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One-third of Australia's coastal terrestrial aquaculture at risk from sea level rise

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Abstract

Background Aquaculture is central to livelihoods and food security globally, providing promise to meet growing human seafood and protein demand without surpassing environmental limits. However, the aquaculture industry is vulnerable to climate change impacts, including sea level rise. Queensland is the largest terrestrial aquaculture producer in Australia, largely consisting of coastal pond-based production. However, Queensland is also projected to experience a 0.8 m sea level rise by 2100 (RCP 8.5). Here, we assess the sea level rise risk to Queensland's coastal terrestrial aquaculture industry using existing datasets on coastal inundation and erosion from sea level rise combined with novel, satellite-derived data on current aquaculture production locations and identified aquaculture development areas.

Results We found that over one third of currently producing aquaculture sites are at risk and one quarter of development areas may be unsuitable for aquaculture due to their high exposure to inundation. We also found that over 98% of prawn sites and 50% of the production are expected to be impacted.

Conclusions Our results demonstrate how sea level rise threatens aquaculture production and assets, potentially generating socio-economic repercussions in Queensland and beyond. These results can inform future planning and adaptation measures to minimise losses.

Keywords Climate change, Google Earth Engine, Geospatial analysis, Low elevation coastal zones, Planning

Background

Aquaculture has become an increasingly important aspect of livelihoods and food security [1], offering an important source of protein to the human population and a promising way to meet growing seafood demand while staying within environmental limits [1, 2]. Global aquaculture production has increased at a rate of 6.7% per year over the past 30 years [3],with commercial production of over 652 species in 207 countries and territories [4] across a wide range of methodologies [5, 6]. However, the aquaculture industry is vulnerable to environmental risks [5–10], including shifts in water temperature [5, 9], marine heatwaves [11, 12], extreme events [5, 13] like floods, heavy rainfall [10], storms, and cyclones, diseases [2, 4, 5, 9], low oxygen levels in water [5, 6], and sea level rise [5, 13].

Sea level rise(SLR) has accelerated in the twentieth century, driven by mass loss of ice sheets and thermal expansion from global warming [14]. It is estimated that sea level has increased at a mean rate of 3.3 mm per year globally over the past 3 decades. Low elevation coastal zones (LECZs), situated less than 10 m above mean sea level (MSL), contribute approximately US$1 trillion to global wealth but are usually more exposed to

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floods and storm surges [15, 16]. SLR leads to increased coastal flooding and erosion by itself, but can become a greater hazard in extreme combinations with storm surges, waves and high tides [17]. Such inundation and erosion can cause damage to humans, infrastructure and the natural environment. The extensive socio-economic and environmental repercussions from intermittent coastal flooding can pose substantial threats to assets, reaching up to 12–20% of the global GDP [18]. Given the proximity of terrestrial aquaculture to the ocean and estuaries sea level rise may threaten production, infrastructure and land uses.

Queensland is the third largest producer of aquaculture in Australia [19] and the leading producer of coastal terrestrial aquaculture using pond-based systems. The industry primarily relies on pond-based operations with some recirculating aquaculture systems (RAS). Pond-based operations utilize earthen structures with water exchange mechanisms, drawing estuarine and marine water through pumping stations for coastal facilities or accessing freshwater from rivers, dams and groundwater for inland operations [20]. RAS facilities, while less common, are indoor enclosed systems incorporating water treatment, filtration, and temperature control to optimize water conservation through recirculation [21]. Queensland's aquaculture experienced a growth of around 354% in production over the past 21 years, largely consisting of tiger prawns (*Penaeus monodon*), barramundi (*Lates calcifer*) and red claw (*Cherax quadricarinatus*) [19]. In addition, Australia's rates of SLR have been above the global average since 1993 [22], with the State Government projecting SLR of 0.8 m by 2100 [23]. The aquaculture industry recognises climate change as a potential risk, with the Australian Prawn Farmers Association's (AFPA) 2020–2025 strategic plan stating "unforeseen climate change on farms" as a significant threat [24]. However, spatial data on aquaculture production is limited and the extent and location of aquaculture areas at high risk from future SLR are currently unknown.

Here we assess the potential exposure of Queensland's coastal terrestrial aquaculture industry to SLR. We use existing datasets on projected coastal inundation and erosion from sea level rise [23] by 2100 from the Queensland government (Representative Concentration Pathway (RCP) 8.5) combined with novel data on current and future aquaculture locations to identify hot spots of risk. In addition, we estimate production losses and their associated economic impacts to the industry. Our results can inform and help the aquaculture industry avoid potential impacts of SLR driven inundation in aquaculture production now and in the future and develop adaptation strategies where necessary.

Methods

In this study we combine projections of SLR with current and future aquaculture production locations to assess sea level inundation risk to coastal terrestrial aquaculture production sites in Queensland by 2100. All analyses were performed in R version 2023.09.1 + 494 (2023.12.0–369) and spatial layers were projected to the Australian Albers equal area projection.

Aquaculture production locations

In Queensland, spatial information on the location of aquaculture sites is lacking. To determine the spatial location of leased sites, we cross-referenced the list of aquaculture lot cadastre numbers provided by the Department of Agriculture and Fisheries (DAF) [25] with cadastre in the spatial database QGlobe [26].

