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RESEARCH

Conservation for production? The benefits of mangroves for sustainable shrimp aquaculture

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Abstract
Mangroves are vital ecosystems that provide ecological and economic benefits to the global and local community, among them climate change mitigation. However, from 1980 to 2005, Indonesia was the country with the largest mangrove area loss, a 40% reduction due mainly to aquaculture development. As demand for aquaculture products continues to grow, there is a need for strategies that can simultaneously enhance shrimp production, prevent further mangrove deforestation, and promote mangrove restoration. Such approaches align with Natural Climate Solutions (NCS), which involve protecting, managing, and restoring natural ecosystems to reduce greenhouse gas emissions and increase carbon storage. To address this, we use a production function analysis based on cross-sectional spatial data and pond management information to assess the importance of mangrove forests for traditional shrimp aquaculture systems in Berau, East Kalimantan, Indonesia. We find that high-density mangrove forests surrounding aquaculture ponds contribute to shrimp production. Thus, avoiding mangrove deforestation and restoring degraded areas can sustain and increase traditional aquaculture production, highlighting win–win opportunities for NCS, sustainable intensification, and improving livelihoods. Our results show the importance of conserving and restoring the underlying ecosystem to sustain shrimp production and highlight the common pool resource problem entailed in continuing the expansion of new ponds that replace mangrove forests.

Keywords Mangrove · Silvofishery · Aquaculture · Shrimp · Indonesia · NCS

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Introduction

Indonesia is home to 3.4 million hectares of mangrove and is one of the top three countries housing the largest mangrove forests in the world (Indonesian Ministry of Forestry, 2025). Mangroves are critical for coastal protection, biodiversity, and local community livelihoods (Asari et al. 2021; Basyuni et al. 2022; Corte et al. 2021; Das et al. 2022; Chen et al. 2024). Mangroves are also key ecosystems for climate change mitigation, harboring significant carbon stocks (Alongi 2014; Donato et al. 2011; Rahman et al. 2021) and providing sequestration in biomass and soils. However, mangroves face significant challenges from current climate change impacts and increasing anthropogenic threats (Ward et al. 2016; Jennerjahn et al. 2017; Goldberg et al. 2020; Monika and Yadav, 2022). Rapid coastal development, driven primarily by aquaculture, natural retraction, and agriculture expansion, has led to extensive and rapid mangrove deforestation in many parts of Indonesia (DasGupta and Shaw 2017; Mohd et al. 2021; Ashton 2022; FAO 2023). At the same time, the effects of climate change exacerbate impacts on mangrove forests by reducing their resiliency and long-term survival (Alongi 2015; Ward et al. 2016; Friess et al. 2022).

The extensive traditional brackish water shrimp aquaculture system in Indonesia operates under the assumption that cultivating large areas will contribute to high yields and that the local environmental system supports productivity by providing natural food sources for shrimp and maintaining water quality. Under this assumption, the expansion of shrimp aquaculture has driven significant mangrove clearance, causing land use changes in coastal regions and the loss of biodiversity (Friess et al. 2019, 2020a). In contrast, intensive aquaculture is conducted on smaller areas (less than 1 ha per pond) and involves sophisticated technology, supplementary feeding, and aeration systems to support higher production yields. While it can also contribute to the degradation of mangrove forests, intensive aquaculture impacts mangroves in different ways (Alongi 2002; Barbier and Cox 2004). There are several examples of intensive aquaculture leading to increased nutrient pollution and eutrophication of adjacent environments, which degrades water quality, disrupts nutrient cycles, and negatively affects the resilience of mangrove forest (Dierberg and Kiattisimkul 1996; Naylor et al. 2000; Alongi 2002; Barbier and Cox 2004; Mack et al. 2024).

Degradation of ecosystem quality of mangroves is widespread, with the expansion of aquaculture practices emerging as a primary driver of mangrove conversion and degradation in many Southeast Asian countries (Richards and Friess 2016). Among different types of aquaculture systems, traditional extensive aquaculture systems are considered a primary culprit for major mangrove forest demise (van Wesenbeeck et al. 2015; Bhari and Visvanathan 2018; Boyd et al. 2022). Traditional extensive aquaculture systems, such as Indonesia's tambak tradisional and tumpang sari (silvofishery), are low-input, low-density pond systems that rely on natural tidal water exchange and ecosystem productivity, often without artificial feed or chemicals (Musa et al. 2020). While they are more environmentally friendly than intensive systems, traditional aquaculture has negative impacts on mangroves when forests are cleared to build ponds, natural hydrology is altered, or when abandoned ponds lead to gradual ecosystem degradation due to lack of recovery and poor long-term management.

These national-level trends are clearly reflected in East Kalimantan, a province with a long history of traditional shrimp aquaculture and ongoing pressure on mangrove ecosystems (Ilman et al. 2016). Although not the highest-producing shrimp region nationally, East Kalimantan remains a significant site for aquaculture, particularly as the source of Monodon (Black Tiger) shrimp.

In East Kalimantan, Indonesia, annual shrimp harvest has massively declined throughout the years; recent estimates suggest that production only reaches 35–40 kg/ha annually in a 10-ha pond (Anggoro et al. unpublished data) compared to ~200 kg/ha during the 1990 s (Ilman 2018) based on per-hectare yield metrics. At the same time, the demand for shrimp continues to increase, incentivizing farmers to continue to clear mangroves for new ponds in order to sustain production and income levels. However, the additional clearing of mangroves for a pond could degrade water quality (Peng et al. 2009) and provide economic instability (Ashton 2008).

