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The impact of ocean warming on selected commercial fisheries in New Zealand

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Abstract

Warming oceans affect the growth, reproduction and location of fish species. Using a bioeconomic framework, we estimate the relationship between sea surface temperature (SST) and the catch of de facto open-access commercial fisheries of flatfish, trevally and jack mackerel in New Zealand. Assuming either a logarithmic or quadratic relationship between the SST and the carrying capacity of the fish stock, we consider three fishing methods (bottom trawl, set net and midwater trawl) and two measures of effort (count and duration). We show that ocean warming results in an increase in catch for all species if we assume a logarithmic relationship, with the highest marginal product of SST (MP_{SST}) for jack mackerel caught using midwater trawl. The highest marginal revenue product (computed by the MP_{SST}, current price and fished area) is found for flatfish caught by set net. However, when assuming a quadratic relationship, there is a threshold above which catch starts to decrease, with the maximum catch of species ranging between 10 and 12.2°C. These results also vary spatially, with higher values of MP_{SST} observed in areas closer to the South Pole. Our findings are relevant for any review of fisheries management systems in response to ocean warming.

KEYWORDS

bioeconomic model, flatfish, jack mackerel, ocean warming, sea surface temperature, trevally

JEL CLASSIFICATION

Q54, Q57

1 | INTRODUCTION

Oceans have been warming over the past several decades, and this process has been accelerating more recently. The increase in ocean temperature is expected to continue in the next few decades, due to anthropogenic climate change, even if all the Paris Agreement voluntary reductions in greenhouse gas emissions were implemented as promised (Bindoff et al., 2019). The Intergovernmental Panel on Climate Change (IPCC, 2021; p. 1221) has observed that '… it is now very likely that global mean SST changed by 0.88°C [0.68–1.01°C] from 1850–1900 to 2011–2020, and 0.60°C [0.44–0.74°C] from 1980 to 2020'. They further note that: 'It is virtually certain that SST will continue to increase in the 21st century at a rate depending on future emission scenario'.[1]

The ocean surrounding Aotearoa New Zealand (henceforth NZ) is warming as well. Sutton and Bowen (2019) showed that the sea adjacent to NZ has warmed by approximately 0.12–0.34°C per decade in the last 40 years.[2] There is regional variability with most of the warming occurring off the east coast of the North Island south of the East Cape, and the least along the northeast coast (Sutton & Bowen, 2019). Using earth system models, Law et al. (2018) project that the sea surface temperature (SST) of oceans around NZ will increase by approximately 0.8°C under the Representative Concentration Pathway (RCP) 4.5 scenario (optimistic) and 1°C under RCP 8.5 (most pessimistic)[3] by 2050, compared with the period 1976–2005. By 2100, the SST is projected to increase by approximately 1.1°C under RCP 4.5 and approximately 2.5°C under RCP 8.5. There are also spatial differences in the projected increase in temperature within the subantarctic waters south of the Chatham Rise, which are projected to have the greatest warming, and the Central Tasman Sea, which is expected to be the least affected. Given this past and future spatial variability in warming, the environmental and ecological impacts of climate change are likely to vary across marine areas in New Zealand.

Increasing ocean temperatures have been identified as a driver of regional shifts in the distribution and abundance of marine organisms (Cheung et al., 2012; Poloczanska et al., 2013). An increase in ocean temperature affects the availability of prey and the reproduction and survival of fish species. The redistribution of species may also result in the transfer of invasive species, predators and fish diseases. These changes inevitably affect the volume and composition of fish catch and pose a challenge to the management of fisheries (Bindoff et al., 2019). The general migration of marine species towards the poles and to deeper waters affects species interaction and is expected to affect fish catch in NZ.[4]

For example, Parsons et al. (2020) predict that snapper catch in NZ will decrease by 29 per cent in the most pessimistic scenario of climate change but increase by 44 per cent in the most optimistic scenario. The latter is in line with the observation that climate change-induced warming promotes the growth of nearshore snapper and tarakihi (Morrongiello et al., 2021). Aquaculture species such as salmon and mussels (Broekhuizen et al., 2021) and marine birds (McKechnie et al., 2020) are also affected by ocean warming. A shift in the distribution range in response to warming has been reported for different marine species (Poloczanska et al., 2013), and so the projected increase in SST may result in increasing dominance of warmer-water

[1]'Virtually certain' is a very strong statement according to the IPCC terminological conventions.

[2]This rate is faster than the increase in land surface temperature estimated to be around 0.1°C per decade (Mullan et al., 2018).

[3]Representative Concentration Pathways (RCPs) are climate modelling pathways that describe projected changes in radiative forcing resulting from greenhouse gas concentration trajectories under different socio-economic assumptions (van Vuuren et al., 2011).

[4]In 2018, commercial fisheries and aquaculture contributed NZD 1.13 billion to the economy (equivalent to 0.4 per cent of the country's gross domestic product (Stats NZ, 2020)).

species in NZ waters. Cummings et al. (2021) reported that ocean warming may potentially affect up to 23 out of 32 fish species groups in NZ, and more recently, Dunn et al. (2022) predict a larger effect on the distribution of inshore finfish clusters as opposed to offshore clusters from climate change.

What these local and regional changes in fish stocks mean for commercial fisheries in NZ has not yet been investigated. In this paper, we explore the relationship between SST[5] and the catch of several de facto open-access commercial species caught by bottom trawl, midwater trawl and set net within NZ's exclusive economic zone (EEZ).[6] We use high-frequency catch and effort data from each statistical area of NZ matched with SST data in an open-access bioeconomic model first developed by Barbier and Strand (1998), and focus on the three main NZ de facto open-access fisheries: flatfish, jack mackerel and trevally.[7]

Jack mackerel was worth NZ$62 million in export value in 2019 and ranked 7th below rock lobster, ling, hoki, etc. (SeaFIC, 2019). Flatfish and trevally rank medium to low in export value. Together, the three species provide insights into the mechanisms through which ocean warming may affect the economic value of commercial fish species. We contribute to the literature by conducting analyses for multiple species and gears in contrast to the single-species, single-gear focus of the studies mentioned above. An added value of our focus on three separate species is our ability to demonstrate the similarities, and some differences, between the impact of SST on these three species, and therefore provide insight into the likely differences between these species and other economically important species such as hoki or snapper. In a warming ocean, understanding these relationships is crucial for the design of a quota management system regulating the catch of commercially important fisheries.

