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RESEARCH ARTICLE

Environmental Change and Trends in Brackishwater Pond Milkfish *Chanos chanos* Production in the Philippines Over Six Decades: Insights to Possible Resiliency

Benjamin Vallejo Jr [1,2*], Raymundo P Addun[2], John Warner M Carag[2,3]

[1] *Institute of Environmental Science and Meteorology, College of Science, University of the Philippines Diliman, Quezon City*
[2] *Science and Society Program, College of Science, University of the Philippines Diliman, Quezon City*
[3] *National Institute of Geological Sciences, College of Science, University of the Philippines Diliman, Quezon City*

ABSTRACT

The sixty-six (66)-year brackishwater pond production trends from 1952 to 2018 in the Philippines reflect low metric tonnage and low productivity per hectare despite increasing mangrove conversion to fishponds and increasing aquaculture intensification nationwide. These trends were related to yearly climatological means by graphical analysis and regression. Our analysis suggests that the likely cause of the sharp decline in production and productivity starting in 1993 is the 1991 Mt. Pinatubo eruption and other environmental stress factors, including a warming climate. Environmental stress factors have contributed to about 85,500 MT of production loss every year since 1993 and a slight yearly productivity decline between 0.04 kg ha^{-1} and 0.1 kg ha^{-1} since the early 1970s. Increases in mangrove conversion to fishponds did not increase production nor productivity. Despite aquaculture intensification and shifts in production modalities, the mean production of milkfish in 2018 is similar to records taken in the late 1980s. This implies unsustainability as a result of environmental changes and has serious implications for food security.

*Corresponding Author: *bmvallejo1@up.edu.ph*
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1. INTRODUCTION

Is milkfish *Chanos chanos* (Forsskål, 1775) aquaculture resilient to environmental variation and, more specifically, climate change? This question has great importance to food security, fisheries, and human culture in Southeast Asia. For these reasons, there is a need to assess the future resilience and sustainability of milkfish production given that this is the first farmed tropical finfish species in human history and is a major commodity to the present.

We look at this question by looking at the historical trends in production, environmental land use changes, the Pinatubo volcanic eruption of 1991, and increasing trends in temperature as documented by synoptic stations of the Philippine Atmospheric and Geophysical Services Administration (PAGASA) in the last five decades. Considering that milkfish production has been plagued by almost yearly fish kills in recent decades, the question of sustainability is at the fore. The proximal causes of these fishkills are likely due to eutrophication, toxic algal blooms, and consequent deterioration of water quality. The distal causes may be related to anthropogenic climate change, but the evidence can be linked by looking at milkfish stress responses to increasing water temperature which is the focus of climate change studies in aquaculture. Outdoor culture systems of milkfish have temperatures normally between 24–33 °C (Hanke et al. 2019). These systems can be subjected to extreme temperatures of > 40 °C. However, in the experimental ponds of the Pangasinan State University in Binmaley, Pangasinan, Luzon Island, Philippines, we recorded using a temperature sensor in May, during the hot and dry season of 2014, temperatures reaching up to 34 °C at 1400H. These temperatures are within the stress range in milkfish (Hanke et al. 2019).

While anthropogenic global warming is often cited in studies on threats to milkfish aquaculture (Guerrero 2017), very few studies document a potential link between global warming effects and milkfish production. A few studies have focused on the impact of current aquaculture practices on climate-related to intensification (Henrikson et al. 2019).

1.1 Milkfish culture in the Philippines

Milkfish was first cultured in Indonesia and the Philippines around 1100 CE in shallow earthen brackishwater ponds (30–40 cm depth) along estuaries and mangrove areas (Adams 1939). This aquaculture system and practice figures much in the culture of Southeast Asian peoples and still supports an industry that supplies a significant source of protein for coastal communities.

Also known as bangus in Filipino, it has a wide distribution spanning the whole of the tropical Indian Ocean to the central Pacific (Bagarinao 1991). The habitats where they are most likely to be found are the coastlines of Southeast Asia (Garcia 1990; Ross et al. 2013).

In the Philippines, aquaculture production was 2,349,252.01 MT in 2022 (PSA 2022). Milkfish accounted for 416,488.03 MT or 17.72 % of total production, which is second only to seaweeds, which contributed to 62.5% of aquaculture production. Milkfish brackishwater pond culture accounted for 183,428.31 MT or 44.04% of total milkfish production, while brackishwater pen production was 15,690 MT or 3% of total milkfish production. Brackishwater pond culture still contributes a large percentage to total production. Indonesia remains the world's top producer of milkfish at 832,270 MT in 2020, the majority of which come from brackishwater ponds.