In response to declining shrimp productivity and continued mangrove degradation, integrated approaches such as shrimp silvofishery have been promoted in Indonesia. Silvofishery integrates shrimp farming with mangrove conservation to enhance environmental sustainability and reduce pressure for further forest clearing (Susilo et al. 2018). By locating shrimp ponds within or adjacent to mangrove areas, these systems benefit from the ecosystem services mangroves provide, such as water filtration, shoreline protection, and habitat for aquatic species, which can improve water quality and pond performance (De-León-Herrera et al. 2015). The common silvofishery practices are by planting mangroves inside the aquaculture ponds (McSherry et al. 2023a). A local adaptation of this approach in East Kalimantan is the separated silvofishery system, where the aquaculture and mangrove components are physically divided within the same pond area (Bosma et al. 2014). In this configuration, 50–80% of the area is allocated to mangrove restoration and the remaining 20–50% is retained for shrimp cultivation. This separation allows both components to function independently, supporting natural mangrove regeneration and maintaining shrimp yields (YKAN 2025). Such systems offer potential ecological and economic benefits, and community participation plays a crucial role in sustaining them by aligning conservation with local livelihoods. Further detail on this model is provided in the Supplementary Material 4.

Mangroves are essential for aquaculture success, providing critical ecosystem services such as water quality regulation, nutrient cycling, erosion control, disease mitigation, and nursery habitat for juvenile shrimp (Friess et al. 2019; Friess et al. 2020a; Alam, 2022; Custódio et al. 2020; Lai et al. 2022; Rahman et al. 2020). They act as natural buffers against coastal erosion and storm surges, protecting aquaculture facilities and communities from extreme weather (Bao 2011; Cao et al. 2016; Sánchez-Núñez et al. 2019; Asari et al. 2021). Their dense root systems filter inland runoff, trapping sediments, nutrients, and pollutants to improve water clarity and prevent algal blooms (Truong and Do 2018; Chaudhuri et al. 2019; Friess et al. 2020b). Mangroves also function as nutrient sinks, absorbing excess nitrogen and phosphorus, ensuring sustainable aquaculture operations (De-León-Herrera et al. 2015; Hastuti and Budihastuti 2017; Pérez et al. 2021; Wang et al. 2021). Their role in aquaculture is indispensable.

Building on these essential ecosystem services, mangroves not only enhance the sustainability of aquaculture operations but also directly contribute to coastal livelihoods and food security, particularly through their close relationship with traditional shrimp farming practices in Indonesia. However, widespread mangrove degradation has led to declining productivity, raising concerns about the long-term viability of these systems. Despite growing ecological evidence that mangroves improve water quality, stabilize coastlines, and enhance nutrient cycling for aquaculture, there remains limited economic understanding of how mangroves function as a contributing input to shrimp production. This gap is especially relevant in the context of sustainable aquaculture development and the broader agenda of Natural Climate Solutions (NCS), which link ecosystem restoration with climate mitigation and livelihoods. This research aims to understand how different conventional (labor, shrimp fry, pond size, etc.) and biophysical factors (adjacent mangrove buffers and mangroves inside the ponds, etc.) contribute to traditional shrimp aquaculture production in Berau, East Kalimantan, Indonesia. We do so by modeling inputs and shrimp output with translog and Cobb–Douglas production functions. While the biophysical studies cited in previous paragraphs show that mangroves enhance aquaculture production by supporting water quality and nutrients, no economic study, to our knowledge, has explored the role of the underlying ecosystem as a production factor in shrimp aquaculture (MacDonnell et al. 2017; Nerrie et al. 1990; Rönnbäck 1999; Sharma and Leung 1998; Asamoah et al. 2012; Asche and Roll 2013; Bukenya et al. 2013). Hence, one key contribution of our work is to assess the importance of mangroves for shrimp production in traditional ponds in Indonesia. We also simulate how reforestation, regeneration, and conservation of the current high-density mangrove canopy in the 100 m buffer surrounding the ponds would affect shrimp production and carbon sequestration, linking sustainable production and climate change mitigation. By elucidating the impact of various biophysical factors, our research is expected to provide valuable insights into production and ecosystem dynamics and their relevance to the success of extensive shrimp production as a form of traditional aquaculture in Indonesia. This knowledge is essential for informing effective management and conservation strategies aiming to balance mangrove protection, ecosystem restoration, and sustainable aquaculture.

Material and methods

Site description

This research focused on the delta areas of Berau Regency, East Kalimantan Province, Indonesia, located on the large tropical island of Borneo, which is divided between Indonesia, Malaysia, and Brunei (Fig. 1). Berau Regency has a total administrative area of 36.962,37 square kilometers (km^2), consisting of 22.232,54 km^2 of land area and 14.729,86 km^2 of water bodies (BPS 2023). Upland areas are generally tropical deciduous forests, while coastal and delta areas are generally mangrove forests. The areas experience a tropical rainforest climate with high temperatures and humidity year-round. The region receives substantial rainfall, averaging around 2500 to 3000 mm annually, with the wettest months typically between November and April due to the influence of the northeast monsoon. Berau's topography is varied, featuring coastal plains, lowland rainforests, and hilly terrain that gradually rises towards the interior. The region is also known for its rivers and streams that play a significant role in shaping the landscape, contributing to the area's lush vegetation and supporting its extensive network of wetlands and mangrove forests along the coast (Hidayat et al. 2017). The regency borders Bulungan Regency, North Kalimantan Province, in the north and west, the Sulawesi Sea in the northeast, and Kutai Timur Regency in the south. Berau has a population of around 258.537 people as of the end of 2022 and a population density of 12 people/km^2 (BPS 2023).

