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RESEARCH ARTICLE

Are restoration plans missing the target? Land tenure and cyclone risks reshuffles priorities for mangrove restoration

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Coastal wetlands, vital for fisheries habitats, have suffered extensive losses. Ecosystem restoration offers opportunities to improve fish catch and restore the valuable services these ecosystems provide. Successful restoration is dependent on choosing a site where restoration is feasible, which encompasses biophysical, social, governance, logistical, and resource factors. However, factors that influence feasibility such as land tenure (governance feasibility) and future climate risks (biophysical feasibility) are often overlooked in quantitative analyses of site selection. We ask how spatial priorities for restoration change when considering how feasibility is affected by land tenure, cyclone risk, and both factors together. Specifically, we analyzed a case-study of mangrove restoration to improve fish catch in Queensland, where there is interest in restoring coastal habitats to support fish habitats. We found that the rank order of planning units by restoration feasibility was highly influenced by both land tenure and cyclones, with cyclones changing ranks with clustered regions along the coastline and land tenure variably changing ranks throughout. In planning units where fisheries benefit is expected to be high, but cyclone risk substantially reduces restoration feasibility, practitioners could consider strategically planting mangroves near established mangrove forest and selecting resilient species for restoration. Formalizing regulations for incentives to private land holders and amending legislation for easier permitting are additional suggestions for addressing land tenure challenges. Our study emphasizes the importance of systematic approaches to considering feasibility in spatial planning for restoration to minimize the risk of failure.

Key words: biophysical, fisheries habitats, governance, restoration feasibility, site selection, spatial planning

Implications for Practice

- Incorporating both biophysical and governance factors systematically in restoration planning to enhance the feasibility of coastal wetland projects can reduce the likelihood of project failure.
- Amending legislation and formalizing incentives for private landholders can increase governance feasibility by making it easier to obtain permits and encouraging private participation in restoration efforts.
- Implementing thorough risk assessments that include future climate risks and land tenure issues can better inform site selection and restoration strategies, ultimately improving fishery habitats and ecosystem services.

Introduction

Coastal wetlands play an increasingly important role in mitigating the effects of climate change through carbon sequestration (Mitsch et al. 2012; Lovelock et al. 2023) and shoreline protection (Gedan et al. 2011; Costanza et al. 2021), and are vitally important for providing habitat for fish species (Sheaves et al. 2017; Lefcheck et al. 2019). They deliver economic benefits such as supporting commercial crustacean and fish species by providing refuge throughout several life stages, including nursery habitats which allow species a protective haven from predators, weather, and a reliable food source supply (Meynecke et al. 2007; Sheaves et al. 2015; Jinks et al. 2020). However, coastal wetlands have been subject to widespread loss (Davidson 2014; Li et al. 2018). A decrease in commercial fish catch over recent years has been linked to over exploitation and the degradation of coastal

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wetlands (Brown et al. 2019), including clearing of mangroves (Valiela et al. 2001) and agricultural overgrazing in saltmarshes (Creighton et al. 2015). For this reason, restoration of coastal wetlands is highlighted as integral to re-establishing fish populations (Allan et al. 2013). In addition, to achieve the "30 by 30 restoration goal" (i.e., 30% of degraded ecosystems under effective restoration by 2030) (Convention on Biological Diversity 2022), restoration actions need to be scaled-up (Waltham et al. 2020) and the planning of coastal restoration actions needs to focus on the most successful and feasible strategies to avoid wasting valuable time and resources (Bell-James et al. 2023*c*).

During the planning stages of coastal restoration actions, comprehensive assessments of feasibility can be overlooked. Feasibility in this context broadly refers to the probability that a project will achieve its stated objectives, and can be influenced by biophysical, social, governance, logistical, and resource factors, and although multiple factors may be considered during planning stages, they are not always explicitly assessed (Piccolo et al. 2024). Often, site selection of restoration actions is dependent on land governance and laws relating to land tenure (McLain et al. 2021; Rakotonarivo et al. 2023). Legal restrictions, or lack thereof, can result in restoration occurring in areas that are not biophysically suitable for plant growth (Lovelock & Brown 2019). Biophysical factors could include terrain suitability (Ellison et al. 2022), hydrological appropriateness (Pérez-Ceballos et al. 2020), or future risks such as sea-level rise (Lovelock et al. 2015), and extreme events including bushfires (Maund et al. 2022) and cyclones (Hagger et al. 2018). For example cyclones could have substantial impacts on the long-term survival of mangroves, particularly if restoration efforts are undertaken in reoccurring cyclone paths (Rogers et al. 2023), and if cyclone intensity is predicted to increase with climate change (Saunders et al. 2022). When coastal wetlands are destroyed by cyclones there can be loss of fisheries productivity (Heck et al. 2021). Identifying areas with suitable land tenure and lower vulnerability to cyclones is important for achieving successful restoration outcomes. Therefore, spatial planning for restoration should include multiple feasibility factors.

The integration of multiple feasibility factors into spatial planning for restoration actions has been approached in various ways. Practitioners may base site selection on biophysical constraints and subsequently exclude areas that lack community or stakeholder support (Maginnis et al. 2014; Howie et al. 2024). In academic literature feasibility is a parameter used in cost-effective analyses for identifying priority sites for conservation or restoration (Wilson et al. 2011). Cost-effectiveness in this context is estimated by multiplying the expected benefit of conservation by the feasibility of a conservation action, divided by the costs of taking that action (e.g. Carwardine et al. 2008; Martin et al. 2018). In the past, a large focus in marine restoration has been on estimating the cost and benefit of restoration actions, and there is less robust quantitative information available on feasibility and how it specifically might affect prioritization of restoration investment (e.g. Bayraktarov et al. 2016). Where feasibility has been considered in cost-effective analyses, there has not been a systematic analysis of how different types of feasibility influence priorities (Martin et al. 2018).