Aquaculture production locations (sites) were separated into four categories for further analysis: lots (as described above), farms, productive lots and productive farms (Fig. 1). Analysing SLR risk to aquaculture sites by lot enables stakeholders to understand the risks to both potential future and current aquaculture production in each planning unit, while assessing by aquaculture farms may be more intelligible to managers as multiple adjacent lots may be administered by the same industrial group (Fig. 1). In addition, analysing additional aquatic features (e.g. lake, reservoir, raceway, water course) on farms enabled us to estimate where and how much production occurs in each farm and how the potential impact of SLR on productive areas. Farms were grouped based on Authority numbers provided by DAF, which signify lots operated by the same industrial group.

The aquaculture leased allotments dataset sourced by DAF did not provide information on whether a lot or farm site was actively producing aquaculture. To identify actively producing leases, we first ground truthed each lot location using Google Earth. For each location we recorded information on whether there was visible aquaculture infrastructure (i.e., ponds, buildings, raceways). If such infrastructure was present, we documented the number of ponds or other structures and recorded whether infrastructure was contained within designated lot limits or not. During this process, additional aquaculture production areas trespassing allotment areas were identified and included in the analysis, where appropriate.

Next, we automated the identification of water in aquaculture sites to identify ponds, which we then classified as productive areas. We acquired and processed Sentinel-2 MSI satellite image acquisitions between January 2020 and December 2021, within a 1 km buffer around aquaculture sites, including those from DAF and additional allotments identified during ground-truthing.

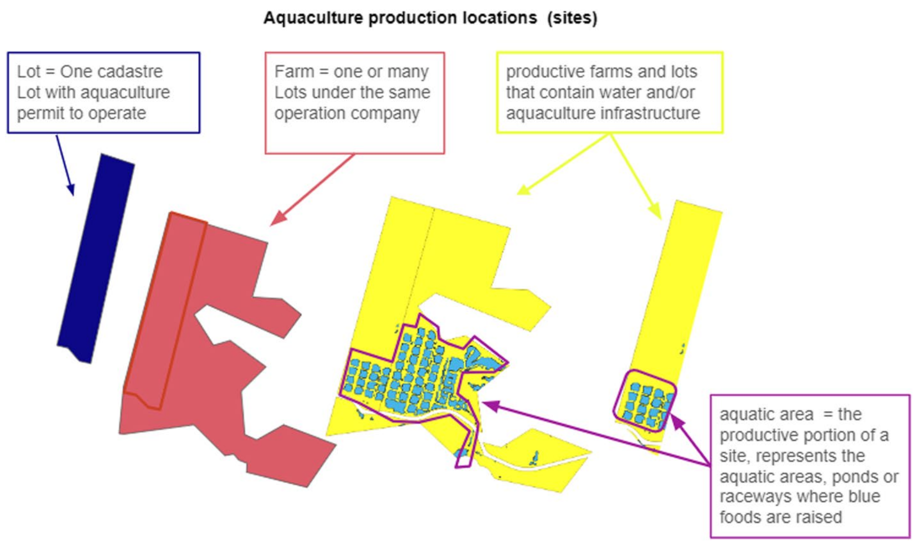

Fig. 1 Infographic of aquaculture production location (sites) assessment: lots, farms, productive farms and productive lots and aquatic areas (open air water systems such as ponds)

The satellite image processing was performed on the Google Earth Engine. The process involved building a time series stack of Sentinel-2 imagery (both Level-1C and Level-2A collections), implementing a robust pre-processing workflow that included a probability-based per-pixel cloud masking function. This function excluded pixels with cloud probability greater than 10%; the temporal density of the Sentinel-2 timeseries allowed use of a conservative threshold that ensures different cloud types and cloud artefacts are removed, without affecting the amount of high-quality imagery available for analysis. The analysis also incorporated multiple spatial masks, including land/water separation using OpenStreetMap data and coastal ecosystem probability, to restrict the analysis to relevant coastal areas while excluding land masses and areas with high tidal influence. After preprocessing, we calculated the Normalized Difference Water index (NDWI) [27, 28] for each pixel and date in the image stack. NDWI was developed to detect the presence of water in a satellite image pixel, enabling water bodies to stand out distinctly from surrounding areas uncovered with water, such as soil and vegetation [29]. NDWI ranges between −1 to 1, with positive values greater than 0.2 usually representing water bodies.

The sum and the 80th and 20th percentile of the NDWI were calculated for every pixel in the Sentinel-2 image stack for different time periods. This enabled discrimination of water features at individual dates, as well as allowing individual pixels to be characterised by how often they were inundated with water over longer time periods. The 20th percentile was used to identify water while accounting for the fallowing periods when farms experience a temporary cessation of production, the 80th percentile was used to identify semi-permanent water features, and a threshold applied to the NDWI sum identified areas with consistent water content. We aggregated these three measures to create a final data layer of permanent, semi-permanent and temporary water features within aquaculture sites areas in Queensland.

To isolate likely aquaculture ponds and water systems from adjacent water bodies (e.g., rivers and tidal areas), we intersected the combined NDWI water features layer with the full set of aquaculture sites (excluding the buffer). We then manually corrected any inconsistencies in productive areas from our ground-truthing. Finally, for each aquaculture lot, farm, and aquatic area we identified the likely species being cultured based on information from DAF to assess difference in SLR risk to different culture types. The dataset included nine species types: prawn, barramundi, red claw crayfish, freshwater fish, hatcheries, ornamental, other (including marine finfish and eels), aquarium, and unknown. Both barramundi and red claw represent a single cultured species, while categories like prawn, freshwater fish and marine finfish contain multiple species. For example, prawn aquaculture in Queensland is dominated by tiger prawns but also consists of other species such as banana prawns (*Penaeus merguiensis*). In addition, freshwater fish may represent several species such as jade perch (*Scortum barcoo)*, silver perch (*Bidyanus bidyanus*), Murray cod (*Maccullochella peelii*), and marine finfish are represented by cobia (*Rachycentron canadum*) and Grouper (*Epinephelus lanceolatus*) The "others" category includes shortfin eel (*Anguilla australis*) and longfin eel (*Anguilla reinhardtii*).