1.2 Intensifying aquaculture practices, production, and environmental change risks

In the Philippines, milkfish is cultured in brackishwater ponds and increasingly in fish pens and cages in freshwater and marine environments. The size of ponds ranges from less than 1 ha to 20 hectares or more. Ninety-five (95) percent of these ponds were converted from mangrove areas (Primavera 2000). Milkfish aquaculture production in the latter half of the 20th century has taken an intensive culture modality, with higher stocking densities and more intensive feeding practices using artificially formulated feed. This is in contrast to the extensive traditional practice first developed in Southeast Asia based on natural food sources.

The traditional extensive method utilizes natural or inorganic fertilization of ponds to facilitate the growth of benthic green algae and cyanobacteria which the milkfish feed on. The algal complex is called "lablab" in the Philippines and is from 6% to 20% protein. To boost production, farmers may use supplemental feeding using formulated feeds. The traditional extensive fish stocking density is < 1000 fingerlings ha^{-1}. Fish are harvested after 4–6 months.

Many farmers also have shifted to the modified extensive or semi-intensive culture practice wherein stocking densities are from 1,000 to 1,500 fingerlings ha^{-1}. In this practice, there is supplemental feeding, and fish are harvested usually after 4 months, which allows up to 3 croppings in a year. The intensive culture practice has a stocking density of 7,000–15,000 fingerlings ha^{-1}. This is completely dependent on formulated feeds and fish may be harvested at 4 months of culture or even less.

The effects of anthropogenic climate change on milkfish aquaculture and distribution have not yet been fully assessed with most studies focusing on the effects of increasing temperatures on milkfish stress physiology (Chang et 2016; Hanke et al. 2019) and reviews of possible climate change-driven factors in aquaculture ecological systems (Macusi et al. 2015; Ahmed et al. 2019). These concerns are reflected in focused group discussions among milkfish fish farmers in Iloilo, Philippines, in 2010 (Network of Aquaculture Centres in Asia-Pacific 2010); anthropogenic climate change is likely to impact badly on fishpond and cage culture practice, where temperature extremes may result in fish kills and stunted growth.

Extensive to semi-intensive aquaculture of milkfish is used by a majority of Philippine fish farmers. This modality is believed to be most at risk for climate change under Intergovernmental Panel on Climate Change (IPCC) scenarios. A proposed adaptation strategy is to increase intensification to ensure high production levels in all culture modalities. However, this strategy may not be environmentally friendly as the effects of intensification may cause eutrophication in the coastal environment. Intensification is also hypothesized as the biggest contributor to greenhouse gas emissions in aquaculture.

This paper presents an exploratory approach to the possible link of major environmental changes in the Philippines in the last six decades to trends in milkfish production. This we propose to link with the potential resiliency of milkfish brackishwater pond aquaculture in a warming climate scenario, which could be a subject for future investigation.

This study is a modeling study and is limited by the availability of relevant time series data on climate, mainly on temperature, which was directly observed by PAGASA weather observers in the last six decades. We could have included rainfall estimates, but this likely will introduce temporal autocorrelation variables with temperature (Di Cecco and Gouheir 2018), and this autocorrelation as a factor in aquaculture ecological systems warrants a separate investigation. As for mangrove conversion spanning 66 years, we cannot separate the purpose of mangrove conversion for milkfish and shrimp farming, and so is a limitation. Even with these limitations, we aim to point ways forward to future studies such as relating environmental change using remote sensing, climate, aquaculture conversion estimates, sedimentation rates, land use change, and reclamation with aquacultural ecological processes, including its social and economic impacts.

2. MATERIALS AND METHODS

In this study, we used yearly milkfish pond production, pond area, and temperature to analyze the possible link of productivity with climate warming. Milkfish production data is taken from the yearly Philippine Fisheries Profile published by the Bureau of Fisheries and Aquatic Resources (BFAR 2022). Area in hectares was also published by BFAR but discontinued in 1991. Pond hectarage from 1991 to 2018 was extrapolated from available data on mangrove conversions (Asian Development Bank 2014). It must be noted that mangrove conversions were not only for milkfish culture but for other species as well. There is no available data on mangrove conversions specifically for milkfish culture alone.

As a climate proxy, we used temperature data) from 1973 to 2016 from nine PAGASA stations, namely Baguio, Dagupan, Hinatuan, Laoag, Legazpi, Mactan, Tagbilaran, Tuguegarao, and Virac. We analyzed the temperature anomalies and graphically juxtaposed them with production and productivity trends. We divided the 1973–2016 period into two periods (relatively cool and warm periods) by estimating the linear trend of the anomalies relative to the mean of the period. The year when the trend line crossed the x-axis is marked as the year when the climate became relatively warm. We then used ordinary least squares regression to measure changes in production and productivity from the two periods. We used year as a dummy variable whose values are 0 for the relatively cool years (1973–1992) and 1 for the relatively warm years (1993–2018) to measure the impact of environmental stress variables, including the warming climate and the eruption of Mt. Pinatubo in 1991.