Pond census data collection

We employed a mixed-methods approach, collecting quantitative pond census data in the second half of 2023 and combining it with biophysical mangrove data from a geographic information system (GIS) analysis using 2022 images (see below). A total of

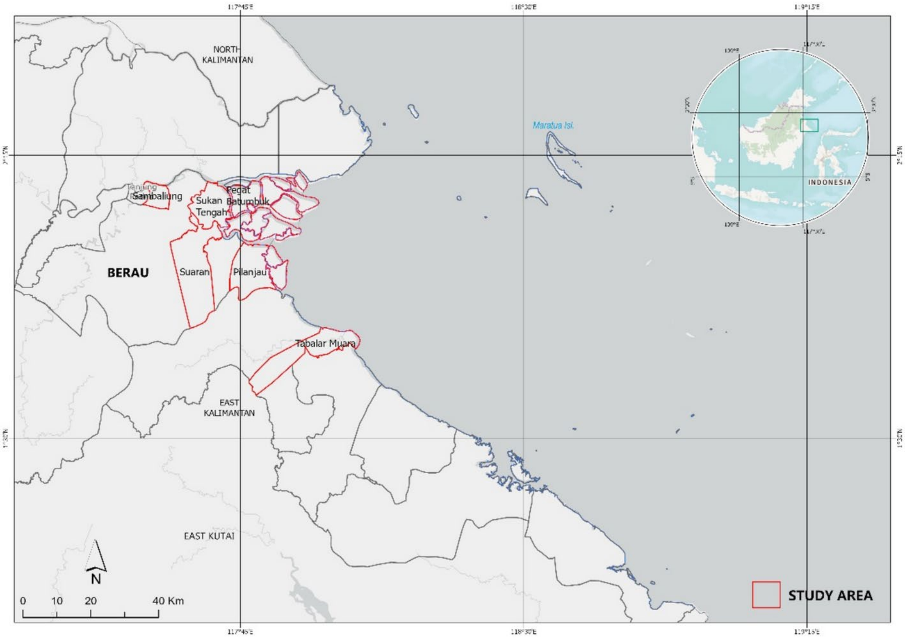

Fig. 1 The study area is located in Berau Regency, East Kalimantan Province, Indonesia. The census data covered six villages within the regency: Suaran, Tabalar Muara, Pegat Batumbuk, Pilanjau, Sukan Tengah, and Gurimbang

811 respondents participated in the survey, representing the majority of active aquaculture operators in the region. Two types of data were obtained from the shrimp aquaculture pond census: (1) production factors/aquaculture inputs and management data, including pond area, number of harvest cycles per year, shrimp fry, labor, pesticide, organic fertilizer, and other inputs; and (2) annual and cyclical shrimp production data in both weight and monetary value. In addition, the census also collected other supplementary data, such as farmer's background, land tenure security, fish production, crab production, agro-climatic or extreme weather events' impact on aquaculture production, and producers' perception of the tangible and intangible benefits of mangrove and shrimp aquaculture. Census respondents were pond owners or pond managers. The questionnaire had both multiple-choice scales and open-ended questions (see Supplementary material 5).

GIS spatial data

We used GIS-based analysis to assess the proximity of mangrove ecosystems to key land cover and infrastructure types, including saltwater and brackish water sources, hatcheries, roads, settlements, and urban centers. Mangrove biophysical data, referring to the spatial distribution of mangrove cover, were obtained from satellite imagery processed by Prakoso et al. (2023), who applied a supervised classification using the Random Forest (RF) algorithm on Google Earth Engine (GEE). The dataset is based on multi-temporal imagery/ from Landsat 5 (1990), Landsat 7 (2000), Landsat 8 (2019), and Sentinel-2 (2019) and was developed for the same geographic area as the current study.

We specifically used the 2019 dataset to represent current mangrove conditions. Field verification and comparison with on-the-ground observations indicated no significant changes in mangrove extent between 2019 and the time when socio-economic data on shrimp pond operations were collected. This alignment strengthens the reliability of the data and justifies its use for analyzing current spatial patterns and proximities relevant to the study objectives. We used the center point of each pond as the reference to calculate the horizontal distance to surrounding land cover and infrastructure types, using the Near Feature method as implemented in ArcGIS Pro version 4.3 (Longley et al. 2015). For example, to calculate a pond's distance to a brackish water feature, we used the presence of mangroves as a proxy for brackish water availability and measured their distance to center points of the ponds.

To calculate the distance of a pond to a saltwater feature, we calculated distances along the continuum from the river branching zone to the river mouth of the estuary. To calculate the distance of a pond to fresh water, we used physical boundary parameters such as mangrove distribution and estuarine areas derived from Landsat 8 satellite imagery (2019) to delineate saltwater, brackish water, and freshwater river systems. To obtain elevation and slope, we used zonal statistics from DEMNAS (National Digital Elevation Model) data downloaded from https://tanahair.indonesia.go.id/, which combines a digital elevation model and bathymetry data for Indonesia and has a 0.27-arcsecond spatial resolution using the EGM2008 (Earth Gravitational Model 2008) as vertical datum (BIG 2018). We consider canopy density in mangrove areas as an important factor that could influence aquaculture systems. Mangrove canopy density was used as a proxy for mangrove abundance and structural complexity, due to the difficulty of quantifying individual mangrove attributes in large-scale field conditions. Higher canopy density is associated with greater root development and ecological function, which can influence shrimp pond conditions by improving water quality, stabilizing sediments, and providing habitat structure. This metric was derived from remote sensing data and integrated into the analysis to assess its relationship with shrimp production. Previous studies have reported positive correlations between.