We were unable to define hatchery and ornamental species using the data provided, therefore we focused our analysis on aquaculture used within food systems, which included prawn, barramundi, freshwater fish, red claw, marine finfish and hatcheries. Sites with multiple species made up a small proportion of area and were considered in each species specific assessment.

Aquaculture production distribution models

Following the identification of productive aquaculture sites, we developed an aquaculture production distribution model to estimate the potential volume (tonnes) and economic value of aquaculture potentially at risk from SLR inundation in Queensland. To do this, we used basic information commonly used for terrestrial crop production allocation models [28] including stocking rate (i.e., the number of individuals of each species group that can be produced by unit area), harvest weights, annual harvest rates, and productive area within each lot (calculated based on productive areas described above). We estimated production distribution for two of the major aquaculture species produced in Queensland (by volume and value), tiger prawn (*Penaeus monodon*) and Barramundi (*Lates calcifer*). We used publicly accessible production data for the financial year 2020/2021 [19] to validate our production estimates with reported production levels.

To estimate prawn production distribution, we used the midpoint of industry reported stocking rates [30], which range from 25 to 40 prawns per square metre (midpoint = 32 prawns/m^2). Individual harvest weights typically range between 30 to 35g [30], with a midpoint of 32.5 g. We assumed that each area was harvested once per year. While some farms between Cardwell and Cooktown can achieve two harvests annually, most Queensland farms are limited to one harvest per year [30] due to temperature constraints and the necessary dry period between production cycles [20]. Additionally, we considered a production mortality rate of 20%, which is consistent with global estimates [20, 31], not considering disease outbreaks.

For barramundi aquaculture production, we used direct yield values of 15–30 tonnes per hectare [32] (midpoint 22.5 tonnes/hectare), and converted to km^2. We did not find values for mortality and disease outbreaks in literature, therefore production mortality was not considered in the barramundi production distribution estimates.

For both species, to distribute production across sites we multiplied the midpoint of yield ranges (production/km^2) by the identified pond area (km^2). Notably, in some parts of Queensland there are farms using indoor recirculating aquaculture systems (RAS) which could not be detected using our pond detection method because water is not visible in the satellite imagery and therefore could not determine whether they are or not productive. Consequently, RAS facilities were not included in our aquaculture distribution model. However, they were incorporated into our broader analysis of sea level rise exposure at the lot level.

Aquaculture development areas

Aquaculture development areas (ADAs) are land-based regions that have been defined by DAF for the state of Queensland, Australia to promote sustainable aquaculture development. In December 2018 a list of six ADAs was published [33] and in 2021 two additional ADA's were added forming a total of eight areas [34]. ADAs were identified using criteria and a scoring protocol including characteristics such as (1) distance of land to water source, (2) water quality and quantity accessible for intake, (3) land tenure and local government area zoning, (4) land elevation—height above sea level, (5) topography, and (6) land subject to tidal influence (the less influence the better) [31]. The ADAs were later reviewed and approved by an Aquaculture Advisory Committee and are, therefore, official areas promoted for aquaculture expansion in Queensland. While none of these areas are currently under development, we aimed to assess their risk to SLR. Given that aspects of "land elevation" and "tidal influence" were prioritised within the analysis, we hypothesised high SLR risk to these areas.

Sea level rise

We used sea level rise (SLR) inundation projections from the Queensland Spatial catalogue [23]. This dataset indicates which areas are expected to be vulnerable to coastal erosion and permanent tidal inundation due to a SLR factor of 0.8 m in 2100 [23]. According to the Queensland Government the calculation of the erosion-prone area is based on several key factors: a projected SLR of 0.8 m; a short-term erosion component driven by extreme storm events; a long-term erosion component associated with gradual processes such as channel migration or sediment supply deficits; a dune scarp component, where slumping of the scarp face occurs following erosion; erosion risk due to future SLR, which includes both permanent inundation by tidal waters and the morphological response of the coast to elevated water levels; and a 40% safety factor to account for uncertainties. Further details on SLR and erosion datasets used in this study can be found in the Coastal Hazards Guide [35]. Apart from the composite layer analysis, we also examined each erosion-prone component separately (Supplementary Materials).

This inundation dataset is representative of Coupled Model Intercomparison Project 5 (CMIP5) projection, as downscaled CMIP6 projection are currently unavailable for Australia. The erosion-prone areas dataset was modelled by the Queensland government using the projections available in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (2014) [36]. The IPCC concluded that under SSP5-8.5, with medium confidence, the likely range of SLR globally is 0.63–1.01 m. Therefore, 0.8 m was set as the planning benchmark for the state of Queensland [37] and that is compatible with a SLR estimated by the Government by the end of the century.

Exposure of aquaculture production locations to sea level rise

Risk to aquaculture sites was estimated by intersecting the composite erosion-prone areas layer with aquaculture locations (lots, farms, productive lots, productive farms, and ponds within productive farms) and ADAs. We also assessed the level of aquaculture risk from SLR within each Local Government Area (LGA) [38]. LGAs provide a broader scale measure of risk hotspots and play a key role in local infrastructure, planning, and regulations relevant to aquaculture production and climate change adaptation. Performing the dual-approach analysis—examining both site-level exposure and specific pond area exposure, ensured we maintain a comprehensive understanding of risks to different aquaculture system types, even with the inherent limitations in detecting enclosed water systems.

