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Mixed responses of tropical Pacific fisheries and aquaculture to climate change

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Pacific Island countries have an extraordinary dependence on fisheries and aquaculture. Maintaining the benefits from the sector is a difficult task, now made more complex by climate change. Here we report how changes to the atmosphere–ocean are likely to affect the food webs, habitats and stocks underpinning fisheries and aquaculture across the region. We found winners and losers—tuna are expected to be more abundant in the east and freshwater aquaculture and fisheries are likely to be more productive. Conversely, coral reef fisheries could decrease by 20% by 2050 and coastal aquaculture may be less efficient. We demonstrate how the economic and social implications can be addressed within the sector—tuna and freshwater aquaculture can help support growing populations as coral reefs, coastal fisheries and mariculture decline.

Fisheries and aquaculture are of great importance to the people of the tropical Pacific. Nowhere else do so many countries and territories depend as heavily on fish and shellfish for economic development, government revenue, food security and livelihoods. The contributions to government revenue alone are extraordinary—7 of the 22 Pacific Island countries and territories receive up to 40% of their taxes from tuna fishing licences sold to distant water fishing nations and another 5 countries and territories derive up to 25% of their gross domestic product (GDP) from industrial fisheries and fish processing[1].

Fish is also a cornerstone of food security in the region. Fish consumption, based mainly on small-scale subsistence and commercial fishing for coral reef fish and pelagic fish, including tuna (Supplementary Table S1), is often 2–4 times the global average and supplies 50–90% of dietary animal protein in rural areas[2]. The large inland communities of Papua New Guinea (PNG) are the exception, but even there the freshwater fish catch[1] is four times greater than in Australia. Across the region, 50% of households in surveyed coastal communities earned their first or second incomes from fishing or selling fish[3]. Aquaculture contributes >20% of the average GDP derived from the sector and is locally significant—pearl farming employs thousands of people on remote atolls[4] and fish farming in small ponds is gaining momentum in inland PNG (ref. 5).

Plans have been developed to maintain the substantial benefits Pacific Island nations receive from fisheries and aquaculture in the face of the many drivers affecting the sector, such as population growth and the resulting increased demand for fish and habitat degradation[6]. However, countries and their development partners are now asking whether these plans could be affected by climate change.

To answer this question, we used an end-to-end climate-to-fish-to-fisheries approach[7] (Supplementary Fig. S1). We cascaded changes to the tropical Pacific Ocean and surface climate, projected to occur under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A2 emissions scenario[8] by global climate models, along direct and indirect pathways (Supplementary Fig. S2) to identify: which of the region's diverse oceanic, coastal and freshwater fisheries and aquaculture resources and activities[9] are expected to increase or decline by 2035, 2050 and 2100 as greenhouse-gas emissions increase; the implications for Pacific Island economic development, government revenue, food security and livelihoods; the priority adaptations and policies needed to minimize the threats and maximize the opportunities; and the research still required to improve our understanding of how tropical Pacific fisheries and aquaculture are likely to respond to rapid climate change.

Changes to surface climate and the ocean

The tropical Pacific has warmed substantially over the past 50 years and the intensified hydrological cycle has reduced the salinity of the

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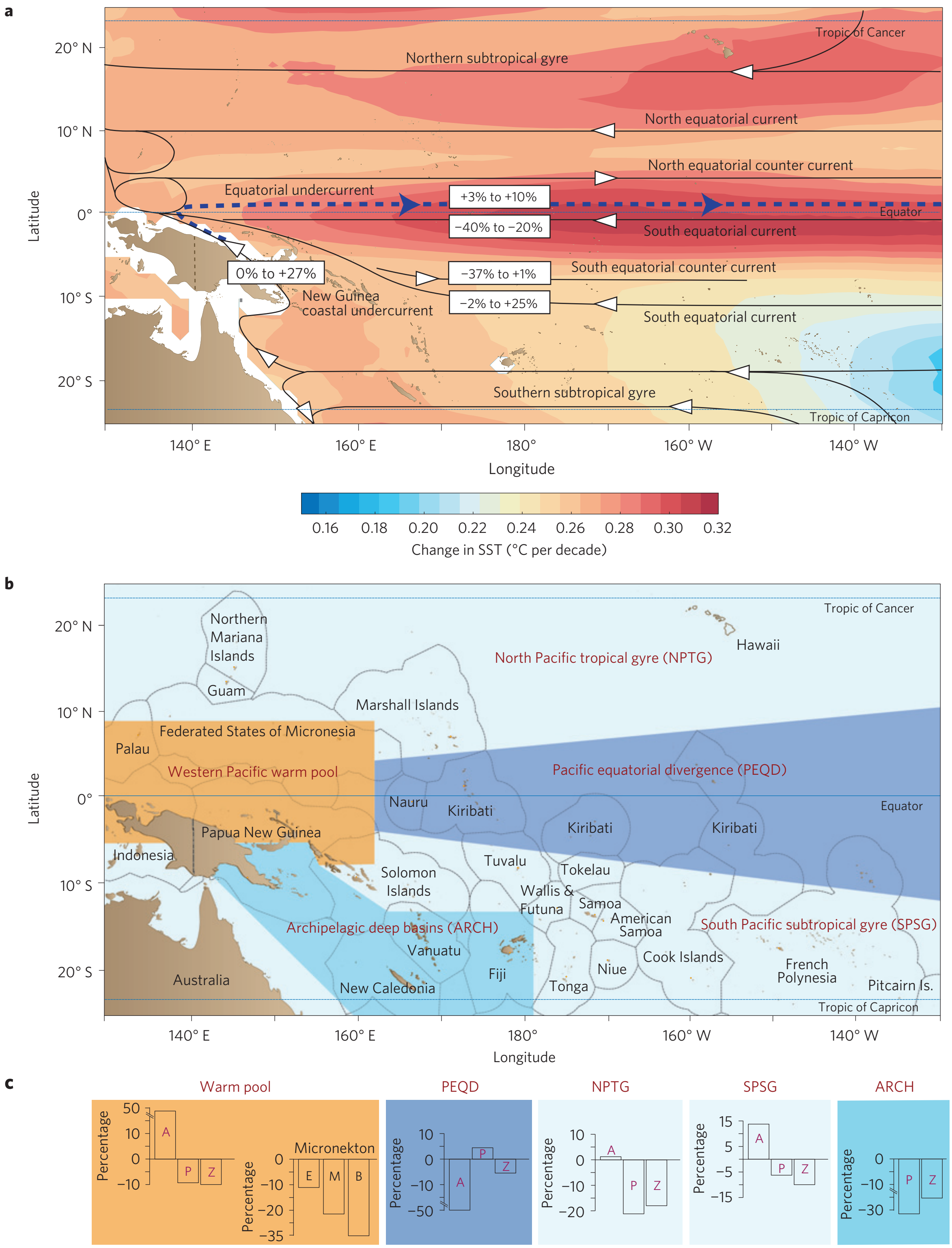