The following provides a brief overview of these three species (also see Table S1 for names and characteristics of species). Flatfish includes species with a wide range of life-history characteristics, ecology and distributions (Gibson, 2005). Ryer (2008) stated that temperature affects the behavioural response of flatfishes regarding their catchability, that is, higher temperature reduces the catchability of flatfishes because they herd more and for longer. Herding is the ordered behavioural response of flatfishes in which they move away from the direction of the trawl and become concentrated in the mouth of the trawl. At low temperatures, flatfish may be more likely to startle in response to ground disturbance by a trawl rather than initiate a herding response. This increases their chances of rapidly passing over the trawl footrope and into the net. The swimming endurance of some flatfish species also decreases with temperature, thereby increasing the catchability. Cheung and Oyinlola (2018) project that climate change-driven changes in ocean conditions, including temperature changes, will affect the distribution and productivity of flatfish stocks. There is also an expected range shift for flatfish both in latitude and depth. Flatfish are generally less mobile relative to other active pelagic and demersal species. Their capacity to adjust to climate change is thus relatively lower, making flatfish more vulnerable. However, there is

[5]Many factors are important in estimating sea subsurface water temperature, including SST, salinity, height, pressure, heat capacity and density (Akbari et al., 2017). In the absence of readily available subsurface sea temperature, researchers routinely use SST as an indicator for warming (see Akbari et al., 2017 for an overview of the complex relationship between SST and other oceanographic variables).

[6]Fisheries in NZ are managed through a quota management system. A total allowable commercial catch (TACC) is set for each species for different management areas, and individual transferable quotas grant commercial fishers a share of fish stock (Mace et al., 2014; Ministry of Primary Industries, 2021). We investigate only fish for which the actual annual catch is significantly below the TACC, thus substantiating a de facto open-access assumption.

[7]The total catch for these species has been consistently below the TACC for these species over time (Fisheries New Zealand, 2020). The low prices for quota and annual catch entitlements of all three species support the assumption that there is no pressure to catch a volume that is greater than their respective TACC.

spatial variability in the expected impact whereby the reduction in catch potential is mainly projected to occur in the tropical regions while there will be an increase in the Arctic region (Cheung & Oyinlola, 2018). Flatfish species that have narrow geographic distribution, narrow thermal tolerance range, and relatively larger body size are most at risk from these changes. The restricted range of some species limits their ability to adjust to ocean warming with poleward migration (Cheung & Oyinlola, 2018).

Trevallies are important fishery resources throughout subtropical and warm temperate oceans. Silver trevally (*Pseudocaranx georgianus*) is the only species of trevally found in NZ. A report of the Ministry of Fisheries (2008) noted that there is a positive correlation between SST during surveys and relative biomass of trevally in NZ. Walsh et al. (2014) suggest that temperature strongly influences spawning and larval survival of trevally in NZ. Fowler et al. (2018) show that adult movement of trevally in south-eastern Australia primarily occurs over smaller distances than the current spatial scale of management, making this species quite vulnerable to ecosystem changes. A study on another trevally species (*P. dentex*) showed that the hatching rate and egg size decrease as ocean warms (Nogueira et al., 2018).

The three species of jack mackerel present in NZ have different geographical distributions. *T. novaezelandiae* are in shallower (<150 m) and warmer (>13°C) waters while *T. declivis* is generally found in deeper (up to 300 m) and cooler (<16°C) waters. The other species, *T. murphyii*, lives in deeper waters and has a wider latitudinal range reaching up to equatorial waters of the Galapagos Islands and the eastern Pacific along the coasts of Chile. Patterns of vertical and horizontal movement of jack mackerel are poorly understood. Jack mackerels are presumed to be generally off the bottom at night, and surface schools can be quite commonly observed during the day (Fisheries New Zealand, 2020). Harris et al. (1992) find that ocean temperature can affect the distribution of krill, leading to fishery failures for jack mackerel who feed on krill. Lima et al. (2020) note that overall, climate variability together with economic forces can explain the abrupt declines in jack mackerel stock sizes that have been observed in the South Eastern Pacific.

Given the potential effect of SST on reproduction and growth for flatfish, trevallies and jack mackerel, we use a comprehensive database of NZ's Ministry of Primary Industries to establish the relationship between SST and catch in a bioeconomic framework as follows.

2 | METHODS

We employ a bioeconomic model in order to establish the relationship between SST and the catch of flatfishes, jack mackerel and trevally within New Zealand's EEZ. We focus on the top three fishing methods used to catch these species—bottom trawl, midwater trawl and set net.[8]

2.1 | Data

We use a large database of catch and effort by species and by statistical area for each fishing event (trip) within the EEZ of NZ. The data are from the Ministry of Primary Industries'

[8]Trawls are fishing gears consisting of a cone-shaped body towed by one or two boats. Trawls have a large front part made with very large mesh or ropes and narrow end that retains catch. Bottom trawls catch fish species living on or near the bottom of the sea and target benthic and demersal species. Bottom trawls interact with the bottom sediment resulting in damage of seaweeds and corals, stones and other large objects. Midwater trawls are designed to fish in surface water and midwater targeting pelagic and sometimes demersal fish. This fishing gear has low bycatch rate as it usually targets a single species. Midwater trawls are bigger in size compared with bottom trawls. Set nets or set gillnets are passive fishing gears anchored to the sea floor by weights. These gears hang like vertical walls in the water and capture fish as they swim through the mesh of the nets. Set nets capture pelagic, demersal and benthic fish species (FAO, 2021).

TABLE 1A Summary statistics: Average annual catch and effort by statistical area, 1990–2018.

Fishing methods/species	n	Average catch per ha (g)	Average effort count per ha ($\times 10^{-4}$)	Average effort duration per ha ($\times 10^{-4}$) (h)
Flatfish				
Bottom trawl	1392	40.84	35.33	93.25
Midwater trawl	21	0.08	0.01	0.07
Set net	1235	116.89	11.18	750.83
Jack mackerel				
Bottom trawl	1472	54.79	6.41	25.65
Midwater trawl	906	557.33	36.86	129.93
Set net	638	1.27	0.15	5.50
Trevally				
Bottom trawl	1019	43.34	12.10	33.86
Midwater trawl	57	4.32	0.19	0.63
Set net	966	19.46	2.49	52.73

Enterprise Data Warehouse (Ministry of Primary Industries, 2019). Fishers report effort and catch for all their fishing activities by date, fishing trip, statistical area and other relevant variables such as vessel characteristics. We exclude observations that were not dated (0.02% of total observations) or did not identify the statistical area of the fishing event (0.75% of the total observations). The catch and effort data were matched with vessel characteristics through a vessel identifier. Thus, we have information on the total annual catch and effort for each statistical area for the period 1990–2018. Table 1a provides summary statistics on catch and effort by statistical area for three species and three fishing methods. The table shows the average annual catch, effort count and effort duration per hectare for statistical areas that reported effort during a specific year.