To assist decision makers and restoration practitioners in considering the inclusion of multiple feasibility factors during spatial planning, a number of tools have been established, including the Society of Ecological Restoration of Australasia's National Restoration Standards (McDonald et al. 2016), or the IUCN's Restoration Opportunities Assessment Methodology (ROAM) (Maginnis et al. 2014). While these methods have proven valuable, they sometimes overlook crucial factors, such as land tenure influences on restoration (McLain et al. 2021) and spatial variation in feasibility. Quantifying multiple factors that contribute to the overall feasibility of a restoration action enables the consideration of feasibility when prioritizing sites (Molin et al. 2018; Brancalion et al. 2019; Howie et al. 2024). In addition, it aids in comprehending the relative impact of individual factors on restoration success (Brown et al. 2014; Lee et al. 2019; Lovelock & Brown 2019). However, understanding and analyzing the joint feasibility of multiple factors is still lacking in research and planning of coastal restoration. Therefore, it is imperative for management and decision makers to systematically incorporate and quantify multiple feasibility factors into restoration planning to maximize benefits.

Overlooking key factors may contribute to unsuccessful restoration outcomes and corresponding negative impacts on the economy, particularly in ecosystems with important links to commercial fisheries (Meynecke et al. 2008). The important relationship between mangrove ecosystems and commercial fish production is well known, with examples of increases in fish numbers being associated with the increase in area of mangrove habitat (Meynecke et al. 2008; zu Ermgassen et al. 2020). Therefore, mangrove restoration and commercial fish catch provide a good case study for a systematic feasibility assessment. We used mangrove restoration in Queensland, Australia as a case study, with the objective to increase commercial fish catch. Restoration of mangroves and where restoration occurs has been recognized as important for biodiversity offset funding for fisheries (Ma et al. 2022). Mangrove ecosystems also exist in complex and dynamic coastal zones, at times making governance boundaries unclear (Bell-James et al. 2023*a*). In addition, the high-impact coastlines of the tropical regions where mangroves live are subject to extreme weather conditions, potentially influencing the success of mangrove restoration. We aimed to understand how spatial planning of restoration for maximum fisheries benefit changes if we consider multiple feasibility factors. Our specific objectives were to determine how the expected effectiveness of restoration for improving outcomes would change if we (1) considered land tenure, (2) considered cyclone risk, and (3) considered both land tenure and cyclone risk collectively.

Methods

First, we gathered data for mangrove areas, commercial fish catch (Fig. 1A), planning units (drainage basins) (Fig. 1B), land tenure and cyclone paths (Fig. S1A). Second, we linked the fisheries data to potential restoration areas ("planning units"). and calculated expected fisheries benefit from an increase in mangrove area by 1 ha through restoration. Third, we determined what land tenure parcels intersect with the intertidal zone of each planning unit and assigned a feasibility classification to each land tenure type to determine the proportion of each planning unit's intertidal zone that is feasible to restore in when considering land tenure. Fourth, we estimated the probability of a cyclone occurring in the next 20 years after restoration in each planning unit. Fifth, we ranked planning units for restoration based on the benefits for commercial fish catch, and compared these to ranks that additionally considered land tenure feasibility, cyclone feasibility, and land tenure and cyclone feasibility jointly.

Planning Units, Intertidal Extent, and Mangrove Area

Planning Units. We used coastal drainage basins as planning units ($n = 56$) because they typically have their own management plans. Drainage basin data was obtained from the Department of Natural Resources (Department of Resources 2022).

Intertidal Zone. We used the DEA Intertidal Extents (Landsat) model from Geoscience Australia to identify areas where mangrove restoration may occur within the intertidal zone of each planning unit (Bishop-Taylor et al. 2019). We used a Digital Elevation Model (DEM) (Geoscience Australia 2015) to exclude areas that were above 10 m to account for the inaccuracies of the DEA intertidal extents model as mentioned in Bishop-Taylor et al. (2019).

Mangrove Area

We obtained data on total mangrove area by intersecting each planning unit with Queensland Wetlands Mapping version 5.0 (Department of Environment and Science 2021). To account for areas of wetland that extended beyond the coastline, a 5 km buffer zone was created for each basin polygon based on a visual inspection of the existing mangrove extent, and manually trimmed to extend only from the coastline of each boundary before area calculations.

Calculating Commercial Fisheries Benefit From Mangrove Restoration

Fisheries Data. Fish catch and effort data was obtained from the Queensland Government Department of Agriculture and Fisheries QFish database (State of Queensland Department of Agriculture and Fisheries 2022). The dataset was based on commercial fisher's daily logbook of records between 2010 and 2019. Data was recorded 30-nautical-mile grids along the coast of Queensland. We selected estuarine associated fish species and taxonomic groups based on Meynecke et al. (2008). Species that were caught in less than 1% of grid cells were classified as "rare" and removed (five species), resulting in a total of 20 species and 165 grid cells (sampling units) being used for analysis (Table S1). Species were caught by line, pot, net, and beam trawl fisheries and were selected by kilograms of catch. Catch-per-unit-effort (CPUE, catch divided by effort; kg/day) for each species was calculated in each grid sampling unit. Errors in the logbook reporting of catches and efforts are expected to be less than 10% of the mean values (Meynecke et al. 2008), so these errors are unlikely to affect our rankings, because spatial variation in CPUE spanned approximately three orders of magnitude.