Figure 1 | Projected changes to the tropical Pacific Ocean under the IPCC SRES A2 emissions scenario. a, Trends in SST and major surface (black) and subsurface (dashed) currents between 1980–2000 and 2080–2100. Values for currents are volume transport ranges (90% confidence interval for multi-model means). **b**, The five ecological provinces relative to Pacific Island countries and territories. **c**, Changes in area (A), net primary production (P) and zooplankton biomass (Z) of provinces (see **b** for definitions) between 2000–2010 and 2090–2100. The area of ARCH does not change by definition. Changes in epipelagic (E), mesopelagic (M) and bathypelagic (B) micronekton in the warm pool are also shown.

western Pacific warm pool[10,11]. These observed changes are expected to intensify (Supplementary Fig. S3 and Table S2). Notwithstanding uncertainties associated with the South Pacific convergence zone[12] (SPCZ) and warm pool[13], the models project large increases in rainfall along the western SPCZ and intertropical convergence zone, and decreases for parts of the subtropics. The greatest increases in rainfall are projected for the equatorial Pacific, whereas decreases are expected to occur in the southeast of the region

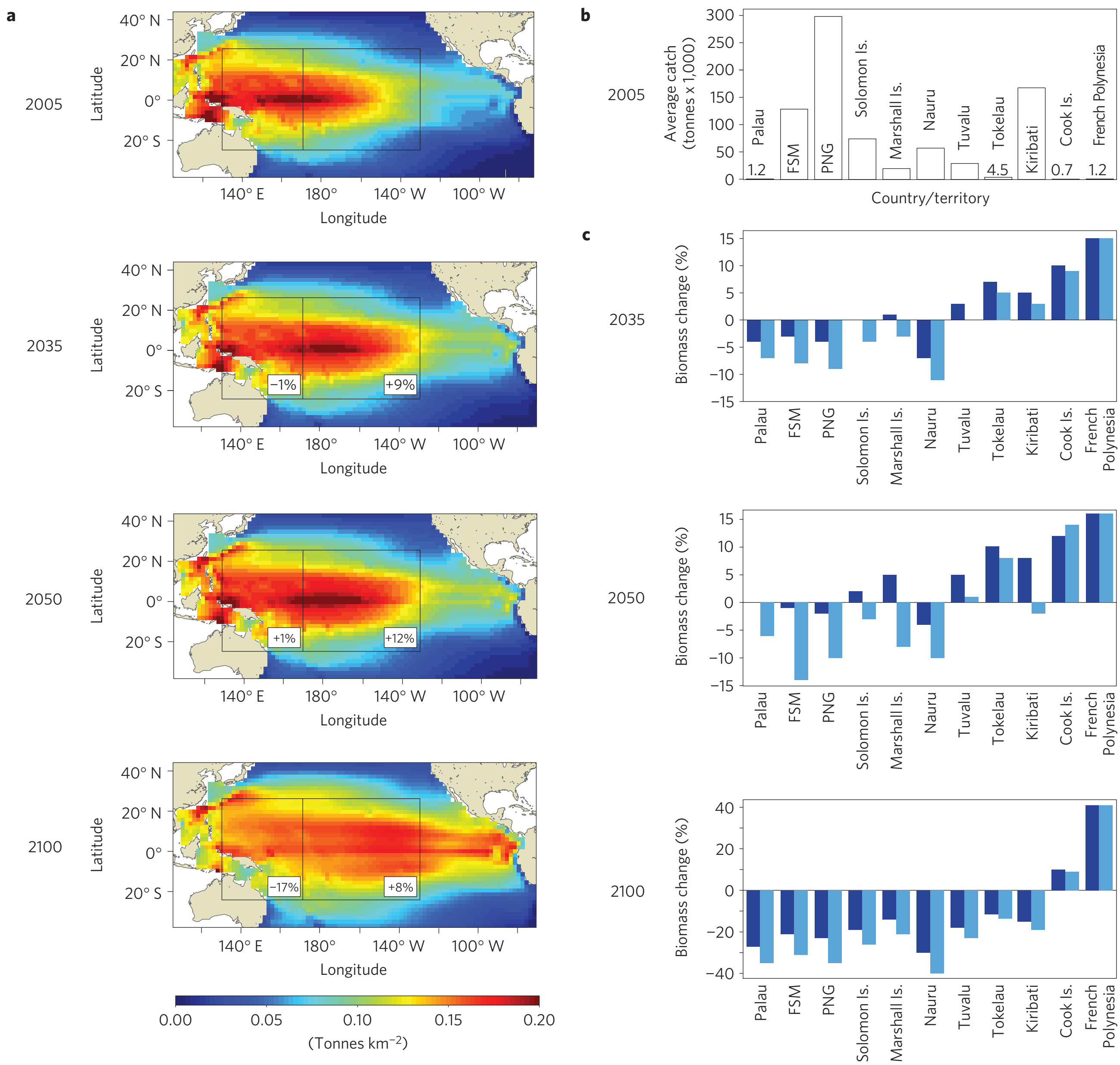

Figure 2 | Projected distributions of skipjack tuna biomass across the tropical Pacific Ocean under the IPCC SRES A2 emissions scenario. a, Simulation for 2005, and projections for 2035, 2050 and 2100, derived from the SEAPODYM model (see Methods), including projected average percentage changes for the outlined areas east and west of 170° E. **b**, Recent average annual catches of skipjack tuna (2000–2010) from EEZs of selected Pacific Island countries and territories; FSM, Federated States of Micronesia. **c**, Estimated changes in biomass relative to virgin stock levels (dark blue), and incorporating fishing effort 1.5 times greater than the average for 1990–1999 (light blue), for 2035, 2050 and 2100.

(Supplementary Fig. S3 and Table S2). These changes are consistent with rapid warming of the central equatorial Pacific Ocean and slower warming in the southern subtropics[14] (Fig. 1a). The combined effects of higher sea surface temperature (SST) and freshening will increase stratification of the upper water column, particularly in the warm pool[9,15]. There is little agreement among models about how the El Niño/Southern