The Centennial In Situ Observation-Based Estimates of the Variability of SST and Marine Meteorological Variables, version 2.9.2 (COBE-SST2), by Japan Meteorological Agency (JMA) data are used to measure SST (Hirahara et al., 2014).[9] The monthly SST for 1° latitude/longitude grids is aggregated by year and statistical area.[10]

2.2 | Model

We build on the production function approach pioneered by Barbier and Strand (1998) and subsequently adopted by other studies (see Barbier et al., 2002; Foley et al., 2010). Mediodia et al. (2023) and Mediodia (2021) used the Barbier and Strand model to investigate tuna fisheries in the East Pacific, and included SST as an input affecting catch through the carrying capacity of the fish stock. We employ the same modelling approach here, that is, we derive a long-run harvest function where SST is modelled as a function of both carrying capacity and the intrinsic growth rate of the fish stock (a detailed bioeconomic model is provided on pp. 6–10 in Mediodia et al. (2023) where harvest is modelled as a function of intrinsic growth rate, SST, carrying capacity and effort).

[9]COBE-SST2 data used in this study are available at https://www.esrl.noaa.gov/psd/.

[10]We also used SST data from the optimum interpolation climate-scale in situ and satellite SST analyses by the National Oceanic and Atmospheric Administration (NOAA OISST; Reynolds et al., 2002) and arrived at similar results. NOAA OISST Version 2 data are available at https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.html.

Depending on whether a logarithmic or quadratic relationship between SST and carrying capacity is assumed, the estimation equation varies slightly in functional form as shown by Equations (1) and (3). The motivation for including a quadratic equation is the hypothesis that the relationship between SST and carrying capacity may experience an inflection point. While several single-species ecological studies have shown some increase in carrying capacity with moderate increase in temperatures, it is widely assumed that those ecological benefits will not be sustained with larger changes in temperatures and the accompanying ecological change these imply. We therefore estimate a quadratic form that enables us to identify this inflection point. We thus perform both linear and nonlinear (logarithmic and quadratic) estimations and find the latter to be a better fit. This is in line with Mediodia et al. (2023) where nonlinear estimations also provide a better fit. See also Blamey et al. (2023), who identify the complex nonlinear relationship between carrying capacity and another environmental variable (in their case, river flow characteristics).

NZ fisheries are divided into quota management areas (QMAs) for each fishery (e.g., FLA1-10 for flatfish in Figure 1), which are further split into statistical areas (not shown here) for catch reporting requirements. Estimations for Equations (1) and (3) for the three species were applied to data by statistical area and aggregated to QMA level (Figure 1).[11]

We use the marginal product at means (MP_{SST}) to estimate the effect of SST on catch, that is, the MP_{SST} is defined as the change in catch due to a 1°C Celsius increase in SST given mean values of effort and SST. As discussed, we assume either a logarithmic or quadratic relationship between the SST and the carrying capacity of the fish stock. Mediodia et al. (2023) show that for the logarithmic specification, we get

$$Catch_{it} = \beta_1 E_{it} \times lnSST_{it} + \beta_2 E_{it}^2 + \varepsilon_{it}, \tag{1}$$

where $Catch_{it}$ is the total catch of species in kilograms per hectare in the statistical area i in year t, E_{it} is the total composite effort measure per hectare in the statistical area i in year t, $lnSST_{it}$ is the natural log of the mean SST in the statistical area i in year t, β_1 and β_2 are the parameter estimates, and ε_{it} is the error term.

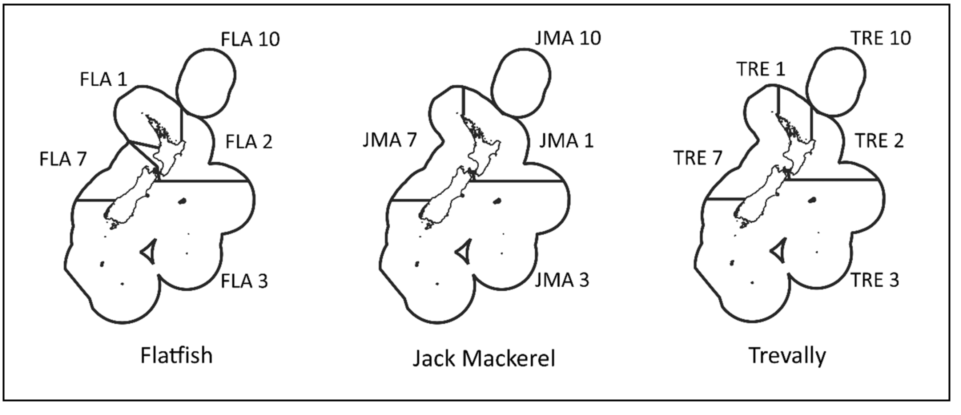

FIGURE 1 Quota management areas of flatfish, jack mackerel and trevally. QMA and EZZ shapefiles are from MPI Open Geospatial Data Portal: https://data-mpi.opendata.arcgis.com/.

[11]The data that support the findings of this study are available from the Ministry of Primary Industries in New Zealand. Restrictions apply to the availability of these data, which were used under licence for this study. Data are available from the authors with the permission of the Ministry of Primary Industries.

If a logarithmic relationship between SST and carrying capacity is assumed, then the marginal product of SST at means is computed as

$$MP_{SST} = \frac{\partial Catch}{\partial SST} = \beta_1 \frac{E_{it}}{SST_{it}}. \quad (2)$$

For the quadratic specification, we get

$$Catch_{it} = \beta_1 E_{it} \times SST_{it} + \beta_2 E_{it} \times SST_{it}^2 + \beta_3 E_{it}^2 + \varepsilon_{it}, \quad (3)$$

where the variables are defined as in Equation (1). When assuming a quadratic relationship between SST and carrying capacity, the marginal product of SST at means is computed as

$$MP_{SST} = \frac{\partial Catch}{\partial SST} = \beta_1 E_{it} + 2\beta_2 SST_{it} \times E_{it}, \quad (4)$$

The marginal revenue product (MRP) of SST (MRP_{SST}) is computed by converting the MP_{SST} to NZ dollar terms for the total fished area for each species and fishing method (see NOTES under Table 2 for computation details). FishServe[12] provides average port prices for the three species, and we use the most recently available price at the time of writing this study (2017–2018) to calculate the economic impact on commercial catch. The average port prices per kilogram of green weight are 4.59 NZD for flatfish, 0.29 NZD for jack mackerel and 1.24 for trevally.[13]

We use a composite effort measure given that trevally, jack mackerel and flatfishes are caught together with other species of fish using vessels of different sizes. The composite effort measure is calculated as a multiplication of effort measure and vessel characteristics following Pradhan et al. (2003) and Campbell and Nicholl (1994), that is, the composite effort measure (E_{it}) is computed as

$$E_{it} = Eff_{it} \times \%\,Catch_{it} \times VLength_{it}, \quad (5)$$

where E_{it} is the standardized effort measure in the statistical area i in year t, Eff_{it} is the total effort measure in the statistical area i in year t, $\%\,Catch_{it}$ is the percentage of catch of species to total catch in the statistical area i in year t, and $VLength_{it}$ is the average vessel length in the statistical area i in year t.