Estimates for current productive aquaculture ponds were derived by intersecting the erosion-prone areas layer with our production distribution models for prawn and barramundi. To assess potential loss in production, we tested a range of inundation values where we assumed pond inundation above a certain percentage threshold would result in the complete loss of the pond, and thus it's production. Given no information on inundation thresholds and their impact on ponds was available in the literature, we tested threshold values ranging from 2 to 100% of pond area affected by coastal erosion. For each threshold, ponds with percentage of area affected below the threshold were only considered to lose the inundated area (km^2) and its associated production, while ponds exceeding the threshold were considered as entirely lost. We assumed these ponds would become unviable due to compromised structural integrity, potential stock escape, and/or water quality impacts. This analysis enabled us to calculate potential production losses (AUD and tonnes) across different vulnerabilities.

Results

Aquaculture production locations

According to the DAF dataset there were 727 km^2 (265 lots, 262 farms) approved for aquaculture production in Queensland as of 2024. Through our ground truth and remote sensing analysis, we identified an additional 76 lots, most of them adjacent to areas in the DAF dataset. In addition, we excluded the Awoonga dam (79.86km^2) as no aquaculture is developed in the lake and aquaculture activities are restricted to a small building (*personal communication* [39]). This resulted in a final dataset covering 647.14 km^2 (341 lots, 275 farms).

The automated detection using Google earth engine found ponds in 234 of all lots (192 farms), which covered 121.21 km^2 of land. Of these productive lots, an estimated 16.30 km^2 was identified as ponds and water bodies used in aquaculture production. Among those water bodies 11.71 km^2 were used for prawn production, 2.15 km^2 for barramundi, 0.32 km^2 for freshwater fish, 0.86 km^2 red claw crayfish, 0.18 km^2 for ornamental species, 0.21 km^2 for marine finfish and 0.063 km^2 for hatcheries (table S3). In some cases, multiple species were produced in the same lot, which occurred across an estimated 0.12 km^2 (7 lots). An additional 0.75 km^2 of ponds detected did not have any information on the species cultivated.

Across 11.71 km2 of prawn production area, the potential production ranges between 7,026 and 13,115 tonnes, while for barramundi, the 2.15 km2 of identified aquaculture ponds, assuming Queensland aquaculture industry production ranges from 1,500 to 3,000 tonnes/km^2 (midpoint 2,250 tonnes/km^2) and could potentially produce between 3,225 and 6,450 tonnes. For both species, the observed production in 2020/2021 (8,003 tonnes for prawns and 3,478 tonnes for barramundi) falls within these calculated potential ranges, supporting the validity of our production distribution estimates.

Aquaculture exposure to sea level rise

We found that 34% (116 of 341) of all lots are likely to be affected by SLR and erosion by 2100. Our results indicate that among the sites exposed, the majority (54.7%, 64 lots) are anticipated to have over 50% of their area affected by SLR. Additionally, 44 lots are projected to be highly impacted, with over 75% of their area exposed to SLR (Fig. 2A). Prawn lots were identified as the most vulnerable to SLR (98%(54 lots)) along with marine finfish (100%(2 lots), followed by hatcheries (50%, 4) and barramundi lots (44%, 22) (Fig. 2A and table S3). Red claw crayfish, freshwater fish and ornamentals were found to be less vulnerable to SLR, with only 8% (6 lots), 12.8%(5) and 7.6%(1) of these lots likely to be affected, respectively. Of productive aquaculture lots, 43.5% (102 of 234) may be exposed to SLR. We estimated that around 55% of these productive lots will face more than half of their area exposed to SLR.

Among the Local Government areas (LGAs) in Queensland, considering all lots, the most affected were Cassowary Coast regional (3.89km^2, 71%), Whitsunday Regional (3.63km^2, 39%), Gold Coast Regional (3.04 km^2,