3. RESULTS

3.1 Trends in production and productivity

Total production generally increased from the 1950s to the early 1990s (Figure 1). This was due mainly to expanding pond areas and, starting in the

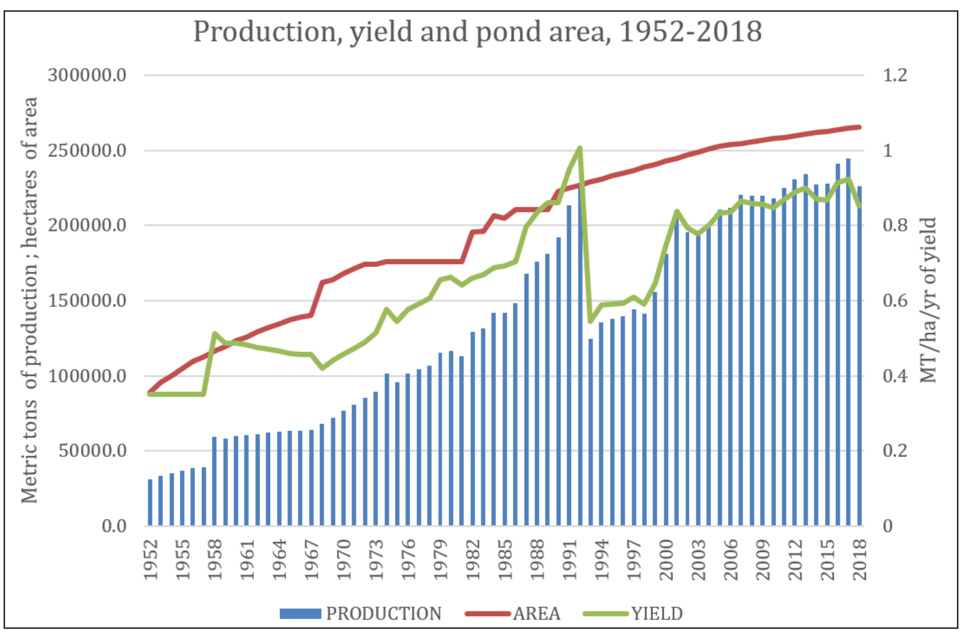

Figure 1. Trends in production, pond area, and yield from 1952 to 2018.

1970s, to productivity gains due to new aquaculture pond technologies. Productivity first reached a first peak in 1958 (0.51 MT ha^{-1}) but declined in the 1960s due to a faster rate of area expansion than increases in production. Productivity again peaked in 1992 (1.0 MT ha^{-1}) but dropped drastically in 1993 (0.54 MT ha^{-1}) along with the big drop of production in the same year. Productivity and production again showed a recovery from the late 1990s but never reached the pre-1993 level of production until 2012. The first decade of the 21st century to the present appears to exhibit a flattening at around 230,000 MT of milkfish and 0.9 MT ha yr^{-1} of yield. However, in 2022, the brackishwater milkfish production is 183,428.31 MT, which is lower than our models estimated.

3.2. A volcanic eruption, warming climate, and milkfish production

The drastic drop in milkfish production in 1993 can be attributed largely to the Mt. Pinatubo eruption in 1991. This is not a factor in long-term global warming, as the eruption resulted in a short-term -0.5 °C cooling of atmospheric temperatures in 1992. The Pinatubo eruption largely affected the fishponds of central Luzon. This was not the reason for the decline in production in other regions. If it were, then there should be no noticeable decrease in production in the areas where ash and other pyroclastic materials did not reach, notably in the Visayas and Mindanao regions. However, an examination of the regional trend of production in the years 1992 and 1993 revealed that the decrease in production had been general for all regions except the National Capital Region (Table 1).

The Philippine climate has been warming, as attested by the PAGASA, from increasing greenhouse gas emissions (PAGASA 2020). For this study, we examined the temperature anomaly relative to the mean temperature of nine synoptic stations in the 1973–2016 period. These synoptic stations are Baguio, Dagupan, Hinatuan, Laoag, Legazpi, Mactan, Tagbilaran, Tuguegarao, and Virac. The climate proxy is the average temperature of these weather stations. Temperature readings from these stations were only available from 1973, and therefore, our analysis of production and climate change started from that year. Coincidentally, the year when temperature anomalies started to be above the average of the 1973-2016 period was 1993, the year when a drastic decrease in production and productivity started to be observed (Figure 1). Looking at the 5-year running average yield, we can see an increasing yield up to the early 1990s, a downward trend in the late 1990s, and a flattening of the yield to the level of the early 1990s in the first decade of the 21st century (Figure 2).

3.3. Diminishing yields

The average yield in the last 10 years before 1993 is higher than the average of the years from 1993 to 2018. This suggests a diminishing yield. To further test for diminishing yield, we estimated milkfish production as a function of pond area using linear and quadratic models and different period datasets, namely 1973–1992, 1973–2018, and 1993–2018. This we define as productivity. The results are shown in Table 2. The results show that the quadratic models have a better fit than the linear models for all data

Table 1. Brackishwater milkfish production by region, 1992 and 1993.