Oscillation (ENSO) might change, but the importance of this primary driver of regional interannual variability is expected to be maintained[16]. Interactions between ENSO and enhanced warming may also cause more extreme fluctuations of the SPCZ towards the Equator during strong El Niño events[17]. Tropical cyclones are projected to be less frequent with the strongest events potentially becoming more intense[9,15].

Weakening of the equatorial and northeast trade winds, and stronger southeast trade winds (Supplementary Fig. S3), are expected to help drive significant changes in ocean circulation. The strength of the south equatorial current near the equator is projected to weaken by an average of 30% by 2100 (Fig. 1a and Supplementary Table S2), whereas the New Guinea coastal undercurrent and equatorial undercurrent are expected to strengthen in the western Pacific[9,18,19] (Fig. 1a). The south equatorial counter current is also likely to weaken (Fig. 1a and Supplementary Table S2) and extend less to the east. These circulation changes are expected to have knock-on effects for nutrient delivery to the photic zone[9], although local island processes, poorly resolved in present climate models, are likely to be important[20].

Increasing atmospheric CO_2 concentrations are projected to drive decreases in the pH of surface waters from ~8.1 to ~7.8 by 2100, reducing aragonite saturation (Ω) from 3.9 to an average of 2.4 (ref. 21; Supplementary Table S2). Regional sea-level rise is likely

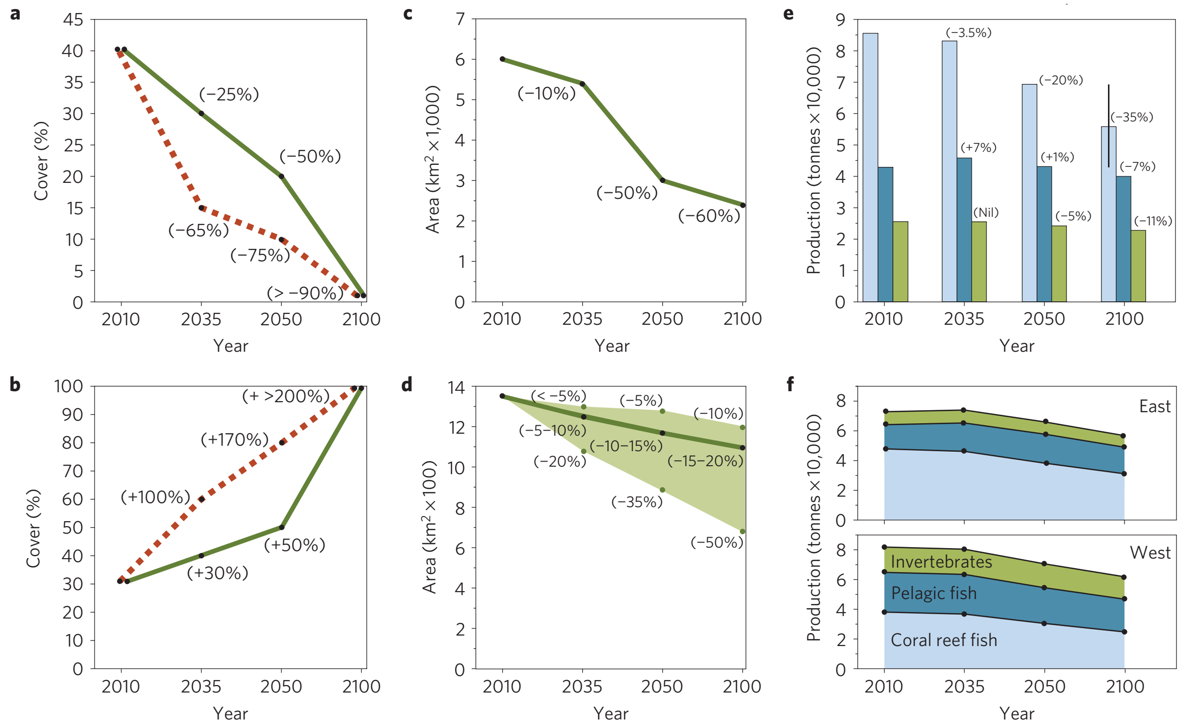

Figure 3 | Projected changes in tropical Pacific coastal habitats and fisheries production. a, Live coral cover under strong (solid) and weak (dashed) management. **b**, Seaweed cover under strong (solid) and weak (dashed) management. **c**, Total mangrove area. **d**, Total seagrass area (shading indicates range of seagrass loss among countries). **e**, Total catches for coastal fisheries categories (see **f** for legend); vertical line represents estimated range. **f**, Total catches for coastal fisheries categories east and west of 170° E, reflecting differences in pelagic fish catch in the east and west (see Methods). Information in brackets represents change relative to 2010.

to be close to the global average, with estimates for 2100 ranging from 23 to 58 cm (from climate models[22]), to more than 1 m (from semi-empirical models[23]; Supplementary Table S2).