Vessel length accounts for the differences in the characteristics of fishing vessels. This measure is positively correlated with other vessel characteristics such as beam, draught, gross tonnage and engine power. We use two measures of fishing effort: total fishing duration in hours and total number of sets. Separate estimations are conducted for each of the effort measures.

2.3 | Estimation procedure

Regression through the origin (RTO) is applied to exclude the unrealistic possibility of positive catch without fishing effort. RTO is routinely applied in fisheries production functions such as

[12]FishServe is a privately owned company that provides administrative services to the New Zealand commercial fishing industry (https://www.fishserve.co.nz/).

[13]Port prices are very stable with standard deviations less than 0.1 for inflation-adjusted prices between 2011 and 2018 for all three species. Port prices can be provided by the authors upon request.

in Armstrong et al. (2016), Thuy et al. (2013), and Foley et al. (2010). Parameters were estimated using the ordinary least squares method for pooled data using STATA 16.

We extended Equations (1) and (3) by incorporating statistical area fixed effects and time trend individually and simultaneously. Statistical area fixed effects are included to control for time-invariant, area-specific factors that may affect catch, such as location and bathymetry. A time trend is included in a specification to account for technological progress. Finally, we use the Akaike information criterion (AIC) to evaluate the different model specifications.

3 | RESULTS

3.1 | Summary statistics

Bottom trawl and set net are the most common methods used to catch flatfish (Table 1b). Though only used in 57.1 per cent of the reported events, bottom trawl accounts for 88.1 per cent of total flatfish catch from 1990 to 2018. Both bottom trawl and set net are multi-species fishing methods with the set net being more efficient in targeting flatfishes (83.3%) compared with bottom trawl (36.7%). However, the catch per unit effort (CPUE) in terms of duration is greater at 99.6 kg per hour for bottom trawl compared to the set net at only 10.7 kg per hour.

Table 1b shows that 76.9 per cent of total jack mackerel caught in NZ was by midwater trawl; however, midwater trawl (39.5%) comes second to bottom trawl (50.6%) in terms of fishing events. The share of jack mackerel to total catch is the highest for midwater trawl at 54.5 per cent compared with 17.2 per cent for bottom trawl and 10.6 per cent for the set net. Midwater trawl is included in our analysis for jack mackerel only as this method is not relevant to flatfishes and trevally.

Similar to flatfishes, bottom trawl and set net are the top two methods used to catch trevally, with bottom trawl accounting for 71.5 per cent of the total trevally caught. The CPUE in terms of duration for bottom trawl (205.8 kg per hour) is a lot higher than that for set net (27.4 kg per hour). The average share of species to total catch for each fishing method for the statistical areas is presented in Figure S1.

The total catch in metric tonnes by species and fishing method used is presented in Figure 2. The concentration of catch of flatfish, jack mackerel and trevally occurs close to the shores. The catch of bottom trawl flatfish is high in the south of the North Island waters and all coastal statistical areas in the South Island. The catch of trevally is concentrated in the coastal areas of the North Island. Jack mackerel is caught by midwater trawls in most of the statistical areas relatively homogeneously. There are very few areas in which trevally and flatfishes are caught using midwater trawls.

Figure 3a shows the average annual SST by statistical areas in NZ from 1990 to 2018 using COBE-SST2 data. The SST ranges from a high of 22°C in subtropical areas to a low of 7°C in areas closest to the South Pole. The waters in NZ EEZ are warming over time as shown by the upward trend in the annual mean SST (Figure 3b).

3.2 | Modelled impacts of SST on carrying capacity

The estimation of parameters for models with different specifications (Equations 1 and 3 with time trends; fixed effects; etc.) showed that the lowest AICs are found for models which include both a time trend and statistical area fixed effects, for both assuming a logarithmic relationship (Equation 1) and quadratic relationship (Equation 3; see Table S2). Table 2 shows the MP_{SST} of flatfish, jack mackerel and trevally for the three fishing methods using the model with trend and statistical area fixed effects for estimations with more than 200 observations.

TABLE 1B Summary statistics: Average annual catch and effort by fishing event, 1990–2018.

	Fishing events		Catch (tonne)		Effort count			Effort duration (hours)			Per cent catch of species to Total catch
Fishing methods/species	**Freq**	**%**	**Total**	**%**	**Total**	**%**	**CPUE**	**Total**	**%**	**CPUE**	
Flatfish											
Bottom trawl	488,743	57.1	274,060	88.1	946,486	83.5	289.6	2,750,649	45.5	99.6	36.7
Set net	363,613	42.5	35,003	11.2	123,396	10.9	283.7	3,282,988	54.3	10.7	83.3
Other methods	2849	0.4	2095	0.7	63,270	5.6	33.1	14,378	0.2	145.7	
Total	855,205	100.0	311,158	100.0	1,133,152	100.0	274.6	6,048,015	100.0	51.4	
Jack mackerel											
Bottom trawl	117,075	50.6	357,879	22.5	146,702	45.1	2439.5	530,284	49.8	674.9	17.2
Midwater trawl	91,373	39.5	1,222,493	76.9	90,886	27.9	13450.8	320,644	30.1	3812.6	54.3
Set net	17,201	7.4	4213	0.3	16,662	5.1	252.9	204,008	19.1	20.7	10.6
Other methods	5898	2.5	5761	0.3	71,026	21.9	81.1	10,932	1.0	527.0	
Total	231,547	100.0	1,590,346	100.0	325,276	100.0	4889.2	1,065,868	100.0	1492.1	
Trevally											
Bottom trawl	191,983	54.5	174,275	71.5	278,418	20.0	625.9	846,806	42.5	205.8	24.1
Set net	92,766	26.4	28,466	11.7	92,300	6.6	308.4	1,040,658	52.3	27.4	22.2
Other methods	67,285	19.1	41,081	16.8	1019,004	73.4	40.3	103,260	5.2	397.8	
Total	352,034	100.0	243,822	100.0	1,389,722	100.0	175.4	1,990,724	100.0	122.5	

Abbreviation: CPUE, catch per unit effort.