REGION	1992 PRODUCTION	1993 PRODUCTION	PERCENT CHANGE
NCR	1067	3844	260.26
REGION I	24554	11195	-54.41
REGION II	853	77	-90.97
REGION III	52573	31953	-39.22
REGION IV	18055	13822	-23.45
REGION V	4546	2645	-41.82
REGION VI	83248	35184	-57.74
REGION VII	8866	7906	-10.83
REGION VIII	3076	1488	-51.63
REGION IX	16170	5737	-64.52
REGION X	3418	1339	-60.83
REGION XI	8485	8375	-1.30
REGION XII	3447	945	-72.58

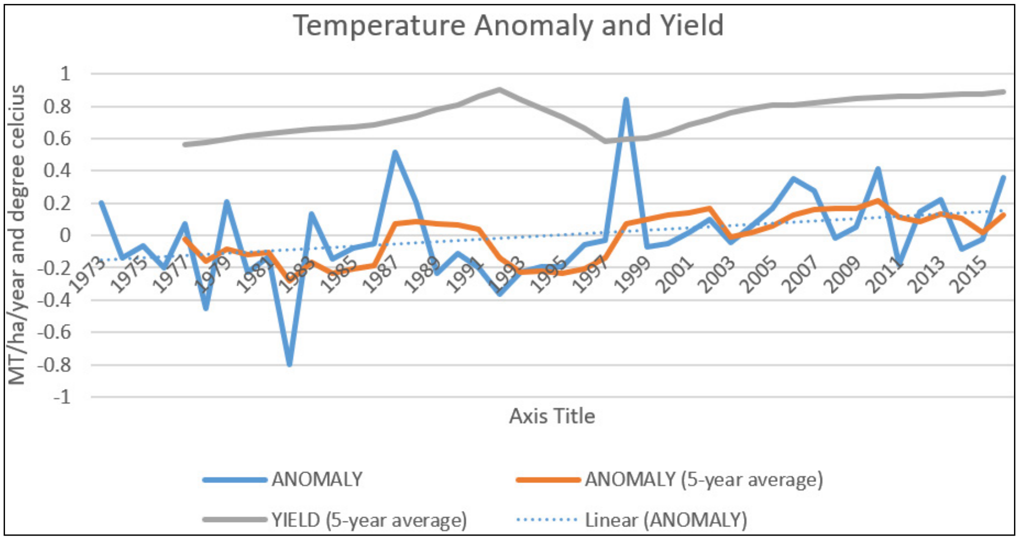

Figure 2. Five-year running average yield and anomaly, 1973–2016.

Table 2. Linear regression estimates for quadratic and linear production functions using different subsets of the data.

a.) Quadratic Model using 1973–1992 Data

Variable	Estimate	Std. Error	t value	Pr (>abs t)
Intercept	1.091e+06	3.587e+05	3.042	0.00736 **
AREA	-1.172e+01	3.662e+00	-3.200	0.00525 **
AREA2	3.474e-05	9.270e-06	3.747	0.00161 **

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 10000 on 17 degrees of freedom
Multiple R-squared: 0.9463, Adjusted R-squared: 0.9399
F-statistic: 149.7 on 2 and 17 DF, p-value: 1.613e-11

b.) Linear Model using 1973–1992 data

Variable	Estimate	Std. Error	t value	Pr (>abs t)
(Intercept)	-2.499e+05	3.045e+04	-8.209	1.69e-07 ***
AREA	1.997e+00	1.552e-01	12.862	1.64e-10 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 13140 on 18 degrees of freedom
Multiple R-squared: 0.9019, Adjusted R-squared: 0.8964
F-statistic: 165.4 on 1 and 18 DF, p-value: 1.639e-10

c.) Quadratic Model using 1973–2018 data

Variable	Estimate	Std. Error	t value	Pr (>abs t)
Intercept	2.545e+	9.990e+04	2.548	0.01459 *
AREA	-3.149e+00	9.373e-01	-3.359	0.00167 **
AREA2	1.300e-05	2.186e-06	5.947	4.73e-07 ***
DUMMY	-8.556e+04	6.858e+03	-12.475	1.03e-15 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 13140 on 18 degrees of freedom
Multiple R-squared: 0.9019, Adjusted R-squared: 0.8964
F-statistic: 165.4 on 1 and 18 DF, p-value: 1.639e-10

d.) Quadratic model without a Dummy variable, 1973–2018

Variable	Estimate	Std. Error	t value	Pr (>abs t)
Intercept	(Intercept) 1.383e+05	2.132e+05	0.649	0.520
AREA	-1.187e+00	1.981e+00	-0.599	0.552
AREA2	5.790e-06	4.519e-06	1.281	0.207