Shrimp production function

We model shrimp production in traditional aquaculture ponds in Berau, East Kalimantan, Indonesia, by using a translog production function that defines output in kilograms as determined by biophysical and socioeconomic factors:

$$\ln y_i = \beta_0 + \sum_{m=1}^{M} \alpha_m \ln x_{mi} + \frac{1}{2}\sum_{m=1}^{M}\sum_{j=1}^{M} \beta_{mj} \ln x_{mi} \ln x_{ji} + \varepsilon_i$$

where.

y_i is the shrimp production for pond i in 2022 (kg),

x_i represents the M conventional (pond area, number of harvest cycles, shrimp fry, labor, pesticide, organic fertilizer, and other inputs) and biophysical (area of mangroves inside and buffering the ponds by canopy density, distance to water types) production factors used in 2022,

$\alpha_m$andβ_m are the parameters to estimate,

ε_i is the stochastic random error.

We assess whether the presence of mangroves, varying in their location and forest canopy density (low, medium, and high inside and around the ponds), contributes to shrimp pond production. We use the translog function (Eq. 1) as our main specification given that it is less restrictive in that it does not assume constant elasticities of substitution between inputs. Our estimator is the conventional ordinary least squares (OLS) with heteroscedastic robust standard errors; the advantage of this approach is that we only have to assume that we have no missing production factors that could be in the error term and that are correlated with any of the other included factors or with the outcome (Wooldridge 2010). This assumption seems reasonable since we are including input, labor, and management variables along with biophysical variables usually not included in these types of models.

We started by estimating the model with only the conventional production factors, then added the biophysical factors one by one to test all the respective interacted variables using the F-test for model comparison, and selected those that render a significant result. For production factors that have values of zero for certain ponds, we applied the correction proposed by Battese (1997) for logarithmic linear models such as Cobb–Douglas since it renders a similar interpretation of results. We assessed the

$$\frac{dE[|\ln y_i| \ln x_i]}{d \ln x_i}$$

We also estimated a simple Cobb–Douglas production function as a robustness check:

$$\ln y_i = \beta_0 + \sum\nolimits_{m=1}^{M} \beta_m \ln x_{mi} + \varepsilon_i$$

In the above equation, the elasticity of any m production factor on shrimp output is directly the estimated parameter β_m.

Simulating mangrove reforestation and deforestation scenarios

We simulated the impacts on shrimp production and carbon sequestration of restoring all areas surrounding the ponds within a 100 m buffer (totaling 2063 ha) to high-density mangroves. This includes enhancing the low- and medium-density mangroves in the 100 m buffer to high density as well as reforesting bare soil areas. We conducted this assessment by identifying areas within different canopy density classes inside a 100-m buffer zone. For the carbon stock analysis, we used reference values of 79.52, 53.85, and 22 tC/ha in aboveground biomass for intact high-, medium-, and low-density mangrove canopies, respectively (Arifanti et al. 2019; Rusolono et al. 2022). Carbon stock gains from mangrove recovery to high-density conditions were calculated based on the differences between these reference values. We assumed that converting high-density mangroves to shrimp ponds results in the complete removal of aboveground biomass, leading to a total carbon stock loss of 79.52 tC/ha.

For assessing the changes in production due to restoration and deforestation, we use the elasticity from the translog production function that describes how high-density mangroves around the ponds increase production. Then, we multiply the elasticity coefficient by the mangrove area to be restored or deforested and obtain the impact on total shrimp production. We assume that the mangrove area change can be assessed as a marginal change using the translog elasticity directly.

Results

The census collected data on 811 (85.73%) ponds out of the total 946 pond population in six villages (Table 1). Some villages have more pond data due to a higher pond population (i.e., Pegat Batumbuk, Tabalar Muara) than others. Pegat Batumbuk has the most abundant pond population and contributed 77.5% of the total data collected. However, in general, we collected data from at least 80% of each village's pond population. In addition to elucidating production levels, the data also show that 589 (95.18%) of respondents rely on aquaculture activity as their primary source of income, suggesting that aquaculture activity has a vital role in respondents' household economy. More than 70% of the respondents also own the ponds, while only 22.08% act as non-owner pond manager and guard.

Following further data exploration and combining the pond census with biophysical production, we ultimately only used observations from 574 ponds, focusing on 20 variables of interest that combine production, inputs, and mangrove canopy area of traditional shrimp aquaculture ponds. Out of the 811 ponds, 574 had a shrimp harvest different than zero and within a reasonable productivity for traditional aquaculture (< 200 kg/ha) in 2022. For conventional production factors, we processed inputs and management from the field census (Table 2): pond area (with and without mangroves), number of annual harvest cycles, number of shrimp fry, labor during harvest, pesticide, organic fertilizers, and saponin. For the biophysical production factors, we processed the mangrove area by canopy type (low, medium, and high) inside and around the pond, within a 100 m buffer, using the 2019 and 2022 mangrove and pond coverage in (Prakoso et al. 2023). We also processed the distance (m) from the center of each pond polygon to the nearest salty, brackish, and freshwater body using GIS analysis.