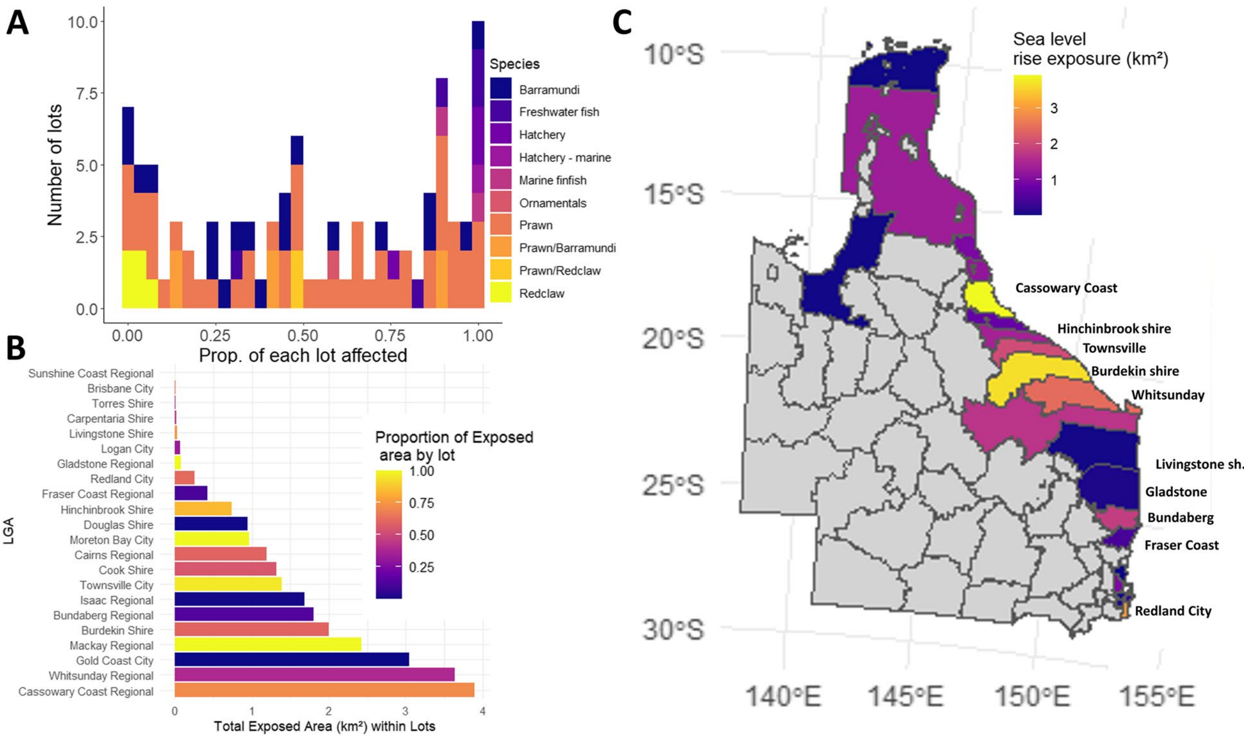

Fig. 2 Aquaculture lot exposure to SLR (**A**) Number of lots exposed to SLR by species group and the proportion of the land in the lots expected to be affected by SLR. **B** Aquaculture lot Exposure of aquaculture area (km2) by LGA (size of bar) and proportion of lots exposed by LGA (colour of bar) and **C** spatial distribution of aquaculture lot exposure by Local Government Area (LGA)

57%), Mackay Regional (2.42 km^2, 100%) and the least exposed areas were within the Sunshine Coast regional (Fig. 2B and C).

For aquatic ponds we found the risk hotspots (Fig. 3A) and the most vulnerable species. The productive lots producing marine finfish, prawn, barramundi and hatcheries were the most exposed to SLR (Fig. 3A). Marine finfish ponds are projected to be fully exposed to SLR (100% of 0.21 m^2) and hatchery ponds could face more than 25% potential pond losses (Fig. 3B). Ornamental ponds are likely to experience 8.8% of the area inundated (0.016km^2), red claw crayfish have an estimated 3.6% loss in aquatic area (0.031km^2), while freshwater fish areas are facing very little inundation (3.43%, 0.011 km^2) (Table S3).

Our sensitivity analysis of pond inundation thresholds revealed distinct vulnerability patterns across species. For prawn aquaculture, potential losses showed considerable variation, with exposed areas ranging from 2.96 (2% threshold) to 10.23 km2 (100% threshold) (25.3% to 87.4% of total area), corresponding to economic losses between AUD$36.9–127.6 million (Table S1). The most substantial change occurred between the 5% and 7.5% inundation thresholds (Figure S1), where the area projected to be exposed to SLR dropped from 10.22 km2 to 5.90 km2 (from 87.3% to 50.4% of total area) and the number of affected ponds decreasing from 40 to 39 of 43 total ponds. Barramundi farms showed more gradual impact patterns, with affected areas ranging from 0.77 to 1.39 km2 (36.0% to 64.6% of total area), equivalent to economic losses between AUD$12.6–22.6 million (Table S2). Two notable transitions occurred: first at the 15% threshold (Figure S2), where affected ponds decreased from 13 to 11 of 14 total ponds (92.9% to 78.6%), with affected area reducing from 1.34 to 1.27 km2, and a second significant drop at 40% threshold, where the number of exposed ponds decreased to 6.

The most vulnerable LGAs regarding productive prawn ponds are the Gold Coast city (1.12km2, 92%), Burdekin Shire (0.59km2, 49%), Isaac Regional (0.36km2, 42%), Cassowary (0.30km2, 20%), Whitsunday Regional (0.26km2, 5%), Mackay Regional (0.073km2, 100%) and the least exposed is Fraser Coast regional (Figure S3). Barramundi ponds were most exposed across Whitsunday Regional (0.43km2, 73%), Douglas Shire (0.23 km2, 44%), Cassowary Coast Regional (0.085km2, 97%) (Figure S2). Areas of high prawn production and high SLR risk occur greatly in the Gold Coast, and in other LGAs such as Mackay, Burdekin, Whitsunday, Bundaberg, Isaac and