Residual standard error: 22990 on 43 degrees of freedom
Multiple R-squared: 0.7828, Adjusted R-squared: 0.7727
F-statistic: 77.51 on 2 and 43 DF, p-value: 5.502e-15

e.) Linear model using 1973–2018 data

Variable	Estimate	Std. Error	t value	Pr (>abs t)
Intercept	-3.267e+05	2.775e+04	-11.774	4.85e-15 ***
AREA	2.390e+00	1.412e-01	16.927	< 2e-16 ***
DUMMY	-7.477e+04	8.872e+03	-8.428	1.18e-10 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 14380 on 43 degrees of freedom
Multiple R-squared: 0.915, Adjusted R-squared: 0.911
F-statistic: 231.4 on 2 and 43 DF, p-value: < 2.2e-16

f.) Quadratic model using 1993–2018 data

Variable	Estimate	Std. Error	t value	Pr (>abs t)
Intercept	-3.077e+06	9.892e+05	-3.110	0.00493 **
AREA	2.313e+01	7.994e+00	2.893	0.00820 **
AREA2	-4.007e-05	1.612e-05	-2.485	0.02066 *

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 8723 on 23 degrees of freedom
Multiple R-squared: 0.9521, Adjusted R-squared: 0.9479
F-statistic: 228.6 on 2 and 23 DF, p-value: 6.676e-16

g.) Linear model using 1993–2018 data

Variable	Estimate	Std. Error	t value	Pr (>abs t)
(Intercept)	-6.204e+05	4.246e+04	-14.61	1.92e-13 ***
AREA	3.265e+00	1.695e-01	19.26	4.21e-16 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 9618 on 24 degrees of freedom
Multiple R-squared: 0.9392, Adjusted R-squared: 0.9367
F-statistic: 370.9 on 1 and 24 DF, p-value: 4.208e-16

sets. This implies diminishing rather than constant productivity. For the quadratic models, the model using the pre-1993 data has a higher instantaneous slope (coefficient of AREA-squared times 2) than the other models, implying higher productivity in the pre-1993 period.

3.4. Effect of evironmental stress factors

Since the pond production system is a closed physical system combining culture technology and ambient conditions, it is possible to estimate the effect of climate factors and technological change by estimating the production function. The dummy variable isolates the effect of the rare event of a massive environmental change as a categorical effect on production. After taking this event's impact on production, other causes for the changes in production can then be attributed to changes in the quantities of inputs, changes in technology, as well as changes in the environmental medium or ambient conditions. In attributing the decrease in productivity to environmental stress factors, we are assuming that brackishwater pond technology has either improved or remained the same during the period under study. In other words, any decrease in productivity cannot come from a decrease in technology, which is an unlikely event. A decrease in production could be attributable to a decrease in the quantity of inputs and or to changes in productivity per unit input.

We used year as a dummy variable to isolate the effect of a rare geological event, the Mt. Pinatubo eruption. Our results show that aside from an abrupt change of production in 1993, there was also a decrease of productivity as seen from the decrease of the instantaneous slope of the production function (coefficient of AREA-squared times 2) from pre-1993 to the post 1993 periods (Tables 2a, 2c and 2f). This change of productivity may be attributable to changes in the ambient conditions of the ponds, assuming technology to be constant or increasing throughout the period of our analysis.

The "lump sum" or abrupt change in production in the post-1992 period, was estimated at 85,500 MT yr^{-1} (see Table 2c). As an estimate from a dummy variable, this loss represents the loss largely due to Mt. Pinatubo, which erupted in 1991, suggesting a large change in the quantity of input when pond areas were rendered non-operational due to volcanic debris. The change in production is due to a change in productivity, which we interpret to be due to changes in ambient environmental conditions in ponds, which is between -0.04 and -0.1 kg ha-yr^{-1}.

4. DISCUSSION

Our analysis of production and yield trends shows the classic pattern of development in aquaculture, which begins with low technology extensive practices to more technology-intensive and higher production-intensive practices. The Philippine government began collecting production statistics during the Commonwealth era (1935–1946), where yield per hectare per year was < 0.2 MT ha yr^{-1}. At present, extensive culture practices based on natural food can yield, on average, < 0.3 MT ha yr^{-1}. Modular pond systems and semi-intensive practices may increase production to 0.6 MT ha $yr^{-1,}$ and intensive practices may increase production to > 1.1 MT ha yr^{-1} (FAO 2012). Pond fertilization can add at least 0.2 MT ha yr^{-1} in yield, and high-density stocking and feeding can add 0.7 MT ha yr^{-1} (Bagarinao 1998).