Translog shrimp production function

Our preferred specification is the translog model that explains shrimp production as a function of the conventional factors of pond area, number of harvest cycles, shrimp fry, labor during harvest, pesticide, organic fertilizers, and saponin; and the biophysical factors of high, medium, and low-density mangrove areas within a 100 m buffer of the ponds as well as high, medium, and low-density mangrove areas inside the ponds, and distance to fresh water. Our model has 43 variables coming from the translog-specified interactions of all the above-listed variables. The regression results show a robust model with a very significant F statistic ($F = 2708.75$ for a $p = 0.0000$) and a capacity to explain most of the variation in the data ($R^2 = 0.989$).

Table 1 Pond census sample and population

No	Village	Pond population	Samples collected (N)	Samples collected (%)
1	Gurimbang	5	5	100
2	Pegat Batumbuk	735	629	85.58
3	Suaran	52	52	100
4	Sukan Tengah	10	10	100
5	Tabalar Muara	107	95	88.79
6	Pilanjau	37	13	35.14
Total pond		946	811	85.73

Table 2 Summary statistics of key census variables

	Pond area including mangrove (Ha)	Pond area not including mangrove (Ha)	Number of harvest cycles	Shrimp fry quantities	Labor during harvest	
Mean	16.8	12.8	2.6	110,758.9	1.8	
Range	78.0	77.5	3.0	495,000.0	8.0	
Variance	130.2	99.7	0.4	3,498,766,467.5	4.5	
Standard dev	11.4	10.0	0.7	59,150.4	2.1	
	High-density mangroves in 100 m buffer	Medium-density mangroves in 100 m buffer	Low-density mangroves in 100 m buffer	Pesticides (liter)	Saponin (kg)	Organic fertilizer (kg)
Mean	1017.2	144.5	3.7	0.9	21.9	1.5
Range	9470.8	5810.0	211.2	30.0	300.0	200.0
Variance	114,393,009.4	9,096,077.2	24,408.0	4.2	1152.5	181.2
Standard dev	1069.5	301.6	15.6	2.0	33.9	13.5

Mangroves inside and around the ponds impact shrimp aquaculture production; the input elasticities show that a 1% increase in the area of high-canopy-density mangroves surrounding the ponds within 100 m raises production by 0.25% ($p = 0.000$). This econometric finding is in line with the local knowledge of the communities and pond managers who identified in the survey that mangroves buffering the ponds act as a breeding ground for native shrimp and provide cover to protect the shrimp from predators. However, only very dense or high-canopy-density mangroves contribute to production; the impact of medium ($p = 0.372$) and low-density mangroves buffering the ponds ($p = 0.308$) is not significant (Table 3).

On the other hand, high-canopy-density mangroves inside the pond do not contribute to shrimp production ($p = 0.265$), while medium-density mangroves slightly reduce production (elasticity of −0.068 with $p = 0.041$), but only low-density mangroves inside the pond contribute to a higher shrimp production with an elasticity of 0.21 ($p = 0.027$). This result also aligns with the knowledge and practice of local farmers who are not entirely clearing the mangroves by leaving a low-density canopy inside the pond to enhance shrimp pond production. Among the reasons for farmers to keep mangroves inside the pond, based on the survey, are the role of coastal defense (44% or 357 respondents assessed), high cost of mangrove clearance (16% or 130 respondents assessed), and other services like providing shrimp with nutrition and protection from predators (38% or 318 respondents assessed). The conventional production factors yield the expected shrimp output increases with the number of harvest cycles (elasticity of 0.981 with $p = 0.004$) and pond area (elasticity of 0.526 with $p = 0.000$) contributing the most, followed by pesticide, shrimp fry, and labor during harvest. On the other hand, we find that the use of organic fertilizers and saponin was detrimental to production (Table 3).

Table 3 Production factor elasticities inferred from the translog model

	Elasticity (% increase in production given 1% increase in input factor)	Significant
Mangroves in 100 m buffer		
High-density mangroves in 100 m buffer	0.249 (0.057)	**
Medium-density mangroves in 100 m buffer	– 0.035 (0.039)	n.sig
Low-density mangroves in 100 m buffer	– 0.031 (0.030)	n.sig
Mangroves inside ponds		
High-density mangroves inside pond	– 0.026 (0.024)	n.sig
Medium-density mangroves inside pond	– 0.068 (0.033)	*
Low-density mangroves inside pond	– 0.209 (0.094)	*
Other production factors		
Pond area	0.526 (0.104)	**
Number of harvest cycles	0.981 (0.433)	*
Shrimp fry quantity	0.426 (0.063)	**
Labor during harvest	0.334 (0.156)	*
Saponin	– 0.173 (0.036)	**
Pesticide	0.49 (0.073)	**
Organic fertilizers	– 0.909 (0.095)	**

Note: *n.sig* for non-significant and * or ** stands for statistically significant at 95% (*) or 99% (**) confidence intervals. Standard errors are in parenthesis

Robustness check

For robustness checks, we use the same conventional and biophysical production factors but combined in the simpler Cobb–Douglas production function, which assumes a constant elasticity of substitution between factors. We obtain similar results as our main specification: high-density mangroves buffering the pond (elasticity of 0.045 with $p = 0.005$) and low-density mangroves inside the pond (elasticity of 0.044 with $p = 0.000$) increase shrimp production, but at lower rates (see Supplementary material 1).