Effects on oceanic ecosystems and fisheries

Changes to ocean currents and temperature are projected to alter both the area and productivity of the ecological provinces of the tropical Pacific Ocean[24] (Fig. 1). Expansion of the warm pool and contraction of the Pacific equatorial divergence (PEQD) province are likely to shift the prime feeding grounds for tuna[25] to the east. Reductions in nutrient supplies to surface waters from greater stratification and weaker eddy activity[9] are expected to substantially reduce net primary production (NPP) and zooplankton biomass in all provinces except PEQD (Fig. 1c). A reduced supply of nutrients decreases the average size of phytoplankton, and increases the number of trophic links within food webs, making energy transfer less efficient[9].

Simulation of the food web in the warm pool (see Methods) indicates that a 9% reduction in NPP by 2100 could cause similar decreases in biomass of epipelagic micronekton—key prey for tuna. Even greater decreases in mesopelagic and bathypelagic micronekton are projected (Fig. 1c) because production/biomass ratios for these groups are <50% lower than for epipelagic micronekton.

Our most recent analysis of skipjack tuna, *Katsuwonus pelamis*, the dominant tuna species in the region (Supplementary Table S3), using the Spatial Ecosystem and Population Dynamics Model[26] (SEAPODYM) indicates that this species is likely to move progressively to the central-eastern Pacific and to subtropical areas[27] (Fig. 2). Ocean warming and reduced productivity, which will make the warm pool less suitable for spawning, and an eastward shift in the convergence zone between the warm pool and PEQD, drive the projected redistribution of this valuable fish. The simulations indicate that skipjack tuna biomass is likely to increase in the exclusive economic zones (EEZs) of Pacific Island countries and territories east of 170° E, and decrease marginally within the EEZs west of 170° E, by 2035 and 2050 owing to climate change alone (Fig. 2a). Greater decreases are expected in the west when the effects of fishing are considered (Fig. 2c and Supplementary Table S4). By 2100, biomass of skipjack tuna is projected to decline substantially in the EEZs of most countries and territories, except those in the far east-southeast of the region (Fig. 2 and Supplementary Table S4).

Effects on coastal ecosystems and fisheries

The coral reefs, mangroves and seagrasses that support coastal fisheries in the tropical Pacific are under threat from climate change. More frequent coral bleaching events driven by increasing SST (Fig. 1a), and reduced ability of corals to calcify due to decreasing Ω (ref. 28), are projected to reduce the biological and physical complexity of coral reefs[9]. Even under good management (for example, controlling runoff), coral cover is expected to decrease from the present-day maximum of 40% to 15–30% by 2035 and 10–20% by 2050 (Fig. 3a), matching the rate of decline over the past 30 years[29]. As coral cover decreases, the ability of corals to compete with macroalgae (seaweed) for space will be reduced[9], potentially leading to 40% seaweed cover on reefs by 2035 (Fig. 3b).

The steep terrain of islands in the western Pacific, where most mangroves occur[30], will limit the capacity of this habitat to migrate landward with sea-level rise. Furthermore, faster sea-level rise (Supplementary Table S2) could outstrip the capacity of mangroves to adapt owing to their limited tolerance to extended immersion in sea water[9]. Higher temperatures, increased turbidity, sedimentation and nutrient loads associated with greater rainfall, and more intense tropical cyclones, are likely to have negative effects on seagrasses. Loss of seagrass habitat is expected through increased burning of leaves at low tide, reduced light, overgrowth by epiphytic algae, smothering by sediments or scouring of meadows by storm surge[9].

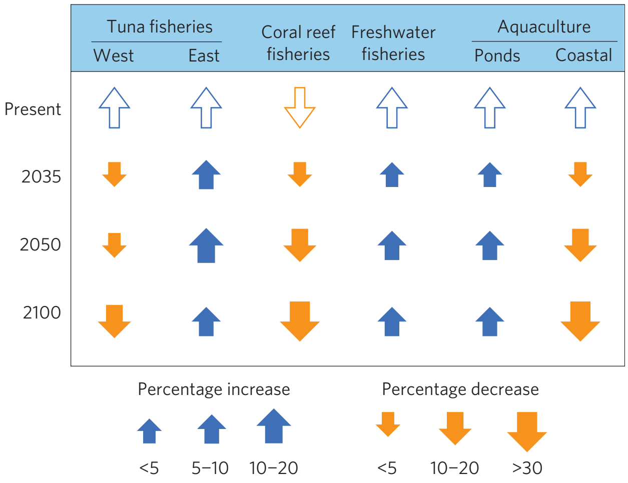

Figure 4 | Projected directions of existing plans to derive more livelihoods from fisheries and aquaculture resources, and effects of climate change on these plans. Projections are for the IPCC SRES A2 emissions scenario in 2035, 2050 and 2100, summarized as estimated increases (winners) or decreases (losers) in broad percentage categories. Oceanic (tuna) fisheries are separated into those east and west of 170° E. Projections for pond and coastal aquaculture (mariculture) are not relative to present-day production (which has potential for increase) and indicate estimated changes in production efficiency.

Although increased CO_2 concentrations should promote growth of mangroves and seagrasses, on balance, large losses of these habitats are projected (Fig. 3c,d).