Production increased with the introduction of semi-intensive and intensive practices in the mid-1950s, which were recommended to boost production in Third World countries (Pullin 1989). The Philippine government received a 23.6 million USD loan from the International Bank for Reconstruction and Development (IBRD) in 1950 for pond development. The BFAR dataset reflects this with an increase in production from 39,414 MT in 1957 to 59,624 in 1958. Yield increased from the extensive average of 0.35 to 0.512 MT ha^{-1} while the increase of pond area was only 3935 ha. Increasing yield from the 1960s to the 1980s can be attributed to the adoption of more intensive culture practices and the conversion of mangrove areas into ponds. Freshwater pen culture was introduced in 1973 in Laguna de Bay in southern Luzon. By the end of the 1970s, total milkfish production from all modalities, including freshwater pen culture, was 135,951 MT, of which 97,205 MT was from brackishwater pond production. Marine cage culture was introduced in 1996 in Bolinao, Pangasinan. The latter reflects the latest technological development in culture.

The major decrease in production was in 1992–1993, with a decrease of 103,848 MT, which translates to a yield loss of 0.478 MT ha yr^{-1}. This drastic decline is generally attributed to the Mt. Pinatubo eruption in Zambales of 1991, which affected Bulacan, Pampanga, Zambales, and Bataan provinces, which are the largest milkfish producers in Luzon (Bagarinao 1998) and the whole country. However, other factors of the decline in production cannot be discounted as we observed that the decrease in production was general throughout the country and not confined to the areas around Mt. Pinatubo.

The highest milkfish production and yields are in Type I climates. The highest production is noted in areas with a defined dry and wet season. In the Type I climate of provinces of Bulacan, Iloilo, and Pangasinan, a yield of 0.5 MT ha yr^{-1} is possible under favorable conditions, even under extensive culture practices. With semi-intensive to intensive practices, a yield of 1 MT or greater is not unusual with four cropping cycles a year. Fish farms in Type I climates are expected to be adversely affected by a warming climate with a disruption in the expected onset of the southwest monsoon and more extreme temperatures disrupting cropping cycles. This is compounded by the frequency of strong tropical cyclones.

Do the 1973–2018 production trends show a definite environmental change signal? The answer is "yes" since isolating the effect of the 1991 Pinatubo eruption through dummy variable regression did not fully account for the general decrease of production in the country from 1993 onwards. After the Mt. Pinatubo eruption, total production was only able to catch up on the pre-1993 levels in 2016. Productivity is yet to catch up with the 1.0 MT ha yr^{-1} reached in 1992, an unlikely eventuality given the diminishing yield trend as pond area expanded as additional areas for ponds came from mangrove conversion. This suggests unsustainability and if production is compared before

1993, productivity has been generally declining as reflected in the yield as MT- ha^{-1} $year^{-1}$ index.

Are the production trends reflective of warming episodes? The 44 years from 1973 to 2016 trend may not clearly reflect the effect of a warming climate as to the effect of El Niño events. Figure 3 shows the trends in brackishwater pond milkfish production in the Philippines from 1973 to 2016 and the average temperature anomalies of the nine synoptic stations. The arrows point to the temperature anomalies that coincide with moderate to very strong El Niño events in 1997–1998.

It is reasonable to hypothesize that the series of El Niño events of 1995 and 1997 have negatively impacted brackishwater milkfish national production. This resulted in a slow recovery of production at 1992 levels that was only breached in 2012 as a result of an 8% percent increase in production in marine cage culture, which was more than double that of the estimated yearly increase in brackishwater pond production. A gradual increase in production, which translates to a recovery in production, happened only after the extremely strong 1997 El Niño. More recent BFAR statistical data suggests that from 1997 to 2022, the yearly increase in brackishwater pond production is estimated at 3253 MT yr-1, while for marine cage aquaculture, it is 6887.1 MT yr^{-1}. This net increase has been through the expansion of marine cage aquaculture, where the production rates per year are double that in brackishwater pond culture. In 2000, 99% of milkfish production was from brackishwater pond culture and 1% from marine cage culture, while in 2022, brackishwater culture accounted for 48% and marine cage culture at 52%. From 2019 to 2022, brackishwater pond production has decreased by an average of 15,553 MT yr^{-1}, and this is expected to continue as there are fewer mangrove areas to convert into ponds and coastal land use changes such as reclamation reduce the areas for fishpond expansion, development, and viability.

There is reasonable circumstantial evidence to consider from this modeling study that a warming climate is linked to decreases in brackishwater pond production after 1993 (when the effects of the Pinatubo eruption were statistically isolated). The effect of climate is likely in pond ecological processes and how culture systems and practices respond to this environmental change.

4.1 Can milkfish aquaculture be climate and environmentally resilient?

Resiliency is defined as the capacity to recover from any major environmental disturbance without impacting the sustainability of the resource being utilized. In an aquaculture context, resiliency can be achieved by promoting sustainable practices, more efficient use of farm inputs, diversification of species cultured, and more access to weather and forecasting information to allow farmers to plan stocking and harvest activities.