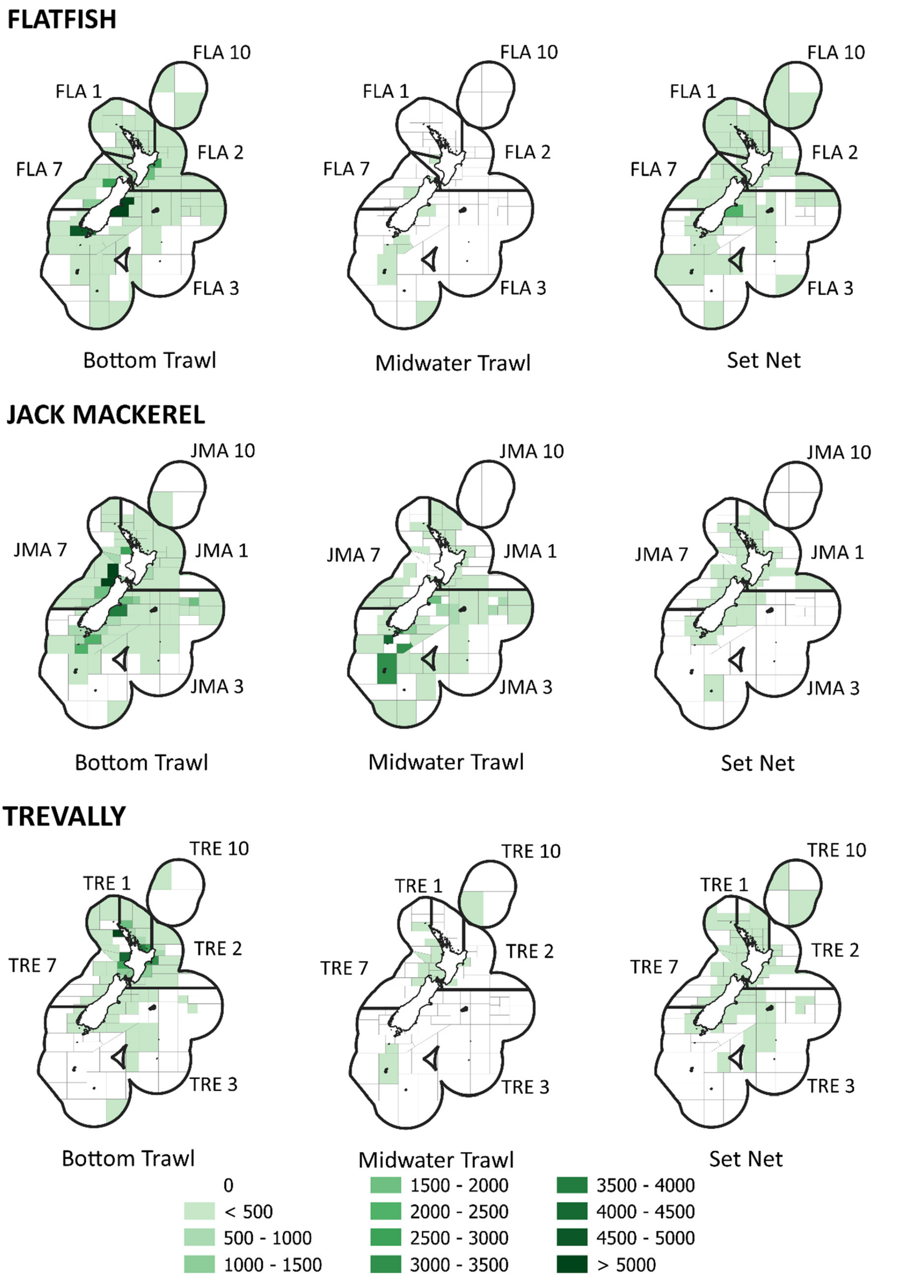

FIGURE 2 Total catch per species and fishing method (1990–2018; in metric tonnes). [Colour figure can be viewed at wileyonlinelibrary.com]

The MP_{SST} computed using other specifications yielded similar results (Table S2). Only the parameter estimates, which are statistically significant at 10 per cent, are considered in the calculation of the marginal products.

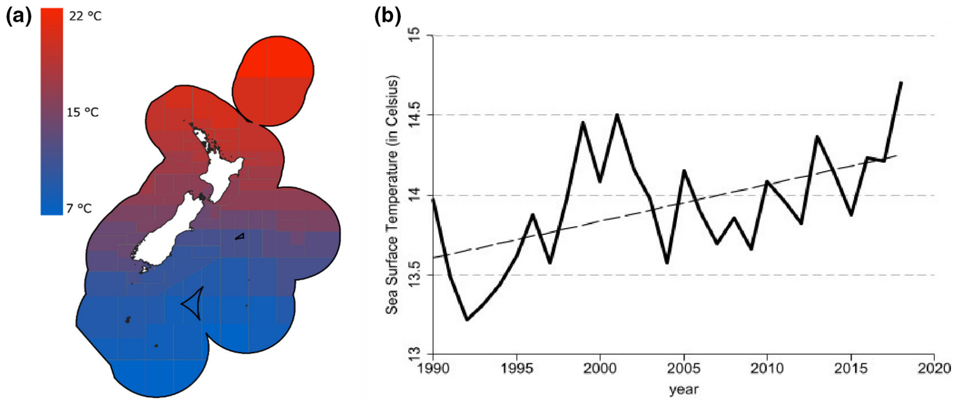

FIGURE 3 Average annual sea surface temperature in NZ exclusive economic zone (a) by statistical area and (b) from 1990 to 2018. [Colour figure can be viewed at wileyonlinelibrary.com]

Assuming a logarithmic relationship between the SST and the carrying capacity of the fish stock, the catch of the three species increases with a 1°C increase in SST for the three fishing methods, albeit only marginally (Table 2). For flatfish, the MP_{SST} for set nets is greater than bottom trawl; that is, the catch of flatfish by set net is expected to increase by 3.89 grams per ha of area fished (3.33% of the average annual catch per ha). This increase has a current economic value of 3.26 million NZD for the whole of NZ (computed by the MRP). The MP_{SST} of flatfish for bottom trawl is 1.05 grams per ha (2.57% of average catch) or a MRP of 1.53 million NZD. The opposite is true for trevally with the MP_{SST} for bottom trawl (0.96 grams per ha or 2.22% of average catch) being higher compared with set net (0.31 grams per ha or 1.59% of average catch). The highest MP_{SST} is found for jack mackerel using midwater trawl at 16.33 grams per ha (2.93% of average catch), translating into a MRP of 552 thousand NZD for the whole of NZ (Table 2).