The large number of fish and invertebrates, especially coral reef species, supporting coastal fisheries in the region precludes the species-specific modelling used for tuna. Other approaches[31,32] are needed to evaluate the status of these resources and their responses to climate change, given the relatively low economic value of each species and limited national capacity for research. Although there is still much uncertainty, changes to SST, ocean currents and pH (Fig. 1a and Supplementary Table S2) are expected to have direct effects on the distribution, reproduction, dispersal, recruitment success, growth and size of fish and invertebrates associated with coastal habitats[9,33,34]. Declines in primary productivity (Fig. 1c) and loss of coral reefs, mangroves and seagrasses (Fig. 3) will also affect these species indirectly. The combined effects on coral reef fish are expected to alter the composition of catches and reduce production. Such changes may be minimal by 2035 and difficult to separate from ongoing effects of fishing and local habitat degradation. However, by 2050 production of coral reef fish is projected to decrease by 20% (Fig. 3e; see Methods). The potential impacts on invertebrates are still poorly understood but considered to be more moderate (Fig. 3e). Productivity of the other major category of coastal fisheries, pelagic fish, is related largely to the response of tuna (see above and Methods); that is, catches in the east are projected to increase under climate change (Figs 2 and 3f).

Effects on freshwater ecosystems and fisheries

In contrast to coastal ecosystems, the net combined effects of climate change have the potential to enhance habitats for freshwater fish and invertebrates. In particular, greater fluctuations in river flow from higher rainfall (Supplementary Table S2) should expand river channel and floodplain habitats in Melanesia and largely overcome the potential negative effects of higher water temperatures, lower dissolved oxygen levels and sea-level rise on freshwater fish habitats associated with global warming[9]. Discharge from the large Sepik River in PNG is projected to increase by 33% by 2050 (ref. 35) and, across much of the region, freshwater habitats are expected to increase by up to 10% by 2035 and >20% by 2100. Taking into account spatial variation in rainfall (Supplementary Fig. S3), and the capacity for vegetation cover to mitigate catchment disturbance[36], freshwater fisheries production in most of Melanesia is expected to increase by at least 2.5% by 2035 and 7.5% by 2100. However, in catchments where runoff from mining, agriculture and logging operations contaminates watercourses, the potential increase in fish production is unlikely to eventuate because freshwater fish and invertebrates are more sensitive to increasing temperature in polluted water[37].

Effects on aquaculture

Climate change should also enhance freshwater aquaculture across the region, but reduce the efficiency of producing commodities in coastal waters[9]. As temperature increases, the main species produced in freshwater ponds, Nile tilapia (*Oreochromis niloticus*), should grow faster and farming will be possible at higher elevations. Greater rainfall (Supplementary Fig. S3) will also allow fish ponds to be built at more locations, including perhaps some equatorial islands where conditions for freshwater aquaculture are now marginal.

The lucrative black pearl industry in Polynesia[4] may be particularly sensitive to increases in SST and ocean acidification. Higher SST affects nacre deposition and pearl quality, and increases the susceptibility of pearl oysters *Pinctada margaritifera* to disease[38]. Survival and growth of wild spat, which provide most of the pearl oysters for farms, are expected to decrease as shells are weakened by lower Ω concentrations. Reduced availability of aragonite—a key component of nacre—may also affect pearl quality[39]. Farming operations for the shrimp *Litopenaeus stylirostris* in New Caledonia will be challenged by sea-level rise. Higher water levels and encroachment of mangroves will prevent existing shrimp ponds from drying out between production cycles—an essential management measure to reduce anoxic conditions[40]. Higher SST and rainfall also cause problems for farming the seaweed *Kappaphycus alvarezii*—warmer SST and lower salinity stress the plants and inhibit growth, resulting in crop losses due to increased outbreaks of epiphytic filamentous algae and tissue necrosis[9].

Implications for economies and communities

Overall, the potential economic benefits to the region from an eastward shift in skipjack tuna (Fig. 2) could exceed the threats. The large contributions that licence fees make to government revenue of atoll nations[1] should increase further until at least 2050 as the biomass and catches of skipjack tuna increase in their EEZs (Fig. 2 and Supplementary Table S4). The effects of declining catches in the west should be relatively minor because tuna fishing and processing make limited contributions to the larger national economies of PNG and the Solomon Islands[1], and because there are several practical ways to secure fish to supply canneries (see below).

Declines in production of coral reef fish (Fig. 3e,f) will widen the emerging gap between the fish needed for food security in rapidly growing Pacific Island countries[2,9] and the fish available through sustained harvests from coral reefs[41] (Supplementary Table S5 and Methods). In such countries (for example, PNG, Samoa, the Solomon Islands and Vanuatu), even well-managed coastal fisheries will not supply the 35 kg of fish per capita per year recommended for good nutrition[2] in the years to come owing to the limited areas of coral reef relative to population size, and rapid population growth. The effects of population growth on availability of fish are profound and declines of 20% in coral reef fish production by 2050 due to climate change are expected to increase the emerging gap only marginally (Supplementary Table S5).

Maintaining livelihoods based on coastal fisheries and mariculture will require some income-earning activities to be switched from resource losers to resource winners (Fig. 4). Coastal fishing effort