Based on the biological requirements of milkfish for pond aquaculture, implementing climate resilience strategies will be challenging. We base our

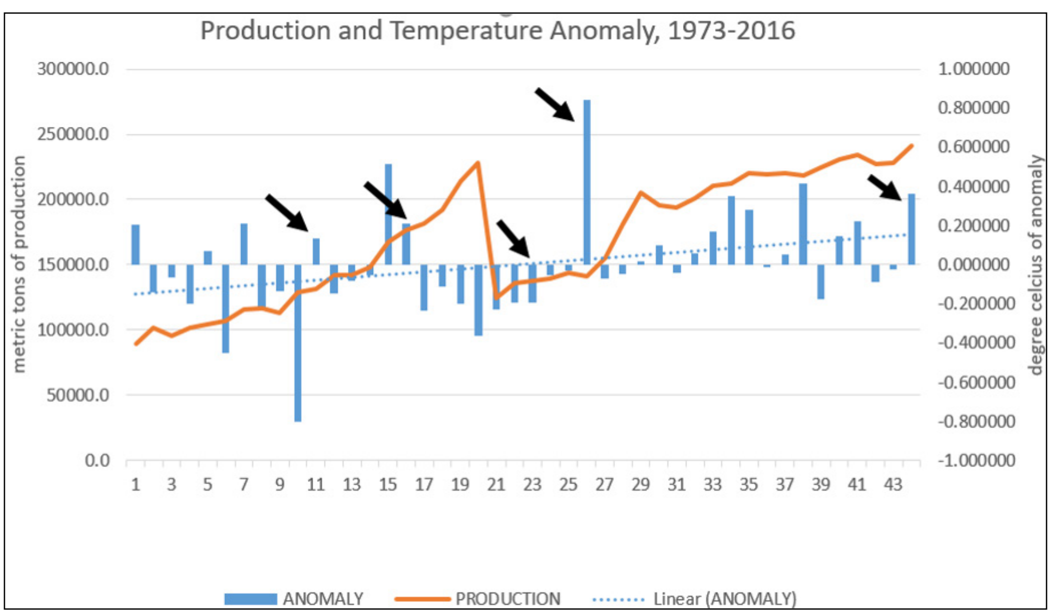

Figure 3. Brackishwater pond milkfish production and temperature anomaly, 1973–2016. Arrows point to El Niño years.

observation on the trends in production from BFAR data in this study and the possible negative effects of a warming climate.

The main reason is the trophic ecology of milkfish. The majority of ponds in the Philippines are still based on natural feeding by fertilization with differential inputs of artificial feeds depending on market forces. The Network of Aquaculture Centres in Asia-Pacific (NACA) suggests a shift to artificial feeding and more intensification as a climate resilience strategy. With this, there is a shift to cage and pen farming and the possibility of deep-water marine ponds. Also, while a desirable trait of milkfish for aquaculture is its tolerance to temperature fluctuations (Garcia 1990) recent research suggests that the shallow pond environment will likely be impacted by increasing atmospheric temperatures and will expose milkfish stocks to more frequent temperature stresses (Hanke et al. 2019). The interplay of climate change and pond ecological processes, especially in eutrophication, is now being investigated and will prove valuable in developing climate-resilient aquaculture practices.

Another possible climate change effect relates to the fact that the majority of fry and postlarval juveniles, which require higher salinities, are collected from nearshore areas. There is a predicted decrease in the supply of fry and juveniles for pond and marine cage aquaculture. One poorly understood area for research is the possible effects of ocean acidification on the development of milkfish fry.

The major constraints to a shift to intensive aquaculture include eutrophication unless the carrying capacity of embayment is properly considered in planning (Jacinto 2011). Other less environmentally critical strategies include shifting to freshwater ponds and pen aquaculture, but the number of suitable areas in the Philippines is much less than in coastal areas. The shift to freshwater production is recommended with the increasing rainfall predicted by global climate models (Bell et al. 2011). The constraint in the Philippines as it is an oceanic archipelago, the suitable areas for freshwater milkfish culture are very limited.

On average, the productive life of intensive aquaculture ponds is 5 years (Patil et al. 2002). Thus, extensive polyculture of milkfish with high-value fisheries is recommended as an environmentally resilient approach (Bergquist 2007). Resilience may be even more ensured by adopting mangrove-friendly aquaculture methods (Primavera 1995; Primavera 2005), which includes polyculture in semi-intensive modalities (Pullin 1989) and ensures the 4:1 mangrove hectarage to pond hectarage ratio (Primavera and Esteban 2008). These resiliency approaches must be within the framework of an integrated coastal zone management philosophy. We strongly suggest that this is the best sustainable approach since BFAR data suggests that despite increasing pond area converted from mangroves, yield never has reached 1992 levels. Production severely decreased beginning in 2018, leading to increased production from marine cage culture. It must be noted that marine cage aquaculture intensification has resulted in serious negative environmental impacts such as fish kills in Bolinao, Pangasinan (Holmer et al. 2002; Jacinto 2011; Yñiguez and Otong 2020). We expect further expansion on intensified marine cage culture of milkfish will have serious environmental impacts as this is often cited in embayments with limited water circulation and exchange (Nacorda et al. 2012).