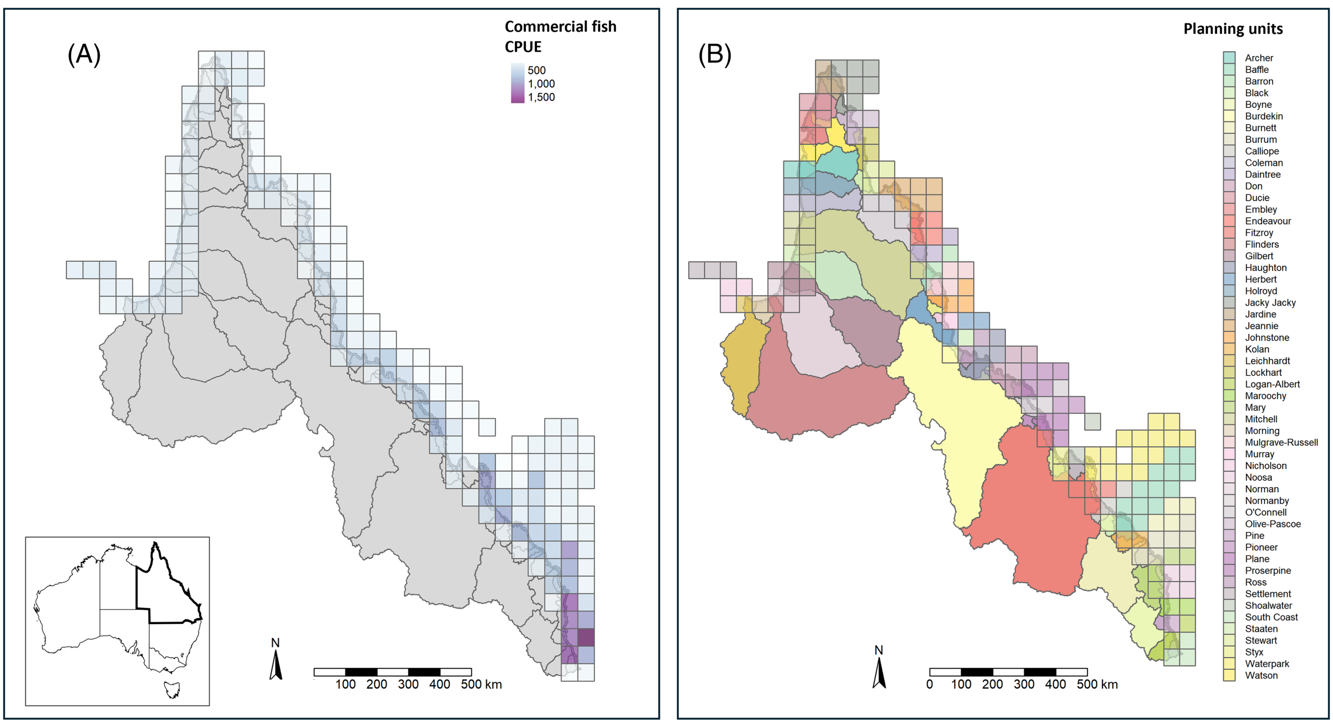

Figure 1. Map of drainage basins (planning units) in Queensland, Australia with (A) commercial fisheries CPUE (catch per unit effort) and (B) planning units assigned to CPUE grids.

Linking Planning Units and Fisheries Data. We allocated fisheries catch to planning units by nearest distance. We assigned a centroid to fisheries grid cells and determined the nearest distance from mangrove area using the centroids of the 5 km coastal buffer zone for each planning unit to each fisheries grid cell centroid. We assumed that those mangrove areas closest to grid cells were most likely to be nursery habitats. For fisheries grid cells that intersected land, grids were allocated to the planning unit that had highest proportion of area cover of the grid. Grid cells that were entirely covered by ocean were allocated to the closest planning unit. Following these allocation rules meant that some coastal planning units were not allocated to fisheries grid cells due to the narrow shape along the coastline or other planning units occupying a larger area within the grid cell (Fig. S1). These planning units have been left out of the analysis rather than assigning fisheries values manually to avoid manual modification of the data ensure that our methodology is repeatable and transparent.

Analysis of Fisheries Benefit Based on an Increase in Mangrove Area. To assess the potential benefits of mangrove restoration on commercial fisheries, we performed a benefit analysis based on evidence that planning units with greater area of mangroves contribute greater fish catch (Meynecke et al. 2008). The expected fisheries benefit per 1 ha of restored mangroves in each planning unit was calculated using the following equation:

$$B = \frac{\text{CPUE}}{A},$$

where B is the expected fisheries benefit per 1 ha of mangroves, CPUE is the total catch per unit area (CPUE) within a planning unit, and A is the total mangrove area within a planning unit. We then rank ordered the planning units from highest to lowest according to their total fisheries benefit where, e.g. the basin with the highest fisheries benefit had a rank order of "1" and the lowest had a rank order of "56."

Determining Restoration Feasibility With the Consideration of Land Tenure

Land tenure parcel data was obtained from the digital cadastral data base acquired from the Department of Natural Resources and Mines (2023). We intersected land tenure with the intertidal zone polygon to select parcels where it is biophysically possible to restore mangroves. We removed the three tenures not applicable (Covenant, Easement and Profit a Prendre) as these are limited rights granted for a specific purpose, and it would not be possible to undertake restorative interventions on these tenures. Land tenure was classified using a likelihood of feasibility (i.e., likelihood of restoration activity being approved on that tenure) (Table 1). The land tenure feasibility classifications are hypothetically based on descriptions provided by the Department of Natural Resources and Mines (Table 1), purely for the purpose of demonstrating prioritisations of restoration using land tenure. All classifications are subject to change, based for individual cases. In Queensland, the boundaries of coastal land are determined by a tidal feature, which is often the Mean High-Water Mark. The seaward side of the boundary is owned by the State (Bell-James & Lovelock 2019). Approvals and permits would be required for restoration to occur both in landward and seaward tenure (Shumway et al. 2021).