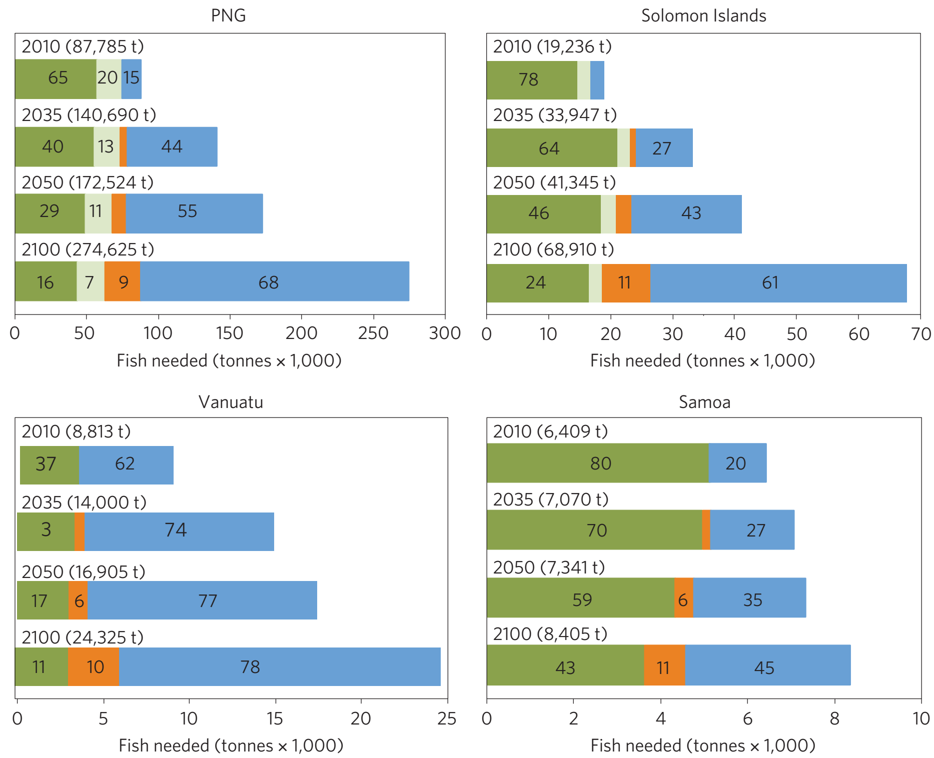

Figure 5 | Percentage contributions of various fisheries and aquaculture resources required to supply selected Pacific Island countries and territories with the fish recommended for good nutrition. Contributions of resources needed to supply 35 kg of fish per person per year in 2035, 2050 and 2100 have been adjusted for the effects of climate change on coastal fisheries[9]. Estimates of the fish required in PNG are based on national consumption of 13 kg per person per year[2] to reflect difficulties in distributing fish to inland areas. Percentages do not always sum to 100 owing to rounding; tuna (blue), coastal fisheries (dark green), freshwater fisheries (light green), pond aquaculture (orange).

will need to be transferred progressively from coral reef fish to pelagic fish, particularly tuna. Ironically, in an archipelagic region, many of the extra jobs in aquaculture in the future are likely to come from farming freshwater fish.

Adaptation options and supporting policies

Careful management of tuna fisheries is needed to enable the smaller nations in the east, already dependent on licence fees, to gain more revenue, and allow those in the west to continue to receive the fish needed for canning operations. Key adaptations will involve development of flexible fishing effort schemes and diversifying supplies of fish for processing. The cap and trade vessel day scheme[42] (VDS) is a win–win adaptation (Table 1). The VDS caters for present-day climatic variability in the distribution of tuna due to ENSO (ref. 25), allowing some benefits to be shared among participating countries regardless of ENSO phase. Redistribution of tuna due to climate change will also be accommodated by the VDS through periodic adjustment of fishing days allocated among countries based on recent catches. The global sourcing provisions of an Economic Partnership Agreement with the European Union (Table 1) are expected to assist countries with canneries to maintain the supplies of fish they need as skipjack tuna move east.

To maintain the contributions of fish to food security, adaptation measures must: minimise the gap between the fish required for good nutrition of growing populations and sustainable coastal fisheries harvests (Supplementary Table S5); and provide access to other sources of fish to fill the remaining gap. Key adaptations to reduce the gap include: conservative fishing practices to maintain the replenishment potential of stocks; safeguarding fish habitats by managing catchment vegetation to reduce transfer of sediments and nutrients to coasts; preventing pollution and direct damage to coral reefs; and planning infrastructure to allow fish habitats to migrate in response to the changing environment (Table 1).

Adaptation options to fill the gap centre on increasing access to tuna—the only resource with potential to meet most of the projected shortfalls in fish for food security (Fig. 5 and Supplementary Table S6). Priority adaptations to increase access to tuna include: distributing small-sized fish (and bycatch) landed in the region by industrial vessels to urban populations—a measure made easier by the recent ban on discarding small tuna at sea by the Western and Central Pacific Fisheries Commission—and installing inshore fish aggregating devices (FADs)[43] to improve catches of tuna and other pelagic fish by small-scale fishers (Table 1). Growing Nile tilapia in ponds, an activity favoured by warmer temperatures, will be a priority adaptation for supplying more fish to PNG's large inland population (Table 1). Nevertheless, care will be needed to minimize exposure of ponds to the increased risks of flooding.

For livelihoods based on culturing pearls, adaptations to reduce the consequences of higher SST and ocean acidification include growing oysters in deeper water, producing selectively bred spat in hatcheries[44] and identifying sites where Ω concentrations are adequate to produce high-quality pearls. For shrimp farming, it will be important to raise the floor and wall height of ponds so they continue to drain effectively as sea level rises[40] (Table 1).

Other examples of adaptations and policies to minimize the threats posed by climate change to the important socio-economic contributions made by fisheries and aquaculture, and maximize opportunities, are provided in Table 1.

Research still required

To improve knowledge about the vulnerability of national plans for fisheries and aquaculture, and optimize adaptations, uncertainty

Table 1 | Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from fisheries and aquaculture, and to maximize the opportunities.