The conventional production factors of area, number of harvest cycles, pesticide, shrimp fry, and labor during harvest contributed positively to shrimp output, as found with the main specification, but with different intensities. Saponin and organic fertilizers were detrimental, aligning with the findings of the main specification. The only noticeable difference is that high-density mangroves inside the pond appear to reduce production (elasticity of -0.03 with $p = 0.021$) according to the Cobb–Douglas specification, while they had no effect based on the main translog equation (see Supplementary Material 2).

Simulating mangrove reforestation and deforestation scenarios

Restoring all areas surrounding the ponds within 100 m (totaling 2,063 ha) to high-density mangroves would increase, on average, total shrimp production by approximately 18.7% (± 4.3% for 95% CI) and sequester 43% more carbon than what is already in the aboveground biomass of the pond buffers (Fig. 2). On the other hand, converting the same area of high-density mangroves within a 100 m buffer around the ponds to new shrimp aquaculture would decrease the production of the existing ponds by 18.7% (± 4.3% for 95% CI), which, netted with the new production coming from the recently converted ponds in the 2063 ha of mangrove, would only increase total production in Berau by 2% on average (± 4.3% for 95% CI). Moreover, this conversion would reduce aboveground carbon stocks by 69.3%. The loss in production due to the loss of high-density mangroves confirms the local knowledge of decreasing production in each individual pond over the last 5 years (64% of respondents) while the total pond area expanded (Supplementary material 3).

Discussion

This study is, to the best of our knowledge, one of the first efforts to assess and model how the condition of the surrounding ecosystem contributes to sustainable aquaculture production, specifically mangroves supporting traditional shrimp aquaculture ponds in Berau, Indonesia. Our combined economic and biophysical model uses a variety of data sources from satellite imagery, administrative records, and field surveys to investigate in detail the impact of conventional production factors and mangrove forest coverage on shrimp aquaculture. Hence, we highlight the multidisciplinary and multi-source method used in our research and how two econometric models (translog and Cobb–Douglas production functions) support our findings. We found these functions useful in disaggregating the complexities of traditional aquaculture systems.

Our study complements existing knowledge by using a comprehensive data collection strategy combining aquaculture components and mangrove canopy density characteristics. We successfully collected data from more than 85% of the pond owner population,

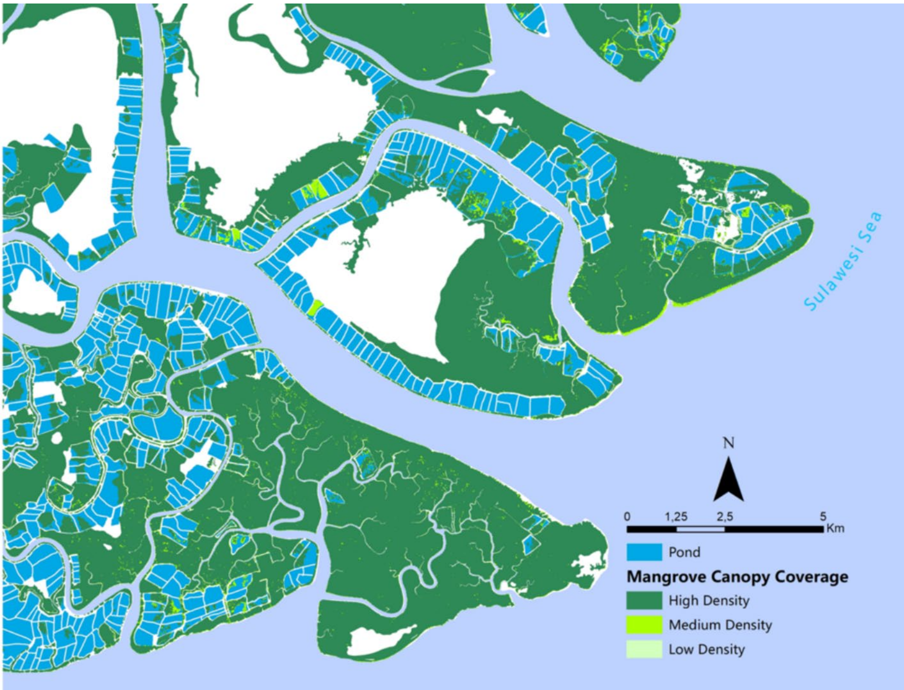

Fig. 2 Study area ponds and mangroves by canopy density using data from Prakoso et al. (2023)

covering more than 85% of pond areas across the study locations, with the exception of one village, which was excluded due to its minimal pond population and limited contribution to the overall aquaculture landscape. We take into consideration socioeconomic data and past harvest success over time to provide a thorough analysis rather than merely a snapshot finding that might not accurately reflect pond productivity. Our results are based on robust data collection and a well-designed model that considers a multitude of factors. To our knowledge, such comprehensive data collection is the first of its kind in mangrove forests in Eastern Kalimantan, Indonesia.