Land tenure parcels were clipped to the intertidal zone in each basin. Each land tenure parcel was then grouped per type and the area summed to calculate the proportion of each feasibility ranking in each basin. Any land tenure parcel classified as "possible" or "likely" was considered feasible for restoration from a land tenure perspective. However, it must be noted that the parcels classified as "likely" will still need the landholder or government agency to consent to the restoration project.

Determining Restoration Feasibility With the Consideration of Cyclone Probability

We first determined the path history of cyclones throughout Queensland to understand the likelihood that a cyclone would change the feasibility of mangrove restoration. Cyclone data was obtained from the Tropical Cyclone database for 20 years (from 24 March 1998) (Bureau of Meteorology 2021). Cyclones were filtered by estimated maximum wind speeds of greater than or equal to 33 m/s (Saffir–Simpson scale category of one and higher) (NOAA's National Weather Service Directives, National Oceanic and Atmospheric Administration, & Department of Commerce 2021). The cyclone data was recorded as points in the center of the cyclone, therefore, to determine the surrounding impact, each point was buffered with the mean radius of gale-force winds and then dissolved into one polygon to create a cyclone path. Cyclone paths were then joined to the planning units to aid in determining the likelihood of cyclones occurring in each one (Fig. S2).

The probability of a cyclone occurring in a 20-year period since restoration was calculated using the geometric equation (Raikar 2024):

$$C = 1 - (1 - p)^n,$$

where p is the historical annual frequency of the cyclones, n is the number of years since restoration, and C is probability of at least one cyclone occurring since restoration.

Ranking Feasibility

Planning units were ranked according to (1) fisheries benefit and (2) feasibility of restoration (land tenure, cyclone risk, and both cyclone risk and land tenure). To calculate the rank order land tenure and cyclone probability, we used the following equation for the expected benefits:

$$R = B \times F,$$

where B equals the fisheries benefit per hectare of mangrove restoration, F is the restoration feasibility. For land tenure, restoration feasibility was calculated as the proportion of the intertidal zone that was classified as "likely" or

Table 1. Land tenure parcel descriptions. The feasibility classification column is the likelihood ranking based on descriptions and brief reading of legislation. The justification column is explaining how likelihood was derived. Details gathered from "A guide to Land Tenure" under the Land Act 1994 (Department of Natural Resources and Mines 2013). Proportions of land tenure within the intertidal zone of Queensland indicated in Table S2.

Type	*Description*	*Feasibility classification*	*Justification*	*Supportive references/ legislation*
Below the Depth Plans	A registered right or interest over a parcel of land where location is defined as below a depth or to a depth below the surface of the earth (e.g. underground coal mines)	Unlikely	Restoration is unlikely to be feasible as land parcels are reserved for underground coal mines. Any restoration would be included in the mining companies rehabilitation management plan.	Based off description alone (Qld Government Abbreviations and Symbols)
Boat Harbors	Land vested under the control of Queensland Transport (Maritime Division)	Less likely	Although owned by the state government, rehabilitation would likely only be included as part of the boat harbor development and would be less likely to occur outside of the agreement and regulations held by those leasing	(Transport Infrastructure [Public Marine Facilities] Regulation 2011)
Freehold	Land held by the State and granted to a private entity in Fee Simple (freehold title). Equivalent to private ownership of land	Likely	Land owned by private landholders, so restoration is feasible (subject to permits being granted, and the landholder consenting in the instance of a third party wanting to undertake the project)	(Land Act 1994)
Industrial Estates	Land vested under the control of the Department of State Development, for the development of State Government industrial estates	Less likely	Less likely to be feasible as land is allocated for a specific purpose	Section 76O-3b (State Development and Public Works Organization Act 1971)
Lands Lease	Leasehold land administered by the Department of Natural Resources and Mines excluding Mining Homestead Tenement Leases. Leased to private entities for a particular purpose and generally for a long period of time	Possible	Restoration is possible, but will depend on the specific terms of a lease (e.g. if a lease is granted purely for grazing, it will be necessary to assess whether restoration is consistent with this purpose)	(A guide to land tenure under the Land Act 1994)
Mines Tenure	Land leased as Mining Homestead Tenement Leases (e.g. MHPL, MHL, and SPMPL) originally issued by the Department of Energy. These leases are now administered by the Department of Natural Resources and Mines. This category does not include Mining Lease or Mining Application Areas, the exception being ML7024 at Weipa, being land set aside under the Commonwealth Aluminium Corporation Pty Ltd. Agreement Act of	Unlikely	Unlikely feasible as land is allocated for specific purposes	Based off description alone (Qld Government Abbreviations and Symbols)

Table 1. Continued

Type	*Description*	*Feasibility classification*	*Justification*	*Supportive references/ legislation*
	1957 and the Alcan Queensland Pty. Limited Agreement Act of 1965 GG1965.2.1441			
NA	Unallocated state land	Likely	Land is owned by the State Government, so more likely to be feasible provided restoration aligns with Government priorities	All land that is not: freehold, road reserve, national park, conservation park, subject to lease, license, or permit, (page 491) (Land Act 1994)
National Park	Land reserved by the Department of National Parks, Recreation, Sport and Racing for a National Park, National Park (Scientific), Conservation Park or Resource Reserve	Less likely	Land is protected under strict regulations so less likely to be feasible	(Nature Conservation [Protected Areas Management] Regulation 2017)
Port and Harbors Boards	Land vested under the control of Port Authorities in Queensland	Possible	Although land is allocated for specific use, agreements could be made on the creation of environmental buffer areas, therefore restoration is possibly feasible when appropriate	(Issue of tenures to a Port Authority/ Corporation: SLM/2013/582 [Formerly PUX/952/062] Version 5.04)—Rationale, page 4–5
Reserve	Land reserved by the Department of Natural Resources and Mines for community or public purposes	Less likely	Although owned by the State Government, land is allocated for a particular use so less likely to be feasible unless restoration aligns with the reserve purpose	Section 32: State leases over reserves (Land Act 1994)
State Forest	Land reserved by the Department of Natural Resources and Mines for State Forest purposes.	Less likely	Although owned by the State Government, land is allocated for a particular use so less likely to be feasible	(Forestry Act 1959)
State Land	Land held by the State of Queensland as Unallocated State Land and other areas vested in the State (or Crown) but not held in Fee Simple or as a lease issued under the Lands Act 1994	Likely	Land owned by the State Government, so more likely to be feasible provided restoration aligns with Government priorities	(Land Act 1994)
Covenant	A registered right or interest over a parcel of land used to restrict usage of that land (shopping mall tenants)	Removed		
Easement	A right or interest on a property that is registered against the title	Removed		
Profit à Prendre	A registered right or interest of use over the property of another that allows the holders to enter and take some natural produce (mineral deposits, timber)	Removed		