Figure 4 shows the MP_{SST} for each statistical area using the logarithmic model. All values are positive for statistical areas with fishing effort, with higher values in areas close to the coast. The MP_{SST} for all species using set nets is low (5.2×10^{-6} to 85 grams per ha), and the values for jack mackerel midwater trawl are high ranging from 1.1×10^{-4} to 101.1 grams per ha.

Assuming a quadratic relationship, the MP_{SST} is negative for flatfish-bottom trawl, flatfish-set net, jack mackerel bottom trawl and trevally set net. For flatfish, a 1°C increase in SST results in 4.61 grams per ha (11.29% of average catch) reduction in catch of flatfish using bottom trawls and 13.47 grams per ha (11.52% of average catch) if using set nets (Table 2). This is equivalent to a reduction in fishing revenue by 6.70 million NZD for bottom trawl and 11.28 million NZD for set nets. The highest catch is expected if SST is at 10.01°C for bottom trawl and 11.61°C for set nets (Table 2). The MP_{SST} is also negative for jack mackerel caught using bottom trawl and trevally caught using set nets. The catch of jack mackerel by midwater trawl, however, is expected to increase by 8.58% of the annual average (47.84 grams per ha) as a result of 1°C increase in SST. The MP_{SST} computed using mean values of the SST and effort for each statistical area are presented in Figure 5. Higher values of MP_{SST} are observed in areas closer to the South Pole with some values being positive for flatfishes by bottom trawl and set net, jack mackerel by bottom trawl and trevally by set net. For jack mackerel caught by midwater trawl, higher values of MP_{SST} are in statistical areas close to the coast.

We group the observations by QMA and run the analysis separately for each QMA for each species and fishing method, that is, Table 3 shows the MP_{SST} of flatfish, jack mackerel and

TABLE 2 Akaike information criterion, R^2, marginal product of sea surface temperature (SST) at means (in grams per ha) and marginal revenue product (in NZD) for each species and fishing method.

		Logarithmic				Quadratic				
Method/species	n[a]	R^2	**AIC**	MP_{SST}	MRP_{SST}[b]	R^2	**AIC**	MP_{SST}	MRP_{SST}	**Opt. Temp**
Flatfish										
Bottom trawl	1392	0.95	−6297	1.05	1,526,289	0.96	−6544	−4.61	−6,701,135	10.01
Set net	1235	0.93	−1524	3.89	3,256,877	0.94	−1690	−13.47	−11,277,670	11.61
Jack mackerel										
Bottom trawl	1472	0.96	−4441	1.81	138,630	0.96	−4510	−2.89	−221,348	12.17
Midwater trawl	906	0.96	216	16.33	552,461	0.96	150	47.84	1,618,479	
Set net	638	0.97	−6791	0.03	1408	0.97	−6853			
Trevally										
Bottom trawl	1019	0.91	−4834	0.96	41,864	0.92	−4862			
Set net	966	0.96	−5327	0.31	18,977	0.96	−5440	−2.38	−145,696	10.65

[a]Observation n refers to the number of statistical areas for which total amount of catch and effort has been recorded each year.

[b]We use COBE-SST2 as the source of SST data and duration as a measure of effort. Marginal revenue product (MRP) = MP_{SST} (grams/ha) × Price (NZD/kilogram) × Total fished area in NZ (ha) × 0.001 (kilogram/gram). 2017/2018 port prices were used to compute MRP.

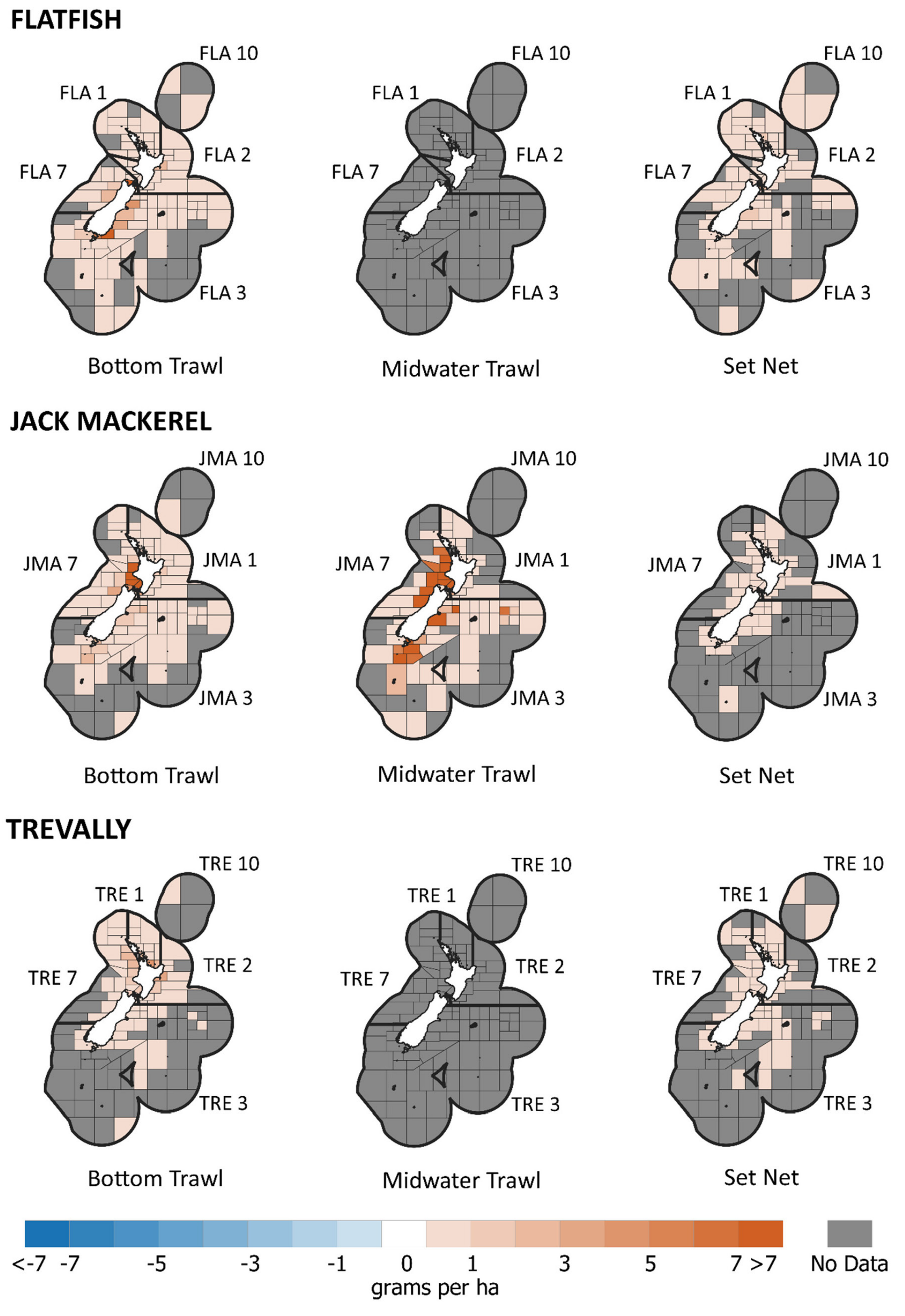

FIGURE 4 Marginal product of sea surface temperature (SST) assuming a logarithmic relationship between SST and carrying capacity of the fishery (in grams per ha for 1°C increase in SST). [Colour figure can be viewed at wileyonlinelibrary.com]

trevally for the three fishing methods for observations grouped by QMA. The model assumes either logarithmic or quadratic relationships between SST and carrying capacity and includes time trend and statistical area fixed effects (the MP_{SST} for a model with time trend only, and a