Previous research attempting to examine the impact of mangrove forests on the productivity of traditional shrimp ponds is widely available (Rivera-Monroy et al. 1999; Joffre et al. 2015; Bosma et al. 2014; Alam 2022). Nonetheless, such studies only focus on limited parameters, rarely combine mangrove characteristic components and aquaculture techniques, and do not examine whether or not these parameters provide synergistic and combinatory effects. Neither have previous studies been able to provide insights into the parameters that are important for the success of traditional pond systems. Therefore, reaching a conclusion on which factors determine pond productivity is difficult. For example, although studies done by Lai et al. (2022) in Vietnam found positive linear correlations between the yield of tiger shrimp and forest cover, this study focuses only on the relationship between yield performance and forest coverage information. It does not incorporate aquaculture components (quality of shrimp fry, pond management, salinity control, etc.) into the analysis, as we did in our study and discuss below, therefore providing only partial information on what really drives an increase in yields. Other researchers have also highlighted the importance of mangrove litter and supplemental feed and found a positive correlation among the parameters used (Alam et al. 2021b, 2022). However, it is unclear how big the contribution of farmers' efforts and pond management is to overall production success and harvest rate.

Our research found that both mangroves and conventional aquaculture inputs contribute to overall yield in traditional extensive shrimp production systems. The area of mangroves by canopy density, pond size, number of cycles, labor, shrimp fry, fertilizer, and pesticides are among the top contributors to the yield of pond shrimp production (Table 3). Most importantly, the regression model developed is robust, with a very significant F statistic ($F = 2708.75$ for a $p = 0.0000$) and the capacity to explain most of the variation in the data ($R^2 = 0.989$).

We find that high-density mangroves around the ponds and the low-density mangroves inside the ponds increase shrimp production. Therefore, restoration and sustainable aquaculture approaches that spatially separate mangrove rehabilitation and shrimp production areas can be highly effective in optimizing both ecological and economic outcomes. In this approach, the majority of traditional pond areas (up to 80%) are restored with mangroves through methods like assisted natural regeneration and the reestablishment of natural tidal hydrology, while the remaining space (approximately 20%) is allocated for intensified shrimp production using sustainable practices, including pond redesign, improved feed management, and low-input systems. The 80% restored mangroves in this system are acting like the 100-m buffer to the dedicated 20% aquaculture pond. This integrated model enhances shrimp productivity while simultaneously maximizing the biodiversity and carbon sequestration potential of mangroves for climate mitigation (see Supplementary material 4 for detail). On the other hand, the widely adopted silvofishery practices that involve planting mangroves inside the pond may not yield the expected increase in shrimp production if the restoration results in medium- and high-density canopy.

Our results suggest that a 10% increase in area of medium-density mangroves inside the pond will decrease the overall yield by 0.7%. In contrast, a similar increase in area of lower-density mangroves will increase yield by 2.1%. Higher-density mangrove cover may lead to negative biophysical conditions within the pond. For instance, dense mangrove stands introduce higher tannin loads from leaf litter, which can be difficult for local microbial communities to break down, resulting in poor water quality that hampers shrimp growth (Hai and Yakupitiyage 2005; Alam et al. 2021b; Gunarto et al. 2025). Excessive shading from high canopy cover can also reduce light penetration, thereby limiting the productivity of plankton and benthic algae, which are key food sources in extensive aquaculture systems (Alikunhi and Kathiresan 2012; Hilmi et al. 2020; Norman et al. 2022). Furthermore, increased organic matter from mangrove leaves significantly consumes dissolved oxygen (DO) during decomposition, leaving less available DO for shrimp, particularly in poorly aerated or traditional ponds (Hai and Yakupitiyage 2005; Wang et al. 2024). A similar observation was made in Vietnam, where silvofishery systems dominate, and it is suggested that shrimp ponds should maintain no more than 60% mangrove cover to sustain high productivity (Truong and Do 2018).

Effective silvofishery systems depend on balancing objectives. Excessive placement of mangroves within shrimp ponds can be problematic for production for several reasons. Relatively high levels of mangroves will deteriorate pond water and sediment quality due to excessive mangrove leaf litter in the shrimp ponds (Johnston et al. 2000; Sukardjo, 2000; Fitzgerald, 2002) and lessen natural food production (Herrera-Silveira and Ramirez-Ramirez, 1996; Lee, 1999). Leaching of extracts from the roots, bark, and stems of certain mangrove species is also toxic to fish and prawn (Alam et al. 2021a, Alam et al. 2022). Most importantly, highly dense mangrove cover could also provide hiding spots for shrimp predators, therefore decreasing overall harvest yield (Bosma et al. 2014; Truong and Do 2018). Thus, although the high density of mangroves could promote biodiversity and store carbon in the local ecosystem, the high density of mangroves directly within silvofishery ponds could be unfavorable for shrimp yield and decrease overall productivity.

Further, placing mangroves within the shrimp pond in the silvofishery design provides limited ecological benefits and functions due to the fragmented nature of mangrove growth (McSherry et al. 2023b). Mangroves grown in the aquaculture compartment are separated by pond embankments and generally experience dwarfism due to limited water exchange with natural tides and poor nutrient supply from the adjacent environment (van Bijsterveldt et al. 2022). In our study areas, our primary observation shows that water exchange in pond areas only happens once every 2 weeks, coinciding with the highest tidal level, limiting the fresh saline water exchange needed by mangroves to grow. Mangrove seedling dispersal from ponds to the broader ecosystem is also prevented by filter fabrics commonly positioned on the pond gate to prevent shrimp from escaping the pond, hampering the natural revegetation important for mangrove forest resilience. Therefore, the aim of silvofishery to increase vegetation coverage and biodiversity and ensure a healthy mangrove forest cannot be fulfilled when a large number of mangroves are located within the aquaculture areas.