"possible." For cyclones, restoration feasibility was calculated as the inverse of the probability of a cyclone occurring in 20 years after restoration.

To compare change in ranks between fisheries benefit and land tenure, and fisheries benefit and cyclone risk, we classified the ranks per basin into three different categories: increase in rank order, decrease in rank order, and no change. To calculate the joint feasibility (land tenure, cyclone risk, and fisheries benefit), we multiplied the cyclone feasibility value by land tenure feasibility value and the fisheries benefit value, then determined the rank for each basin. We then classified the ranks per basin into three categories: increase in rank order, decrease in rank order, and no change.

Results

Fisheries Benefit

The top three basins ranked for fisheries benefit were Haughton (1), Ross (2) situated in central Queensland, and South Coast (3) situated in south-east Queensland (Table S3; Fig. 2A). The bottom three were Fitzroy (52), O'Connell (53), and Coleman (54) (Table S3; Fig. 2A).

Feasibility by Land Tenure

We summarized the impact of feasibility on planning unit priorities by plotting frequency histograms changes in rank (Fig. 3). Consideration of land tenure feasibility altered the ranks of all planning units, with most units changing by 11–20 places (Fig. 3). The top 10 ranked planning units decreased in rank when land tenure feasibility was included in the analysis. Two planning units, "Haughton" and "Watson" decreased by 36 places, seven planning units decreased by 11–22 places, and one planning unit decreased by six places (Table 2; Fig. 4A). Of the lowest ranking planning units, eight increased in rank (9–42), one decreased (9) and one remaining unchanged (Table 2; Fig. 4A). Of the new top 10 planning units after the feasibility assessment of land tenure, nine resulted in low fisheries benefit rankings between 24 and 51, and one with a ranking of 15 ("Pine") (Table S4).

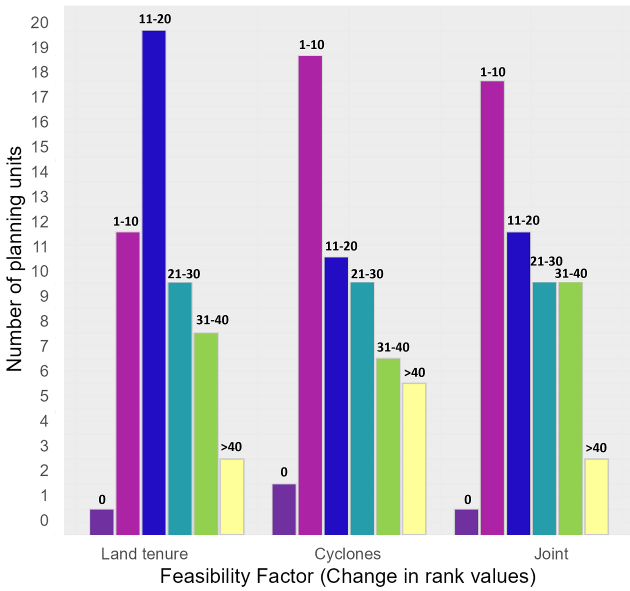

Figure 3. Frequency histograms of the change in feasibility rankings of the planning units for fisheries benefit. Categories for the number of changes in rank values is indicated at the top of each bin. Feasibility factors include land tenure, cyclones, and joint factors (land tenure and cyclones).