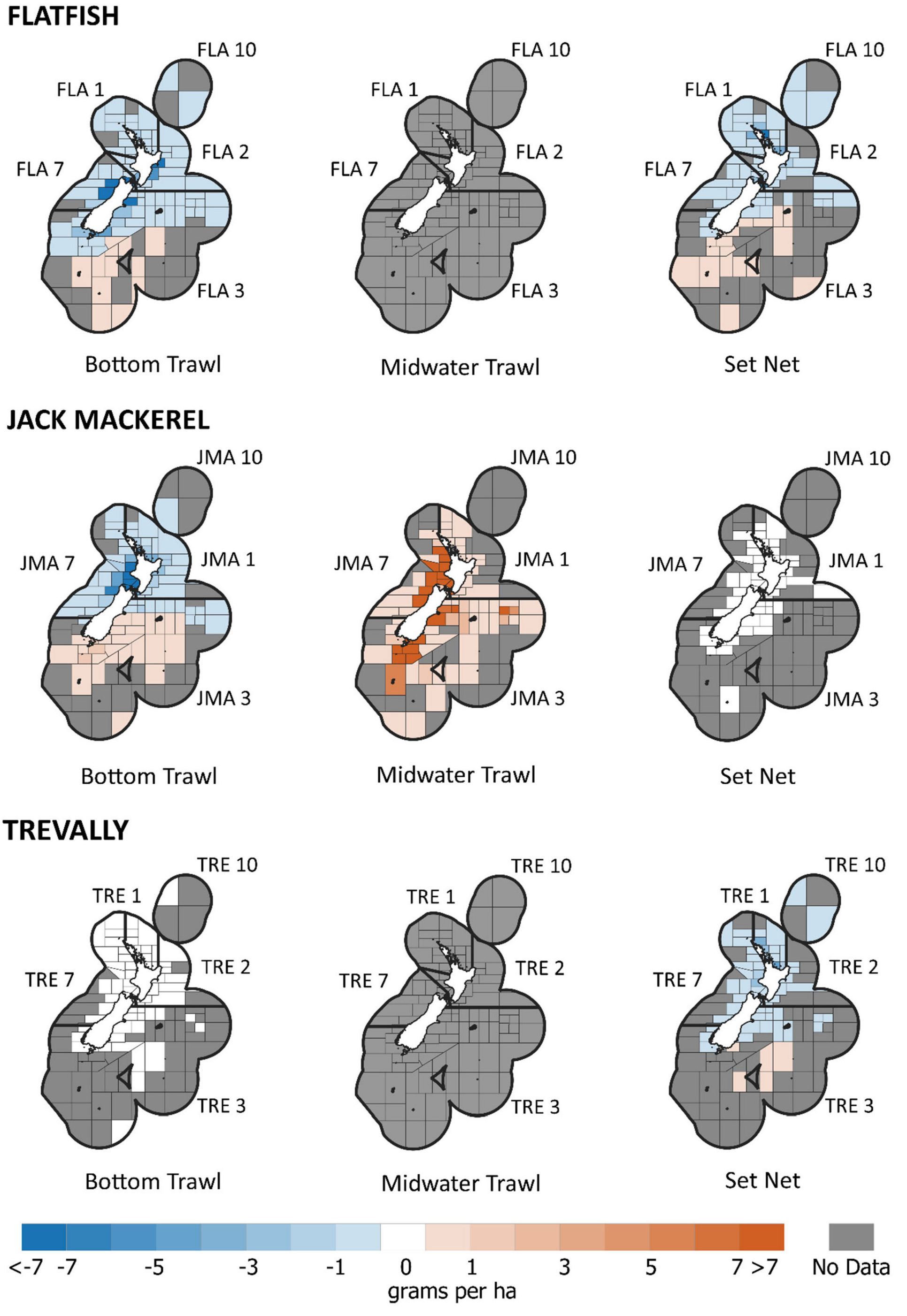

FIGURE 5 Marginal product of sea surface temperature (SST) assuming a quadratic relationship between SST and carrying capacity of the fishery (in grams per ha for 1°C increase in SST). [Colour figure can be viewed at wileyonlinelibrary.com]

model with a statistical area dummy only, are presented in Tables S3 and S4, showing similar results). The MP_{SST} for the logarithmic model is positive while the MP_{SST} is negative when a quadratic relationship is assumed. The QMAs on the western side of NZ have higher MP_{SST}

TABLE 3 Marginal product of SST at means (in grams per ha), Akaike information criterion, and R^2 for each species, fishing method and quota management area (QMA).

			Logarithmic			Quadratic			
Species/method	**QMA**	***n***	R^2	**AIC**	MP_{SST}	R^2	**AIC**	MP_{SST}	**Opt. Temp**
Flatfish									
Bottom trawl	1	358	0.86	−2646	0.14	0.90	−2745	−1.84	10.14
Bottom trawl	2	268	0.95	−1835	0.50	0.97	−1918	−2.86	10.43
Bottom trawl	3	536	0.94	−2272	1.09	0.94	−2315	−5.98	8.19
Bottom trawl	7	227	0.97	−881	2.03	0.98	−912	−11.75	9.85
Set net	1	511	0.93	−205	7.77	0.94	−264	−48.55	11.50
Set net	2	229	0.91	−2003	0.17	0.92	−2014		
Set net	3	308	0.81	−2383	0.14	0.81	−2382		
Set net	7								
Jack mackerel									
Bottom trawl	1	454	0.85	−2919	0.24	0.91	−3164	−4.62	9.72
Bottom trawl	3	555	0.91	−3013	0.75	0.92	−3049	−0.67	10.42
Bottom trawl	7	460	0.97	−917	4.08	0.97	−937	−11.47	11.89
Midwater trawl	1								
Midwater trawl	3	442	0.93	−206	8.11	0.95	−403		
Midwater trawl	7	343	0.97	309	28.94	0.97	297		
Set net	1	292	0.98	−3128	0.04	0.98	−3139		
Set net	3								
Set net	7	241	0.98	−2880	0.01	0.98	−2887		
Trevally									
Bottom trawl	1	268	0.92	−1157	1.11	0.92	−1169		
Bottom trawl	2	206	0.96	−1393	0.77	0.96	−1392		
Bottom trawl	3								
Bottom trawl	7	449	0.91	−2032	1.13	0.92	−2062		