Our data suggest that restoring all areas surrounding the ponds within 100 m to high-density mangroves would increase total shrimp production by approximately 19%. Dense mangroves around the pond's periphery could significantly influence aquaculture operations by improving water quality and providing erosion control and stability (Proisy et al. 2018). Erosion control provides a direct benefit for pond wall stability, as in many traditional aquaculture cases, pond owners do not always have the manpower to maintain pond walls throughout the lifecycle of the pond. Dense mangroves also act as a natural filter, trapping sediments, pollutants, and excess nutrients, enhancing water quality before entering the aquaculture areas and benefiting shrimp's health and growth (Peng et al. 2009; McSherry et al. 2023b). These findings highlight the importance of the strategic placement of mangroves within aquaculture systems by enhancing mangrove growth surrounding the ponds instead of within the pond.

Our findings also suggest that converting existing high-density mangroves within a 100 m buffer around the ponds to a new shrimp aquaculture could decrease the production of existing ponds. Therefore, although opening a new pond may be initially beneficial for the new pond owner, it has negative impacts on existing neighboring owners. The ongoing loss of those high-density mangrove forests due to the implementation of new shrimp ponds decreases the average productivity of the other ponds and even reduces total aggregate production. It is possible that those losses in productivity could be overcome through the use of other inputs (such as organic fertilizers), but those inputs are also likely to pollute and cause long-term impacts on the soil and sustainability of the mangrove forest. The degradation of environmental quality due to the overuse of aquaculture inputs can lead to collective action problems because it often results in negative externalities that affect shared water resources around the mangrove forest. These externalities impose costs on others who are not or directly involved in aquaculture operations, creating a classic "tragedy of the commons" scenario (Gopalakrishnan 2016; Sarkar 2023). When multiple users of pond owners and local communities share a common resource without coordinated management, each may act in their own self-interest, leading to overuse and degradation of the resource. Furthermore, the lack of effective regulation and enforcement exacerbates the issue, as many aquaculture operations are either unregulated or poorly managed, making it difficult to implement sustainable practices. Therefore, designing effective policies and incentives to tackle this collective action problem is a key need for the local population and an opportunity to improve environmental and economic governance for the provincial and regional governments in East Kalimantan.

Finally, while our research uses detailed primary and secondary data, it relies on the cross-sectional variation of information on ponds in the same year (2023) to infer the impact of mangroves on production. Extending our assessment to panel data collected over time for ideally all ponds, or at least a representative sample, could further test our hypothesis of the relationship between mangroves and shrimp production. An ideal research scenario would implement a randomized controlled trial to infer the impact of high-density mangroves around the pond on production, controlling for the other potential confounding factors with even more detail. Additionally, further avenues of research could explore the development of innovative shrimp pond configurations, such as interspersing ponds with mangrove buffer zones rather than placing them adjacent to existing mangrove areas. This approach may present an optimal solution that balances mangrove restoration with the increasing demand for shrimp production. Moreover, integrated mangrove-shrimp aquaculture holds promise as a Natural Climate Solution (NCS), emphasizing the role of mangrove conservation and restoration in mitigating climate change impacts while ensuring sustainable aquaculture practices. However, such experiments are costly, time consuming, and challenging to implement under real-world conditions. In the meantime, this study advances the body of research around optimal mangrove conservation and restoration scenarios in tropical aquaculture systems without limiting income opportunities for farmers.

Conclusions

High-density mangrove forests are key for sustaining the production of existing shrimp ponds, and restoring degraded and deforested areas in the buffer around shrimp ponds can increase aquaculture production sustainably, highlighting win–win opportunities for NCS, sustainable intensification, and improving livelihoods. Our results demonstrate the importance of the underlying mangrove forest for sustaining shrimp production in traditional aquaculture ponds, which aligns with the biophysical academic literature and the local knowledge of farmers. At the same time, our results highlight the positive externality of high-density mangroves surrounding ponds for shrimp aquaculture and the common pool resource problem entailed in continuing the expansion of new ponds, deforesting mangrove forests, and reducing production for the incumbent ponds. Our results also suggest that the current widespread practice of restoring mangroves by planting dense mangroves inside the pond is unlikely to achieve its objective of sustainable intensification. Mangrove restoration programs should prioritize long-term ecosystem resilience rather than simply responding to the global interest in mangrove restoration without considering local ecological contexts. This study found that the conversion of intact mangroves reduces average shrimp pond productivity and total aggregate production. This loss of intact mangrove forests diminishes their role as critical carbon stores, potentially reducing their overall capacity for carbon sequestration. This study adds significant multi-disciplinary data to the literature and describes refined possibilities for balanced mangrove conservation and restoration that ensure climate and livelihood benefits for both people and nature.

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Author contributions Aji W. Anggoro and Miguel Castro : Conceptualization, Data curation, Resources, Project administration and Writing – review & editing. Yustina Octifanny: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Project administration and Writing – original draft. Andi Trisnawati, Rahmadi Muis and Vabian Adriano: Data curation, field work implementation and interview supervision. Dzimar A.R. Prakoso, Yusuf Fajariyanto, Aldo R.A. Prananda and Muhammad M. Bayyan: Spatial Analysis. Arsy Husnanda: Data curation and Methodology. Muhammad Ilman, Sara Leavitt, Basir and Mariski Nirwan: Supervision, Writing – review & editing. Topik Hidayat and Peter Benham: Writing – review & editing.

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Declarations

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