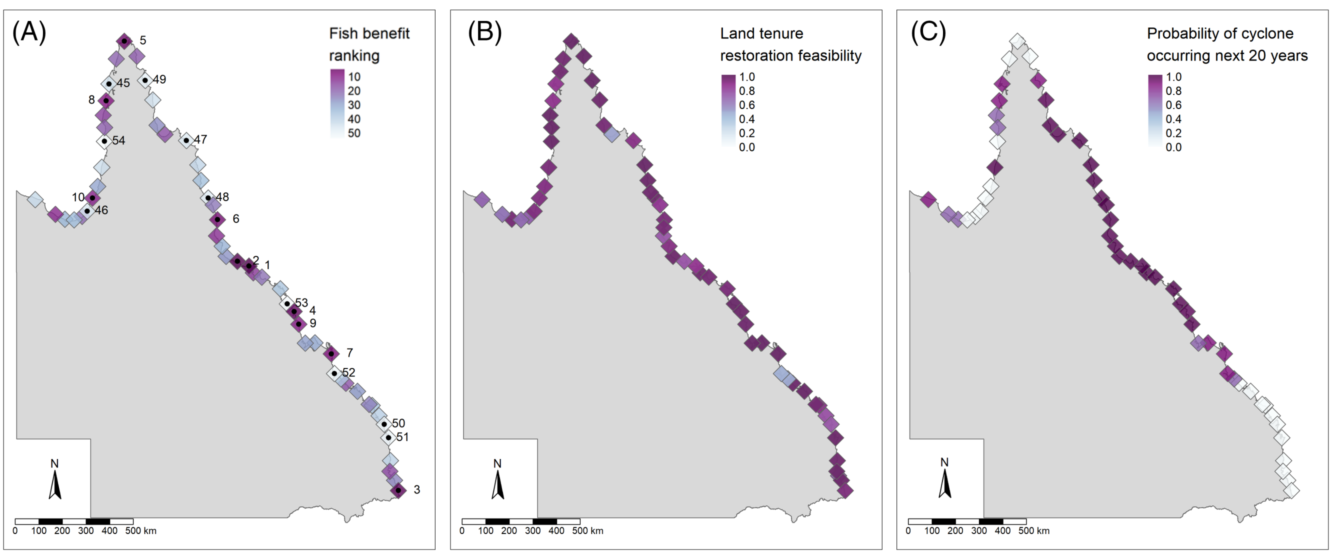

Figure 2. Map of Queensland with each grid representing the coastal centroid of the planning unit. (A) The results of the benefit analysis that predicts expected fisheries benefit based on increase in mangrove area by 1 ha. Benefit rankings are colored dark for high benefit to light for low benefit. Numeric labels and dots indicate the top and bottom 10 ranked planning unit with "1" being the highest ranked. (B) represents the probability (low (0), high (1)) of restoration occurring in each planning unit with CADASTRE land tenure parcels that are classified with "likely" or "possible" rankings. (C) is the number of a cyclones predicted to occur in each planning unit, 20 years after restoration.

Table 2. Top 10 and lower 10 planning units ranked by fisheries benefit and the rank changes when considering land tenure, cyclones, or joint (land tenure and cyclones) feasibility. Purple indicates an increase in ranks and green indicates a decrease. Yellow indicates no change in rank order compared to fisheries benefit.

Planning unit	*Fisheries benefit rank*	*Change in ranking*		
		Land tenure	*Cyclones*	*Joint*
Top 10 sites				
Haughton	1	−36	−53	−52
Ross	2	−16	−41	−37
South Coast	3	−11	−7	−7
Pioneer	4	−18	−28	−24
Jardine	5	−14	−6	−6
Johnstone	6	−19	−42	−37
Waterpark	7	−6	−15	−11
Watson	8	−36	−23	−25
Plane	9	−17	−30	−28
Gilbert	10	−22	−6	−6
Lower 10 sites				
Coleman	54	18	37	37
O'Connell	53	29	15	18
Fitzroy	52	21	29	31
Noosa	51	41	42	42
Mary	50	41	44	42
Olive-Pascoe	49	9	20	20
Barron	48	42	15	26
Jeannie	47	17	−6	−4
Norman	46	0	27	21
Embley	45	−9	8	−4

Spatially, land tenure feasibility caused an increase in ranks for planning units in the south-eastern region, and some north-eastern regions of the state. There were both decreases and increases in ranks of planning units throughout parts of the central coast (Fig. 4A).

Feasibility by Cyclone Risk

Consideration of cyclone feasibility altered almost all the ranks of the planning units, with most units changing by 1–10 places (Fig. 3). Cyclones had a substantial influence on the rankings for the top 10 sites. Six of the 10 planning units had a greater decrease in rank compared to land tenure (23–53 places), and four had a decrease less than land tenure rankings (6–15) (Table 2; Fig. 4B). All but one of the lowest ranking planning units increased by 8–44 places, with "Jeannie" decreasing by six places (Table 2; Fig. 4B). Of the new top 10 planning units after the feasibility assessment of cyclones, eight resulted in low fisheries benefit rankings between 24 and 51, and two with slightly higher rankings: "Pine" (15) and "South Coast" (3) (Table S4). Spatially, cyclone feasibility caused an increase in ranks for planning units in the south-eastern part of the state, and mostly decreases throughout the central and northern regions, with two planning units not changing in rank order (Fig. 4B).

Joint Feasibility

Consideration of joint feasibility (land tenure and cyclones) altered almost all the ranks of the planning units, with most units changing by 1–10 places (Fig. 3). The change in ranks for the top 10 planning units was greater than land tenure and less than cyclones for six planning units (11–52 places), one planning unit ("Watson") was less than land tenure and greater than cyclones rank (25), and three were equal ranking to cyclones and less than land tenure (6–7 places) (Table 2; Fig. 4C). All but two of the lowest ranking planning units increased by 20–42 places, with "Jeannie" and "Embley" decreasing by four places (Table 2; Fig. 4C). Of the new top 10 planning units after the feasibility assessment of both land tenure and cyclones, eight resulted in low fisheries benefit rankings between 24 and 51, and two with slightly higher rankings: "Pine" (15) and "South Coast" (3) (Table S4). Spatially, joint feasibility caused an increase in rank order in the south-eastern part of the state, similar to cyclone feasibility, and mostly decreases throughout the central and northern regions, with only one planning unit remaining unchanged (Fig. 4C).

Discussion

Restoration feasibility must be considered during site selection to help achieve successful restoration outcomes. Feasibility can be influenced by biophysical factors (e.g. cyclone risk) and governance factors (e.g. land tenure). We showed that consideration of feasibility changes which planning units along the Queensland coast will be important areas for restoring mangroves for the objective of increasing commercial fish catch. The spatial footprint of cyclones meant that cyclone feasibility had a substantial influence on the rank order of planning units in central and northern regions of the Queensland coastline. Whereas consideration of land tenure influenced ranks across all regions. The historical cyclone data suggested that some areas of the Queensland coast had a high probability (e.g. approximately 90%) of intersecting with the path of a cyclone in the next 20 years, while others had a very low probability of cyclone occurrence. The variability in cyclone risk across planning units was reflected in the large effect on restoration rank priorities. These results emphasize the importance of considering the influence of weather events, such as cyclones during the planning of restorations actions (Hagger et al. 2018).