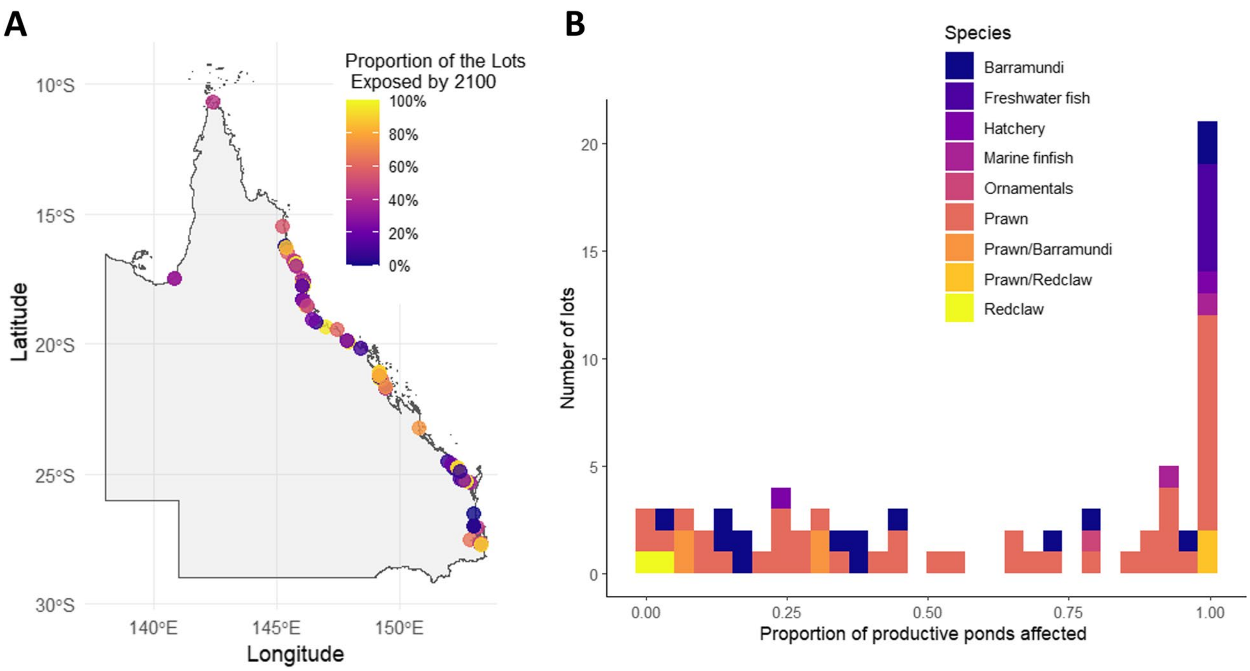

Fig. 3 Current productive aquaculture risk due to 0.8 m SLR (**A**) proportion of each productive lot at risk due to SLR (**B**) proportion of the ponds in productive lots at risk by species and number of lots exposed

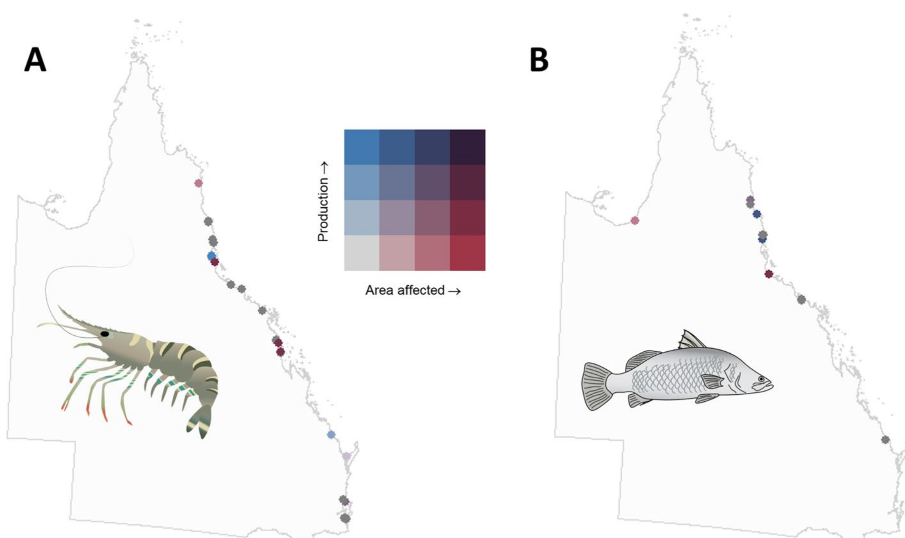

Fig. 4 Aquaculture production and aquatic area (pond) exposure to SLR by 2100 for (**A**) prawn and (**B**) barramundi in Queensland, Australia, showing darker (wine) coloured dots in lots that have both high production and high exposure to SLR. Images of species sourced from ian.umces.edu/media-library [40, 41]

Cassowary (Fig. 4A). Whereas, for barramundi high production and high SLR risk occurs in the Whitsundays most prominently and in Douglas Shire, Cassowary and Cairns LGAs (Fig. 4B).

Effects of sea level rise on aquaculture development areas

One-fourth (2) of ADAs were exposed to SLR, both located at the Hinchinbrook Shire Council (Figs. 5A and B). ADA 7 located in Macknade and ADA 8 located in Halifax and Braemeadows are expected to be highly impacted by inundation due to SLR, with exposure rates

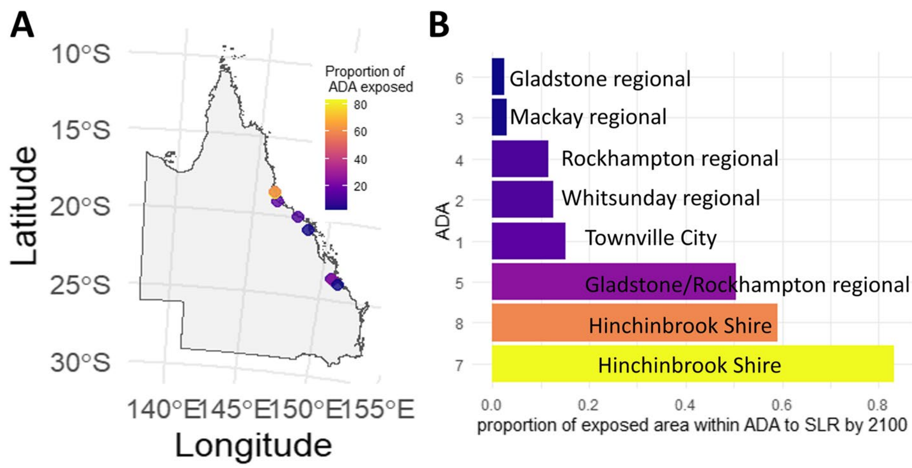

Fig. 5 Exposure of 8 aquaculture development areas (ADAs) in Queensland to SLR spatially (**A**) and by proportion of exposure to each ADA (**B**)