The results of this modeling study can inform research on making milkfish aquaculture more climate and environmentally resilient, as well as more sustainable. We suggest a research approach linking climate envelope models (CEM) with aquaculture production and resiliency. CEM has been used to predict the response of biodiversity in climate change scenarios (Pearson and Dawson 2003) and may prove useful in planning where aquaculture is best situated, given natural and human factors.

The resilience of milkfish aquaculture is likely uncertain in a warming climate scenario and massive environmental change. This has serious consequences for food security unless strategies for sustainable milkfish aquaculture practices are considered and applied. Research on aquaculture resiliency, we suggest, must focus on the climate change resiliency of culture systems, including marine cage aquaculture and pond systems.

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This paper is dedicated to the memory of John Warner M. Carag (1990-2024), a dedicated scientist from and of the Filipino people who, in his life, achieved more for the protection of the environment than any of us has ever done.

AUTHORS CONTRIBUTIONS

Vallejo B: Conceptualization, Methodology, Writing - Original Draft. **Addun RP:** Data Curation, Methodology, Formal Analysis, and Writing - Original Draft. **Carag JWM**: Investigation, Data Curation, and Formal Analysis.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

The study did not require ethics approval since all data and information used in it are publicly available and properly credited. No animal or human subjects were used in the study.

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SUPPLEMENTAL MATERIALS

Table 1. Brackishwater pond production, pond area, yield, and average temperature, 1952 to 2018.

YEAR	PRODUCTION	AREA	YIELD	AVE. TEMPERATURE
1952	31038	88681	0.350	NA
1953	33472	95633	0.350	NA
1954	35034	100097	0.350	NA
1955	36734	104952	0.350	NA
1956	38480	109799	0.350	NA
1957	39414	112611	0.350	NA
1958	59624	116546	0.512	NA
1959	58090	119546	0.486	NA
1960	60119	123252	0.488	NA
1961	60825	125810	0.483	NA
1962	61436	129062	0.476	NA
1963	62044	131850	0.471	NA
1964	62680	134242	0.467	NA
1965	63198	137251	0.460	NA
1966	63654	138968	0.458	NA
1967	63912	140055	0.456	NA
1968	68215	162118	0.421	NA
1969	72408	164134	0.441	NA
1970	76816	168118	0.457	NA
1971	80999	171446	0.472	NA
1972	85372	174101	0.490	NA
1973	89640	174101	0.515	26.7359
1974	101375.5	176032	0.576	26.3919
1975	95815	176032	0.544	26.4642
1976	101485	176230	0.576	26.3327
1977	104180.5	176230	0.591	26.6039
1978	106814	176230	0.606	26.0784
1979	115694.5	176230	0.656	26.7413
1980	116578	176230	0.662	26.3049
1981	113256	176232	0.643	26.3975
1982	129306	195832	0.660	25.7299
1983	131398	196269	0.669	26.6661
1984	142091	206525	0.688	26.3830
1985	141960	205000	0.692	26.4513
1986	148201	210319	0.705	26.4782
1987	167728	210457	0.797	27.0428
1988	175935	210680	0.835	26.7395
1989	181197	210680	0.860	26.2967
1990	191878	222907	0.861	26.4210
1991	213674	224895.333	0.950	26.3341
1992	228358	226883.667	1.006	26.1658
1993	124510	228872	0.544	26.3034

1994	135682	230860.333	0.588	26.3368
1995	137796	232848.667	0.592	26.3401
1996	139372	234837	0.593	26.4767
1997	144076	236825.333	0.608	26.5039
1998	141131	238813.667	0.591	27.3758
1999	155593	240802	0.646	26.4586
2000	180931	242790.333	0.745	26.4831
2001	204862	244778.667	0.837	26.5477
2002	195877	246767	0.794	26.6275
2003	193738	248755.333	0.779	26.4906
2004	200531	250743.667	0.800	26.5870
2005	210652	252732	0.833	26.7019
2006	211841	253726.167	0.835	26.8823
2007	220567	254720.333	0.866	26.8110
2008	219610	255714.5	0.859	26.5162
2009	219977	256708.667	0.857	26.5821
2010	218067	257702.833	0.846	26.9468
2011	224934	258697	0.869	26.3534
2012	231044	259691.167	0.890	26.6797
2013	234478	260685.333	0.899	26.7529
2014	227477	261679.5	0.869	26.4456
2015	227815	262673.667	0.867	26.5093
2016	241203	263667.833	0.915	26.8927
2017	244365.6	264662	0.923	NA
2018	226107.58	265656.167	0.851	NA