Our feasibility assessment suggested that land tenure is an important factor to consider when identifying planning units for restoring mangroves to enhance commercial fisheries catch. This result could be due to most planning units having a large proportion of land tenure coded as "likely" feasible. However, it is likely that land tenure feasibility may vary at finer spatial scales than the basin scale we used. For instance, both freehold land and State land are coded as "likely," but the utility of sites within these land tenure categories for restoration may vary considerably on-ground. The ability to restore on both tenure types is dependent on consent of the private landholder (freehold) or the State, and it will therefore be necessary for the restorative intervention to align with their personal priorities (freehold) or government priorities (State). Due to our classification only including land tenure as a governance feasibility factor, most of the Queensland intertidal zone was classified as being feasible for restoration, and this classification method may lack the nuance needed for a comprehensive assessment. For example there are other governance

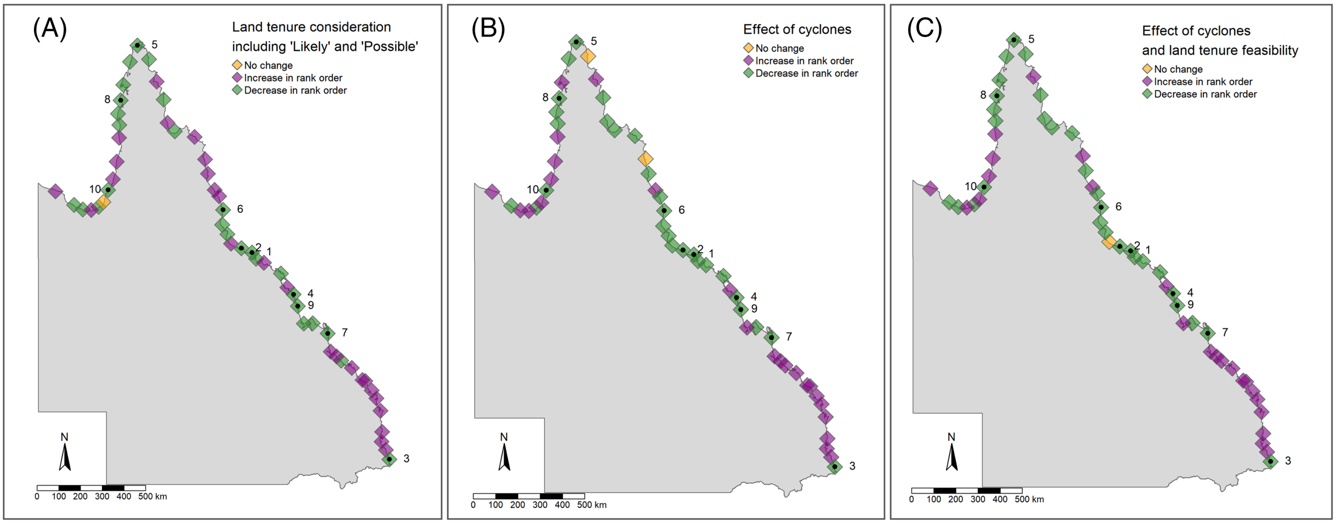

Figure 4. Comparison of three outcomes; fisheries benefit ranking with (A) Land tenure consideration including "likely" and "possible" classifications, (B) effect of cyclones, and (C) effect of cyclones and land tenure feasibility. Purple is an increase in ranking, green is a decrease in ranking, and yellow indicates no change in ranking. Numbered planning units represent the original top 10 rank for fisheries benefit.

factors that may significantly impact on the feasibility of a site for restoration, including the need for rigorous approvals before restoration actions can be undertaken (Bell-James et al. 2023*a*, 2023*b*). The uncertain legality of restoration on specific land tenure types is a long-standing issue (Bell-James et al. 2023*a*), with the cost, complexity and slowness of obtaining permits identified as a major barrier to restoration (Shumway et al. 2021). Some restoration practitioners have found that restoration permits are easier to obtain for public lands than private lands (Welsh et al. 2018; Bell-James et al. 2023*b*). However, restoration on public land may require a proponent to accept ongoing liability for restorative interventions, which may be a deterrent (Bell-James et al. 2023*c*). The issue of conducting restoration on private lands is compounded by the lack of, or uncertainty of incentives that are available to private land holders (Stern 2006; Bell-James et al. 2022, 2023*b*), or when a third party seeks to undertake restoration on a privately-owned parcel, they need to "sell" the benefits to a landholder (Bell-James et al. 2023*c*). This underscores the need for a greater understanding of how land tenure influences restoration feasibility and the need to incorporate the consideration of other governance factors into the identification of more viable sites during restoration planning.

The planning units identified as having low mangrove restoration feasibility when considering cyclone risk and land tenure can also be seen as opportunities for alternative approaches to improve feasibility (Piccolo et al. 2024), particularly in places where fisheries benefit is known to be high. For example in regions that are prone to cyclone occurrence, consideration could be taken in selecting the appropriate species to ensure ecosystem resilience (Krauss & Osland 2020), or planting in areas adjacent to established mangrove forests could help protect smaller mangroves during cyclone events (Smith et al. 1994; Krauss & Osland 2020). The feasibility of restoration on private land could be improved by financial incentives (Selinske et al. 2022), such as Australian Blue Carbon credits (Clean Energy Regulator 2022). Other changes may need to occur at a higher level of government, such as amending legislation for easier permitting of coastal restoration actions (Shumway et al. 2021). Taking into consideration how and what management interventions could change the feasibility outcomes is an important step during the planning stages and can help avoid failed restoration actions.

