2021, Baird and Wood 2018).

A number of modelling assumptions were simplistic, and unlikely to realistically represent seafloor ecosystem dynamics and responses to sediment and fishing stressors. While many of these assumptions are recognised, addressing them requires either new model developments to add complexity, or new data, for example to inform mechanistic relationships between stressors and benthic communities, or data to confirm relationships between land-based sediment inputs and corresponding sediment mud content on the seafloor. Regardless, HBMaC participants commented on the broad learning about seafloor ecosystems that they gained from this process, and the development of the Hawke's Bay Seafloor model and respective scenarios. The Seafloor model also indicated relative order of magnitude of changes required to enable the objective of returning the Hawke's Bay seafloor to a healthier state after decades of pressure from sediment inputs, bottom fishing, and other stressors not explored in this model.

In scenarios for this project, the model simplistically assumed increases or reductions in mud content (reflecting changes in sediment supply) were equally distributed through the model area. While this assumption may be approximately correct based on the distribution of sediment inputs, and satellite-based remote sensing estimates of suspended sediment concentrations using NIWA's SCENZ database, significant knowledge gaps are present in understanding of how the sediment is transported and deposited on the seafloor within the coastal environment. Sediment inputs from individual rivers in the Hawke's Bay have been modelled using SedNet (see Sediment and fisheries data), and spatial variability in sediment inputs are reasonably robustly estimated. High-flow river sediment sampling is also underway to help refine the modelled sediment data. High resolution models of coastal transport and circulation are being developed that can connect sediment sources to locations of sediment deposition (K. Bryan, University of Waikato). Future developments of the model would benefit from allowing input layers that better resolve the temporally and spatially variable sediment footprints based on tidal-, current- and wave-influenced transport and deposition of terrestrial-derived sediments from where they enter the coastal zone.

Models are often used to explore potential changes in marine ecosystems under possible future scenarios, when it is too difficult or too expensive to empirically test these scenarios at the temporal and spatial scale that is required to inform science and management. The model showcased the conditional ecosystem response to management interventions based on spatiotemporal variability in stressor-ecosystem relationships, as well as emphasising gaps in underpinning knowledge. This type of approach highlights the complexities of ecosystem-based management where multiple overlapping uses and stressors must be managed within a complex and dynamic system such as the Hawke's Bay coastal environment. In combination with other decision support tools, approaches such as the Seafloor model help to facilitate pragmatic decision-making despite inherent uncertainty in underpinning knowledge and future outcomes.

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