(Continues)

TABLE 3 (Continued)

			Logarithmic			Quadratic			
Species/method	**QMA**	***n***	R^2	**AIC**	MP_{SST}	R^2	**AIC**	MP_{SST}	**Opt. Temp**
Set net	1	271	0.95	−2119	0.17	0.95	−2117		
Set net	2								
Set net	3								
Set net	7	433	0.96	−2055	0.60	0.96	−2108	−4.20	10.71

compared with other areas. For flatfish, the highest MP_{SST} is in QMA 1 for set net and in QMA 7 for bottom trawl. QMA 7 has the highest MP_{SST} for both bottom and midwater trawls and QMA 1 for set nets for jack mackerel. For trevally, higher MP_{SST} are found in QMA 7. The QMAs that record high MP_{SST} in the logarithmic model have the lowest MP_{SST} in the quadratic model.

4 | DISCUSSION

In this study, we use a comprehensive catch and effort data from Aotearoa New Zealand that allows us to account for vessel characteristics in defining the effort measure. Given the depth of detail in these data, the analysis is conducted for three species of fish and three fishing methods separately. It also allows us to distinguish between different QMA and identify the spatial pattern of these differences.

We establish a nonlinear relationship between SST and carrying capacity of selected commercial fish stocks in NZ using a bioeconomic model pioneered by Barbier and Strand (1998) and implemented in a different context in Mediodia et al. (2023). Our results show that both logarithmic and quadratic relationships yield statistically significant and identifiable patterns, with substantial economic implications for fishers.

Under the assumption of a logarithmic relationship, MRP calculations suggest fishers catching flatfish by set net can benefit from up to 3.26 million NZD from 1°C of ocean warming, but can lose over 11 million NZD if a quadratic relationship holds. These results also vary spatially, with the latter relationship leading to a negative MP_{SST} for most areas but positive for areas closer to the South Pole where temperatures are still lower than the identified inflection point in the quadratic results. Importantly, our results for quadratic relationships show that the catch of flatfish, trevally and jack mackerel initially increases with SST but eventually decrease after an 'optimal' level of SST is reached, where the computed optimal levels are already close to the lower bound of the average annual SST currently obtained in most of NZ's waters (but not yet in the southern management areas). This implies there is a risk that the SST will soon increase above this inflection point, and catch will start to decrease. These results are in line with Mediodia et al. (2023) who also identify the presence of inflection points for tuna in the Eastern Pacific Ocean.

Our findings also highlight the need to conduct analyses specific to each species and fishing method. Flatfishes and trevally are demersal species that have a limited latitudinal range. These species cannot easily migrate to other areas within their temperature preference, potentially yielding negative impacts on commercial fishing. This is in line with Ryer (2008) who shows that the catchability of flatfish decreases as the ocean warms, and a recent review of sustainability measures by Fisheries NZ which acknowledges the risk of changes in water temperature on spawning and larval transport for trevally (Fisheries NZ, 2023). Jack mackerel, instead, is a pelagic species and can swim in a wider latitudinal range. Given the extensive spatial cover of the NZ EEZ, this likely explains why the SST for jack mackerel is still positive under the assumption of a quadratic relationship between SST and carrying capacity.

Our results also indicate a poleward redistribution of catch for flatfish and trevally with ocean warming, that is, the increase in SST results in an increase in catch in areas closer to the South Pole for these two species. This is consistent with the expectations described in Cheung et al. (2012) that marine species move towards the poles as oceans warm.

Based on the results from the three de facto open-access fisheries in this study, it is difficult to predict with certainty how SST will affect higher value species within the Quota Management System where total allowable catch is already binding. However, if the carrying capacity conclusions we reached are also applicable to these other species, it seems clear that quotas have to be adapted dynamically to take the reduced capacity of these fisheries into account. The international literature on the need for adaptive fisheries management under climate change is growing rapidly (e.g., Palacios-Abrantes et al., 2020; Sumby et al., 2021; Vasco et al., 2023), and our study shows the need for fisheries management to consider the responses of species to ocean warming. We show that there are differences in MP_{SST} within each QMA and a blanket policy for all the EEZ, or identical policies for the existing QMA, may be counterproductive, that is, the management of a fishery accounting for temperature increases requires a heterogenous approach to the existing QMAs. For example, JMA 3 may be divided into two QMAs that differentiate areas close to the coast of South Island and areas closer to the South Pole. In this context, one should also question whether the aim of these quotas is to maintain fish stocks in each QMA, in the NZ EEZ more broadly, or even in the southern ocean (including areas outside the NZ EEZ).

Though flatfish, trevally and jack mackerel are commercially fished, there are limited studies on how SST affects the behaviour of these species and few studies (reviewed earlier) about other species. This limits our ability to discuss our results in the context of the biological and ecological drivers of the responses of these species to ocean warming. In the absence of a comprehensive biological assessment, our results therefore provide indicative information about the responses of fish species to increasing SST. All of our conclusions should thus be viewed as indicative, and require further study of the exact biological and ecological reasons that are driving the changes we appear to identify using catch data.

We acknowledge that our work considers species groups, with 6 species of flatfish and three species of jack mackerel. These species are managed in NZ collectively, fishers are not required to report catch of each species separately, and thus, we only have aggregate data on each species group. This is a limitation in so far as each species, within each group, may have a different sensitivity to changes in the ecosystems in which it lives. The different geographical distributions and thermal tolerances of these species of flatfishes and jack mackerels require further investigation, and potentially species-specific policy adjustment in response to ocean warming, once this information is available.

Beyond further investigation of the biological drivers of our findings, and the inter-species differences within the species groups we investigate, further work should also include estimating the economic impacts of ocean warming in terms of revenue, cost of fishing and fisher behaviour to mitigate the impacts of ocean warming. Generally, though, we believe our analysis suggests a need to rethink fisheries management policies in response to fish redistribution due to ocean warming.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the Ministry of Primary Industries in New Zealand. Restrictions apply to the availability of these data, which were used under licence for this study. Data are available from ilan.noy@vuw.ac.nz with the permission of the Ministry of Primary Industries.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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