of 83.14% and 59.15%, respectively (Fig. 5B). The other six ADAs are expected to be less intensively impacted from SLR: 2.34% of ADA 6 located in the Gladstone Regional Council, 2.9% of ADA 3 (Mackay Regional Council), 11.62% of ADA 4 at Rockhampton Regional Council, 12.7% of ADA 2 at the Whitsunday regional Council, 15% of ADA 1 (Townsville city Council) and 25.25% of ADA 5, located at Rockhampton/Gladstone Regional Council (Fig. 5A and B).

Discussion

We assessed the risk to aquaculture sites from SLR in Queensland, Australia. We found potential SLR exposure in over one third of all aquaculture lots (34% among all lots and 43.5% among productive lots), with high SLR exposure for two of the most valuable aquaculture species in Queensland, prawn and barramundi. In addition, 25% of areas identified for potential future aquaculture expansion (ADAs) were also found to be at high risk from future SLR. We found that some highly productive aquaculture areas are also at greater risk from SLR, such as the Gold Coast for Prawn production and the Whitsundays for barramundi production. Our results highlight several challenges for aquaculture production in the face of future climate impacts, while also highlighting opportunities for forward planning and adaptation.

The large potential impact of future SLR on prawn production in Queensland reinforces the concerns of the Australian Prawn Farm Association of the impacts of climate change on production. Previous studies had shown that South East Queensland was highly vulnerable to SLR [42], and our study confirms that the prawn aquaculture industry in the Gold Coast region is the most exposed. Vulnerable areas may face several challenges including damage to aquaculture infrastructure and ponds due to permanent or recurring inundation events, disruption to operations or supply chains due to the submersion of roads and pathways connecting sites, costs of moving infrastructure or acquiring new lands for new aquaculture farms, as well as the cost of obtaining new or additional government permits and environmental licences. We found that hatcheries might face inundation risk, with over 25% of the aquatic areas surrounding the buildings and the assets themselves projected to be affected in the future. The risk to hatcheries has the potential to extend SLR risk further on the supply chain because other sites may rely on these 'at risk' hatcheries for broodstock.

For the future of aquaculture in the region, careful considerations should be taken for high-risk ADAs located in low elevation coastal zones in the Hinchinbrook Shire Council. Developing these areas needs to be adaptable to potential SLR in the future to avoid mis-investment. Queensland's Aquaculture Strategy 2024–2034 [43] could be used to trigger discussion about these ADAs, which is needed in face of our findings. The strategy recognizes that sustainable production relies on sound and well managed natural assets. Therefore, it may act as a catalyst for developing guidelines, sharing best practices and building resilience to climate change. Of course, reducing carbon emissions can attenuate the risks and is strongly recommended, as both CMIP5 and CMIP6 projections demonstrate substantially lower SLR under reduced emission scenarios. However, this involves action at the global scale, and local scale planning and adaptation are still needed.

While our results highlight many challenges for coastal terrestrial aquaculture under future climate change, there are also opportunities for climate adaptation given the long-time scale at which SLR operates. For example, our methods and findings could be directly integrated into existing state and federal programs [44] to provide regular monitoring information to government and industry. In addition, transitioning from traditional aquaculture to more resilient systems such as integrating prawn ponds with nature-based solutions for coastal protection (e.g., mangroves [45–48], green seawalls, artificial reefs, fencing and netting [49]) among other structures could help to protect coastal aquaculture and infrastructure. For example, in Vietnam a study conducted in mangrove and tiger prawn integrated farms identified a positive linear relationship between *P. Monodon* yield, survival rates, and mangrove forest coverage and showed an optimum forest coverage ratio of around 45% to 50% [48]. Policies supporting strategic, planned aquaculture retreat in response to climate risks could also aid farmers to adapt, such as offering special mortgages for acquiring more elevated land within optimal topographies (e.g., three metres above highest astronomical tide for prawn production), while considering other aspects such as water intake. Investing in new technologies such as RAS inland could also provide climate adaptation benefits for the aquaculture industry. For example, some attempts to produce prawn inland have been shown to be successful at a small scale [50] and could reduce SLR risk for prawn production across the state, but may also lead to new production challenges such as high energy demands [39, 51, 52].

Given that red claw crayfish and freshwater fish ponds were found to be less vulnerable to SLR, there is an opportunity to further expand freshwater species production in areas less exposed to inundation and thus diversify aquaculture species production in Queensland. For example, the Brazilian National Water Agency's authorization of cage-based aquaculture in reservoirs [53]could serve as a model for Queensland. For brackish and marine species that require saltwater inputs, systematic planning for future aquaculture development that considers climate risk factors can help to minimise impacts on this growing industry in the future.

While extensive literature exists on aquaculture pond construction and management, specific thresholds for structural failure under inundation and floods events are not well documented [54]. Pond integrity is crucial for aquaculture operations and literature on floods indicate that breaches can compromise functionality and cause stock escape [54]. Pond vulnerability varies depending on factors including breach location, water depth, soil type, permeability, and construction standards. Future research should focus on detailed cost–benefit analyses of adaptation strategies, including infrastructure reinforcement, relocation to higher ground, and post-inundation recovery expenses. This is especially relevant as adaptation measures could significantly reduce GDP losses projected under the RCP8.5—SSP5 high-end scenario for Australia and New Zealand [55].