Our study indicates how multiple types of feasibility can be considered jointly to increase feasibility of achieving stated objectives in restoration. This is timely and important, given that past restoration failures may have been avoided if multiple types of feasibility were considered. For example in 2013, Typhoon Haiyam devastated the Philippines including the vast extent of *Rhizophora* plantations (Villamayor et al. 2016). Of the 20 ha of mangrove previously planted along the shoreline, 45% were severely damaged, particularly the older mangroves, showing a higher vulnerability to extreme weather events. Therefore, to avoid mass mortality, biophysical factors, such as specific species, should be considered when planning coastal restoration actions in cyclone-prone locations. Another example is several restoration projects in Sri Lanka had mangroves planted at low and high points of the intertidal zone without consideration of destructive land uses such as grazing and inappropriate geographical locations (Kodikara et al. 2017). This resulted in only three sites out of 23 projects having over 50% survival rates and nine sites having no plants surviving. The poor survival rates were attributed to post care regimes including unregulated cattle grazing and lack and abundance of tidal inundation (Kodikara et al. 2017). Had these governance factors (land use and post care) been considered during the planning stages, more appropriate sites with higher rates of survival may have been selected, or additional management actions could have been implemented to increase restoration success. Lessons drawn from projects with low survival rates have contributed to the development of planning methodologies for restoration actions. Established frameworks, such as the Society of Ecological Restoration of

Australasia's National Restoration Standards (McDonald et al. 2016) and the IUCN's ROAM (Maginnis et al. 2014) offer valuable guidance to practitioners by incorporating multidisciplinary considerations into the restoration planning process. While these frameworks provide a conceptual approach planning restoration, our approach provides a systematic and quantitative approaches for spatially analyzing the factors influencing feasibility. A systematic approach helps avoid overlooking factors that have an important influence on conservation priorities and helps make decisions more transparent to communities (Game et al. 2013).

Our approach for quantifying feasibility and evaluating fisheries enhancement from mangrove restoration has a number of limitations and caveats. The rankings determined in this study are based off benefits and feasibility as that is the focal point of this study. However, to perform a cost-effective analysis, costs would need to be included. For example there may be areas which have high fish production, high governance feasibility, and high cyclone feasibility, but are expensive to implement actions. Therefore, the action would not be prioritized in that location. Including costs is beyond the scope of this work but offers an interesting avenue for future research. We considered how mangrove benefits per unit area for fisheries may vary by dividing CPUE by mangrove area. Therefore, our analysis accounts for regional differences in the benefit of mangroves for fisheries. However, benefit of mangroves for fisheries depends on more than just their area, particularly at finer scales than our basin-scale analysis. For example connectivity to other ecosystems and tidal regimes influence the benefits provided to fisheries (Meynecke 2009; Sheaves et al. 2015). In our assessment of feasibility, we considered the probability of a cyclone occurring in the next 20 years and the proportion of infeasible intertidal land tenure as having equal weights. However, when considering feasibility in practice, it may be useful to assign different weights if some factors carry greater importance than others when undertaking restoration. Cyclones, unlike land tenure legislation, do not prevent restoration efforts but rather indirectly reduce the feasibility by introducing risk of failure over longer periods. Therefore, it may be preferable to down-weight their importance relative to land tenure when conducting a restoration feasibility assessment. It is also important to consider the beneficiaries of the services being provided through restoration actions. For example the benefits to commercial fishers, particularly when determining sites for offsetting (Ma et al. 2023), or areas of high cyclone risk that may present the opportunity to use mangroves as a Nature-based solution and shoreline protection against cyclone damage to infrastructure (del Valle et al. 2020). These are important factors that would be beneficial to enhance future research and need to be considered during the planning and feasibility assessments of coastal restoration actions.

Our study emphasizes the role of both biophysical and governance factors in determining the feasibility of mangrove restoration for enhanced fisheries outcomes. Land tenure and cyclones emerged as highly influential factors in site selection. When considered in identifying restoration priorities, cyclones primarily reduced the priority of planning units in central areas where cyclone risk is higher, while consideration of land tenure reshuffled priority of planning units across the Queensland coastline. Our results could be used to inform coastal restoration actions as part of a spatial prioritization that considers other factors of interest, such as social factors (e.g. private land holders' willingness to participate), or logistical factors (e.g. accessibility to sites). It could also inform management of mitigation actions that may be required regarding cyclone-prone areas such as northern and central Queensland. At a finer scale, land tenure considerations may be crucial, particularly when considered in tandem with other governance factors. Management interventions for cyclone risk could include identifying planning units with low feasibility and selecting more resilient species. As for land tenure, formalizing incentives and regulations may be an apt intervention. Drawing lessons from historical oversights, we suggest the integration of established frameworks and methodologies into the planning process, while ongoing need for systematic and quantitative approaches to enhance future research and restoration planning. Recognizing the limitations of our approach, we recommend consideration of multiple factors and their spatial interactions to mitigate the risk of restoration failure and promote successful restoration outcomes.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Four planning units excluded from the analysis due to narrow shape along the coast of nearby planning units occupying a larger area of the grid cell.
Figure S2. Historical data of cyclone occurrence from 20-years, joined to planning units.
Table S1. Common names of 20 fish species used in the analysis and derived from Meynecke et al. (2008).
Table S2. Proportion of land tenure within the intertidal zone throughout Queensland per classification.
Table S3. The top ten and the lower ten planning units for fisheries benefit throughout the Queensland coastline.
Figure S3. Comparison of three outcomes; fish benefit ranking with land tenure, fish benefit ranking with potential cyclones, fish benefit ranking with land tenure and potential cyclones.
Table S4. The new top ten planning units for each feasibility factor with the previous fisheries benefit ranking.
Table S5. Caveats to the study on mangrove restoration priorities changing when considering land tenure and cyclones risk during planning and site selection.

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