Adaptation options*	Supporting policies
Economic development	
Full implementation of the VDS to control fishing effort by the Parties to the Nauru Agreement† (W–W)	Strengthen national capacity to administer the VDS
Diversify sources of fish for canneries and maintain trade preferences, for example, an Economic Partnership Agreement with the European Union (W–W)	Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna
Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change (W–W)	Include implications of climate change in management objectives of the WCPFC
Energy efficiency programmes to assist fleets to cope with oil price rises, minimize CO_2 emissions and reduce costs of fishing further afield as tuna move east (W–W)	Apply national management measures to address climate-change effects for subregional concentrations of tuna in archipelagic waters beyond WCPFC's mandate
Pan-Pacific tuna management through a merger of the Western and Central Pacific Fisheries Commission (WCPFC) and Inter-American Tropical Tuna Commission to coordinate management measures across the entire tropical Pacific (L–W)	Require all industrial tuna vessels to provide operational-level catch and effort data to improve models for projecting redistribution of tuna stocks during climate change
Food security	
Manage catchment vegetation to reduce transfer of sediments and nutrients to rivers and coasts to reduce damage to freshwater fish habitats and coral reefs, mangroves and seagrasses supporting coastal fisheries (W–W)	Strengthen governance for sustainable use of coastal fish habitats by: building national capacity to understand the threats of climate change; empowering communities to manage fish habitats; and changing agriculture, forestry and mining practices to prevent sedimentation and pollution
Foster the care of coral reefs, mangroves and seagrasses by preventing pollution, managing waste and eliminating direct damage to these coastal fish habitats (W–W)	Minimize barriers to landward migration of coastal habitats during development of strategies to assist other sectors to respond to climate change
Provide for migration of fish habitats by: prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help plants colonize landward areas as sea level rises; and allowing floodplains to expand as rainfall increases (L–W)	Apply primary fisheries management[31] to stocks of coastal fish and shellfish to maintain their potential for replenishment
Sustain and diversify catches of coral reef fish to maintain the replenishment potential of all stocks (L–W)	
Increase access to small tuna and bycatch caught by industrial fleets through storing and selling these fish at major ports to provide inexpensive fish for rapidly growing urban populations (W–W)	Allocate the necessary quantities of tuna from total national catches to increase access to fish for both urban and coastal populations
Install FADs (ref. 43) close to the coast to improve access to tuna and other large pelagic fish for rural communities as human populations increase and coral reef fish decline (W–W)	Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security
Develop coastal fisheries for small pelagic fish species, for example, mackerel, anchovies, pilchards, sardines and scads (W–W‡)	Include inshore FADs as part of national infrastructure for food security, and undertake regular maintenance and replacement of FADs
Improve simple post-harvest methods, such as traditional smoking, salting and drying, to extend the shelf life of fish when good catches are made (W–W)	Limit tilapia farming to catchments with a shortage of fish and where tilapia are already established to reduce potential risks to biodiversity
Develop hatchery and grow-out systems for expansion of semi-intensive and intensive freshwater pond aquaculture (W–W)	
Livelihoods	
Relocate pearl farming operations to deeper water and sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for growth and survival of pearl oysters, and formation of high-quality pearls (L–W)	Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be climate-proofed and relocated if necessary
Raise the walls and floor of shrimp ponds so that they drain adequately as sea level rises (L–W)	Strengthen environmental impact assessments for coastal aquaculture activities to include the risks posed by climate change
Identify which shrimp ponds may need to be dedicated to producing other commodities (L–W)	Foster partnerships with regional technical agencies to support development of sustainable aquaculture

*These measures are classified as win–win (W–W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or lose–win (L–W) adaptations, where benefits do not exceed costs in the short term but accrue under longer-term climate change[50]. See ref. 9 for the full range of recommended win–win and lose–win adaptations. †The Parties to the Nauru Agreement (PNA) are Palau, the Federated States of Micronesia, PNG, Solomon Islands, Marshall Islands, Nauru, Kiribati and Tuvalu; >90% of the tuna caught from the waters of Pacific Island countries comes from the EEZs of PNA members. ‡Small pelagic fish are expected to be favoured by climate change only where changes to currents and eddies deliver more nutrients to surface waters.

will need to be reduced at many levels, starting with the ecosystem processes underpinning all forms of fisheries and aquaculture production and the socio-economic factors that may affect uptake of priority adaptations. The questions below illustrate some of the tasks that lie ahead (see also Supplementary Table S7).

How will extra nutrients delivered to PNG's coastal waters by increased flows from major rivers change fisheries production?

Will a stronger equatorial undercurrent transport enough iron to the Pacific equatorial upwelling to reduce iron-limitation of primary production[45] and enhance fisheries?

Could decreases in strength of the south equatorial current and south equatorial counter current exacerbate declines in coral reef fisheries by reducing larval dispersal and stock replenishment?

What are the ecological linkages between coral reef, seagrass and mangrove habitats, and what contributions do fish and shellfish associated with mangroves and seagrasses make to coastal fisheries?

Will coral reefs degraded by climate change increase the incidence of ciguatera fish poisoning[9], further reducing availability of coral reef fish for food security?

How should communities be assisted to remove any blockages to expanding the use of inshore FADs and pond aquaculture to improve access to fish for food security?

Which polices best reconcile enhanced opportunities for pond aquaculture with conservation of freshwater biodiversity[46]?

How can mariculture be expanded in ways that help make operations resilient to climate change?

What measures are needed to harmonize opportunities for increased freshwater fish production from floodplains with protection of agricultural land and infrastructure from inundation?

The long-term observations required to answer many of these questions will improve our understanding of the biogeochemical processes needed to improve climate, ecosystem and tuna models—necessary steps towards providing more complete and localized assessments of the vulnerability of fisheries and aquaculture to climate change.

Concluding remarks

The projected redistribution of the region's abundant tuna resources and prospects for enhanced freshwater aquaculture production have potential to strengthen the contributions made by fisheries and aquaculture to many Pacific Island economies and communities. To capitalize on this potential, tuna stocks must be managed to maintain good rates of replenishment and sustainable pond aquaculture must become widespread, especially throughout inland PNG.

Coastal communities can adapt to the projected declines in coral reef fish production by diversifying the use of fisheries and aquaculture resources to meet their needs for food security and livelihoods. Transferring fishing effort from coral reef fish to tuna around inshore FADs will be particularly important.