This project has several limitations that could affect the accuracy and interpretation of our findings. First, spatial data uncertainties exist through boundary precision of aquaculture lot polygons, vertical accuracy of the digital elevation model, and horizontal resolution of the inundation modelling. For example, the Sentinel-2 satellites provided imagery at 10-m spatial resolution, making it suitable for detecting aquaculture ponds which typically range from 0.1 to several hectares in size [56]. However, this resolution might limit the detection of very small water features less than 10 m and some fine details of pond infrastructure. Despite these limitations, Sentinel-2's combination of adequate spatial resolution, frequent revisit time (5 days with both satellites), and free data access makes it an appropriate choice for large-scale aquaculture monitoring. In addition, different geographic areas were noted to have variance in the thresholds for different remotely sensed water indices, in terms of the threshold values and the type of multitemporal metric that was most applicable (e.g. median, sum, percentiles). These threshold choices were tuned manually to ensure validity in our study over large spatial extents, but we expect that future work could focus on both the variance and methods used for automating these choices based on training or reference data sets.

The SLR projections used were based on the bucket or bathtub method, which presents methodological limitations including the binary nature of intersection analysis (exposed/ not exposed), potential edge effects at polygon boundaries, and simplified representation of complex coastal processes. This approach also lacks depth information in the inundation data and excludes factors like floods [54] and elevated groundwater [57] which could increase the inundation area, and salinity that may impact aquaculture [20]. Further, temporal uncertainties arise from variations in sea level rise projections, changes in coastal morphology over time, and the dynamic nature of tidal and storm surge interactions.

Limited disclosed industry and governmental data (i.e., species raised in each site, mortality rates, production by site, production technology) could lead to discrepancies in our estimations, although they fell within reported limits. For example, the study may have underestimated the productive areas in covered aquatic systems (such as RAS) due to incomplete information. Differences in area calculations between our estimates and reported information are likely due to survey methods (i.e., surveys conducted with aquaculture producers vs. remote sensing), while differences in production are likely due to variations in yields between areas, unused pond capacity and expected externalities and losses for Queensland productions that we were unable to fully account for in our model due to lack of data. These factors underscore the need for cautious interpretation of the results.

Conclusion

Our results provide an early warning sign indicating likely impacts on Queensland's aquaculture industry from SLR. Our findings reinforce the need to integrate climate risks into planning and mitigation strategies in coastal industries like aquaculture both in Australia and globally. This information is vital for both state and federal government to guide policy and decision making in the context of securing both the production supply chain and supporting the associated businesses and communities in forward adaptation planning and in future aquaculture development. In addition, our work underscores the urgent need for actions and guidelines to mitigate the projected impacts of SLR on Queensland's most profitable aquaculture sector, highlighting that the industry's ability to adapt to the impacts of climate change will determine the extent of future repercussions.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s44365-025-00009-3.

Supplementary Material 1. Table S1 Productive area loss (km^2) projected due to 0.8m sea level rise (SLR) under RCP8.5 scenario with expected economic impact estimates for prawn (Pennaeus monodon) aquaculture with multiple thresholds. Table S2 Productive area loss (km^2) projected due to 0.8m sea level rise (SLR) under RCP8.5 scenario with expected economic impact estimates for barramundi (Lates calcifer) aquaculture with multiple thresholds. Table S3: Number of terrestrial aquaculture lots and farms and productive lots and farms and the comparison of total and exposed area (km^2) expected to be impacted from projected 0.8m sea level rise (SLR) under RCP8.5 scenario, with associated estimates of economic losses. Figure S1 Sensitivity analysis of percentage of pond exposure projected due to 0.8m sea level rise (SLR) under RCP8.5 scenario with expected economic impact estimates for prawn (Pennaeus monodon) aquaculture with multiple thresholds. Figure S2 Sensitivity analysis of percentage of pond exposure projected due to 0.8m sea level rise (SLR) under RCP8.5 scenario with expected economic impact estimates for barramundi (Lates calcifer) aquaculture with multiple thresholds. Figure S3. Prawn pond risk due to SLR in each Local Government Area (LGA) in Queensland, Australia. Figure S4. Barramundi pond risk due to SLR in each Local Government Area (LGA) in Queensland, Australia. Figure S5. Storm surge hotspots with percentage of area in each lot projected to be exposed to SLR in Queensland, Australia.

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Code availability

The codes are publicly available at https://github.com/Marina6578/QLD_SLR_Aquaculture:QLD_SLR_Aquaculture.
Google Earth Engine code for water detection: https://code.earthengine.google.com/752cf7131156779d4a50624068816963.
Google Earth engine code to use thresholds and to export pond vectors: https://code.earthengine.google.com/2125793fa720d92d7b27ee0552d30826.

Authors' contributions

Conceptualization - MC, CDK. Data curation - MC. Funding acquisition - MC, CDK. Investigation - all authors. Methodology - all authors. Project administration - CDK. Formal analysis - MC, MBL. Visualization - MC, CDK. Writing - original draft - MC. Writing - review & editing, all authors. Supervision – CDK.

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Data availability

The data that support the findings of this study are available from Fisheries Queensland, a service of the Department of Agriculture, Fisheries (DAF) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available and cannot be provided to a third party unless approved by Fisheries Queensland.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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