As profound as the effects of climate change on the supply of coral reef fish for food security are eventually likely to be, they will be overshadowed by the effects of population growth for many years to come. The onus is on governments, communities and their development partners to implement a range of win–win adaptations and supporting policies (Table 1) to address both drivers.

It comes as no surprise that management measures to reduce the impact of local stressors on coastal fish habitats, for example, through restoring catchment vegetation to minimize the effects of sediments and nutrients on coral reefs, are prime win–win adaptations. The need for integrated coastal zone management to maintain coastal fisheries production has been recognized for many years[47] and should help build resilience of coral reefs, mangroves and seagrasses to climate change[9]. Implementing effective integrated coastal zone management is now imperative.

Methods

Projected changes to surface climate and the tropical Pacific Ocean were derived from the output of the Coupled Model Intercomparison Project version 3 (CMIP3) archive[48]. Slightly different subsets of models were used for each variable (Supplementary Table S8). Climate projections were made for the IPCC SRES A2 emissions scenario[8] for three periods: 2025–2045 (2035), 2040–2060 (2050) and 2080–2100 (2100), relative to 1980–2000. Our application of global climate models should be regarded as a snapshot of the present understanding of projected changes to the tropical Pacific Ocean and surface climate under a high-emissions scenario.

Effects on oceanic ecosystems and fisheries. Changes to the areas of the ecological provinces of the tropical Pacific Ocean, and the rates of change of NPP and zooplankton biomass within these provinces, were derived from the Institut Pierre Simon de Laplace - Climate Model 4 (IPSL-CM4), coupled to the Pelagic Interaction Scheme for Carbon and Ecosystem Studies biogeochemical model. The trophic mass-balance ecosystem model, Ecopath with Ecosim, was used to examine the effects of projected changes to NPP on the food web of the western Pacific warm pool province.

We used the SEAPODYM modelling framework[26] to investigate relationships between the influence of fish physiology, the direct effects of physical and chemical changes to the ocean, and the indirect effects of changes to food webs, on the spatial distribution of skipjack tuna. The modelling was restricted to this species because it dominates tuna catches in the region (Supplementary Table S3). The simulation was driven by the physical–biogeochemical fields predicted from the IPSL-CM4 model, coupled to the Pelagic Interaction Scheme for Carbon and Ecosystem Studies biogeochemical model and forced by atmospheric CO_2 for the A2 scenario.

Effects on coastal ecosystems and fisheries. Changes to the ecosystems and stocks supporting coastal fisheries were assessed using the IPCC vulnerability framework, which is based on exposure, sensitivity, potential impact and adaptive capacity. Exposure of habitats was determined from projected changes to surface climate and the ocean. Sensitivity was evaluated by integration of known or estimated responses of corals, mangroves and seagrasses to such exposure. Exposure of coral reef fish and invertebrates (defined here to include species from nearby mangrove and seagrass habitats) was determined by combining the direct effects of changes to surface climate and the ocean on these species, and the indirect effects of alterations to their supporting habitats.

Projected decreases in live coral cover were based on expected changes to SST and aragonite saturation (Supplementary Table S2); and present-day trends in coral loss of 1–2% yr^{-1} (refs 28,29). Projected reductions in mangrove habitat were based on documented losses of mangroves resulting from recent sea-level rise, and expected rates of inundation under conservative estimates of sea-level rise (Supplementary Table S2). Loss of seagrass was based on the combined effects of elevated temperature, storm-related disturbance and turbidity, and sea-level rise. Greater uncertainty accompanies the 2100 projections for seagrass loss owing to a poor understanding of the distribution and species composition of seagrasses in many countries, and the possible intensity of storm events.

Changes to coastal fisheries production were estimated by integrating the direct and indirect effects of climate change on three categories of species: coral reef fish, pelagic fish and invertebrates. Estimates for coral reef fish were based on integrating projections for obligate corallivores and coral residents, reef-associated species and generalist species. Projected changes to production of pelagic fish were derived from the modelling for skipjack tuna and the effects of changes in NPP on other pelagic species. Separate estimates were made for catches east and west of 170° E. Changes to the invertebrate catch were assessed using expert opinion and published accounts of effects of habitat change on abundance of key species.

Effects on freshwater ecosystems and fisheries. Changes in freshwater fish production were also based on the IPCC vulnerability framework and estimated using a three-stage, stepwise qualitative process (see Supplementary Methods). This analysis synthesized information from all freshwater habitats and used recent estimates of freshwater fish catches[1] to identify expected changes in production.

Effects on aquaculture. The IPCC vulnerability framework was also applied to aquaculture. For freshwater fish farming, sensitivity and adaptive capacity of Nile tilapia to changes in air temperature and rainfall were based on published effects of water temperature and exchange rates on growth and survival[49]. Sensitivity and adaptive capacity of black-lipped pearl oysters to changes in ocean pH and aragonite saturation were extrapolated from a closely related species[39]. Effects of changes in sea level on drainage of shrimp ponds were based on comparisons with the tidal heights and periods required to harvest shrimp efficiently and dry out ponds between crops[40].

A more detailed description of all methods, including those used to estimate the gap in fish needed for food security, is provided in Supplementary Methods.

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Author contributions

J.D.B. designed the study in collaboration with J.E.J. and A.J.H., and compiled the manuscript from analyses and written inputs/review by all authors. The model analyses were done by A.S.G. (surface climate and ocean), A.G. (ocean) and R.J.M. (ecological provinces, NPP and zooplankton biomass); S.P.G. did the modelling of micronekton using Ecopath with Ecosim, and P.L. and I.S. modelled the biomass of skipjack tuna using SEAPODYM.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.D.B.

Competing financial interests

The authors declare no competing financial interests.